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**Polymeric Smart Skin Materials: Concepts, Materials, and Devices**

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Multi-sensor paints have been developed for detection both physical (pressure, temperature, shear, etc.) and chemical (corrosion, explosive) phenomena. Such materials have been transitions to practical applications such as wind tunnel testing and infrastructure monitoring and have also been adopted for fundamental studies of fluid dynamics and insect flight. A variety of carbon nanotube applications have been developed including nanotube actuators for both sensing and active control of surfaces. State-of-the-art OLED and photovoltaic materials have been developed for display and renewal energy source technologies. State-of-the-art organic electro-optic materials and device concepts have been developed and adapted to a variety of defense relevant applications including sensing, information management, and guidance. Organic electro-optic materials have been integrated with silicon photonics producing a new generation of nano/microscale device technology in a thin film format. Project research is playing a critical role in enabling emerging technologies including embedded network sensing by permitting the integration of multiple functions in a thin film (smart skin) format.

**14. SUBJECT TERMS** Multi-sensor paints; carbon nanotube materials and devices; OLED, photovoltaic, and electro-optic devices; integrated silicon photonics; embedded network sensing

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**Polymeric Smart Skin Materials: Concepts, Materials, and  
Devices**

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# Polymeric Smart Skin Materials: Concepts, Materials, and Devices

## Final Technical Report

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### Objectives:

Field-responsive polymers can be used as conformal coatings to transform mechanical structures into multifunctional and smart surfaces. Such thin film materials, or "smart skins," can be used to alter the optical signature (absorption, reflection, or emission) of a surface or object for active stealth and stealth in daylight. They can also generate signals for use in targeting alert or object identification in mobile object networks (such as orbiting nano-satellite clusters or ground-based vehicle groups). Such smart skins can employ emission or beam steering to frustrate guided munitions. They can also act as sensors for surface pressure, icing, and corrosion on aircraft and ground vehicle surfaces and for evaluating the aerodynamic performance of airframes and ground vehicle shapes in wind tunnel testing. Electroactive polymer coatings can be used to improve the performance of devices such as space deployable antenna power systems while performing a variety of additional desired functions. Other applications include laser protection via optical limiting or reflection and dynamic wavefront corrections via surface microelectro-mechanical actuator arrays. The research proposed here builds on an impressive track record of success in developing revolutionary conformal electro-optic thin film materials (*Science*, 288, 119, 2000), solar cell coatings, and pressure-sensitive aircraft paints (U.S. Patent 5,965,642, Oct. 12, 1999; now under commercial development at Boeing and Lockheed Martin and under evaluation at NASA Glenn Laboratories). With General Electric (Honeywell, Allied Signal), we have established the state-of-the-art for polymeric (e.g., single wall carbon nanotube) nano and micro-actuators. Preliminary success has been realized in developing phased-array, photonic, and optically reconfigurable radar systems. Optically tunable photonic bandgap (*IEEE J. Lightwave Tech.*, 17, 1956, 1999) materials have been demonstrated. Recently, sub-picosecond, large angle ( $\pi$  radians) optical beam steering has been demonstrated (employing modest switching voltages) by combining novel polymer electro-optic and photonic bandgap materials.

We propose an aggressive program for dramatically improving the performance of electroactive polymers (and dendrimer) materials for smart skin applications. Research activities are categorized according to the following focus areas: (1) light emitting materials for sensor, remote power, and display applications; (2) two photon materials for sensor protection and photolithography; (3) electrochromic materials for ECM and optical control applications such as switching; (4) electro-optic materials for radar, ECM, sensing, display, and information processing; (5) MEMS and opto-mechanical smart materials, and (6) exploitation of the capability of organic electroactive materials to be integrated into thin film structures.. In (1), we will develop nanoscale dendrimers and photonic bandgap materials to realize a new generation of smart skin sensors capable of detecting pressure, temperature, corrosion, and a variety of chemicals and biomolecules. Dendrimers will afford unprecedented specificity, processability, and stability as well as permitting optimization of sensor signal-to-noise. Photonic bandgap materials will permit amplification of sensor response and will permit a variety of new modes of detection to be explored. In (2), we will exploit dramatic improvement in two-photon absorption that has been recently achieved with dendrimer materials. In (3), a new generation of electrochromic materials including low bandgap materials will be developed. In (4), dramatic advances in electro-optic and photonic bandgap materials will be exploited for precise control of refraction phenomena. New phased array radar (EM steering) and optical spatial light modulator (optical beam steering) will be demonstrated as will a variety of other devices including optical switches and optically-based sensors. As a lower priority, we will explore the utilization of novel MEMS and opto-mechanical materials. We will also focus upon the integration of various material and device classes into 3-D structured smart skin materials. Use will be made of recent advances in reactive ion etching and two-photon photolithography for the fabrication of complex 3-D optical circuits (*IEEE J. Sel. Top. Quant. Electron.*, 35, 1146, 1999).

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### **Comprehensive Summary of the Significant Work Accomplished:**

Substantial progress has been made toward all project objectives. State-of-the-art pressure and temperature sensing paints have been developed and have been transitioned for use in wind tunnel testing. Progress has also been made on incorporating other functionalities into paints to be used for diagnostic evaluation of aircraft, ground vehicle, and ship surfaces. Substantial progress has been realized in developing light harvesting and frequency conversion coatings and improving the efficiency of metals by exploiting the site isolation afforded by the core of dendrimers. Significant progress has been made in developing new photonic bandgap materials. The state of the art of polymeric, dendritic, and dendronized polymer electro-optic materials has been dramatically advanced to the point that these materials now significantly exceed the performance capabilities of inorganic materials, such as lithium niobate, in terms of bandwidth and drive voltage requirements. Moreover, new materials have been incorporated into novel new thin film device structures such as ring microresonators that permit novel manipulation of light including active wavelength division multiplexing (time and wavelength information encoding) and voltage controlled wavelength selective filtering. A variety of new sensors have been developed. Flexible devices have been fabricated and evaluated. Significant advances have been made in exploring the potential of carbon nanotubes for smart skin applications including the potential use of these materials for radar absorbing materials and use as MEMS devices. Advances in polymeric thin films for light emitting, electronic, and photovoltaic applications have been realized.

### **Accomplishments/New Findings:**

A new polymeric pressure-sensitive paint based on a platinum tetra (pentafluorophenyl) porpholactone (PtTFPL) infrared active luminophor has been developed and transitioned. The new porphyrin sensor shows strong phosphorescence with a wavelength maximum 740 nm; this is sufficiently red shifted so that this pressure sensitive luminophor can be used together with a second luminophor as an intensity reference. To avoid self-absorption effects, magnesium tetra (pentafluorophenyl) porphine (MgTFPP) was prepared as an intensity reference. The compound is brightly fluorescent in the solid state; the primary luminescence at 650 nm is not self-absorbed. A dual luminophor paint results with "ideal" pressure sensitive measurement performance of 4.5% per psi and a temperature dependency of less than  $-0.1\%/^{\circ}\text{C}$ .

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New temperature sensor paints have been developed based upon dendrimers exploiting chelation of trivalent europium. A pair of newly and independently synthesized luminescent compounds provide lifetime-based dual pressure and temperature sensing when incorporated into the same paint coating. The luminescence lifetime of the Eu luminophore incorporated into a polymer paint ranges from 50 to 500 microseconds at room temperature and shows very little quenching by oxygen. The temperature dependence of the europium paints ranges from  $-2.0\%/^{\circ}\text{C}$ . to  $-6.0\%/^{\circ}\text{C}$ . With a state of the art CCD camera with charge storage capacities of  $10^5$  electrons per pixel, we estimate that  $0.001^{\circ}\text{C}$  resolution can be obtained with a one second exposure.

Significant progress has been made in the development of electroactive dendrimers, dendronized polymers, hyperbranched polymers, and phase-separating block copolymers. Development of such materials represents a fundamental objective of this research providing a systematic route to the control of intermolecular electrostatic interactions, charge perturbations, energy transport, charge transport, and electronic relaxation relevant to development of optimized electro-optic, optoelectronic (light emitting and light amplifying), photovoltaic, and sensing materials. Development of sensing materials has been discussed in the preceding two paragraphs. Significant advances in organic light emitting device (OLED) materials has also been achieved as is evident from the publications and invention disclosures cited below. New materials also appear to address the issue of pin-hole electrical shorts that was a problem with previous PLED materials. New materials for light harvesting and improved emission efficiency have also been prepared and evaluated. The successes in this area are particularly evident in the cited publications where Professor Frechet is a co-author. Improvement in the efficiency of organic photovoltaic materials has been achieved as well as dramatic improvement in the efficiency of electro-optic materials. Research of Professor Jenekhe and his students has produced blue OLEDs that define the state-of-the-art.

Efficient photoinduced charge transfer and separation accompanied by large photovoltaic power conversion efficiencies were achieved in layered nanostructures of acceptor poly(benzimidazobenzophenanthroline ladder) (BBL) and donor poly(*p*-phenylenevinylene) (PPV) or poly(2-methoxy-5(2'-ethylhexyloxy)-1,4-phenylenevinylene) (MEH-PPV) at practical sunlight intensities. A systematic study of photoinduced electron transfer and photovoltaic properties of donor/acceptor bilayers containing donor PPV or MEH-PPV and a series of acceptor polymers with electron affinities in the range 2.7 – 4.0 eV show that both the charge transfer efficiency at the polymer/polymer interface and the power conversion efficiency of the devices were maximized when the highest electron affinity acceptor polymer BBL (EA = 4.0 eV) was used. The observed power conversion efficiencies of 1.5 – 4.6 % for ITO/PPV/BBL/Al cells under white light illumination of 1 – 80  $\text{mW}/\text{cm}^2$  are among the largest achieved to date in polymer solar cells. Optimization of the bilayer film thicknesses and

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improvements in the hole mobility and photooxidative stability of the donor polymers can be expected to increase the power conversion efficiency of polymer solar cells at high illumination intensities. The observed photovoltages originate from the HOMO–LUMO energy levels in the donor/acceptor bilayer cells. Our results demonstrate that the layered donor/acceptor heterojunction is a promising architecture for developing efficient polymer thin film solar cells.

Organic electro-optic dendrimers and dendronized polymer materials have been developed that exhibit electro-optic coefficients exceeding 400 pm/V at telecommunication wavelengths. An important correlated theoretical and experimental (synthesis, characterization, and application) effort has been developed that has the potential for realizing even larger electro-optic coefficients while permitting the optimization of auxiliary properties.

A number of new thin film device structures have been explored including ring microresonator structures that have great potential for active wavelength division multiplexing, voltage-controlled wavelength selective filtering, voltage controlled laser wavelength tuning, and ultra-sensitive sensors. Such devices can play multiple and critical roles in smart skin applications including that of sensing, signal routing, information encoding and multiplexing. Such devices can play a critical role in information management on airborne platforms and in embedded network sensing. Flexible electro-optic devices have also been prepared and evaluated with observation of extraordinary properties. Polymeric electro-optic materials clearly avoid the development of conformal thin film devices—an opportunity that cannot be achieved with inorganic electro-optic or electro-absorptive materials.

Preliminary success has been achieved in exploring carbon nanotubes as microwave absorbing materials. Carbon nanotubes have also been used to develop MEMS devices including optical switches based on single wall carbon nanotube actuation.

We have demonstrated angle-dependent tuning of reflectivity and color of emissive photonic crystals. Such materials can be used in conjunction with adaptive surfaces (i.e. MEM arrays) to alter the optical signature (reflectivity, perceived color) of the surface. These materials may be useful in developing adaptive low-visibility coatings or total immersion environments, both areas of interest to the Air Force.

A new family of organolanthanide coordination complexes that emit at near-infrared wavelengths are promising candidates for optical amplification and electroluminescence have been developed. These materials and their associated devices can be used in a variety of Air Force relevant applications, including optical signal amplification, and on-chip light sources. The long

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excited-state lifetimes of these materials may be advantageous for developing solid-state polymeric lasers.

Substantial progress has been made demonstrating that sophisticated integration of active organic (and inorganic) elements (devices and circuits) can be achieved in a polymeric thin film motif. This represents significant progress toward our objective of integrated smart skin function where sensing, information routing, information processing, response, and power generation are all integrated in a single smart skin structure. In particular, the integration of organic electro-optic materials into silicon photonic circuitry permits active control of light to be effected in devices of nano/microscopic dimensions. Never before achieved phenomena have been demonstrated. Slotted waveguide silicon photonic ring microresonators have been used both for electrical-to-optical signal transduction and for optical-to-electrical signal transduction. A significant advance has been achieved in increasing the functionality of thin film materials adding significant capability to smart skin materials. Integration of novel materials in a thin film format has permitted dramatic advances in specific performance characteristics, e.g., single molecule detection can be carried out.

# Polymeric Smart Skin Materials: Concepts, Materials, and Devices

## Statistical Report

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### Personnel Supported:

#### ❖ **Professor Larry Dalton**

Number of PI(s) and Co-PI(s) Involved: 2

Number of Post Docs Supported: 5

Number of Graduate Students Supported: 7

Other Researchers Supported: 4

PIs and Co-PIs Supported:

- Larry Dalton
- Bruce Robinson

Postdoctoral Fellows Supported:

- Joseph K. Amend
- Bruce Eichinger
- Arumugasamy Elangovan
- Kimberly Firestone
- William P. Weber

Graduate Students Supported:

- Amit Babel
- Joshua A. Davies
- Llewellyn R. Lawson
- Ivan Shuvalov
- Daniel Sluss
- Jocelyn Y. Takayesu
- James Westphal

Other Researchers Supported:

- Kolby Allen
- Alvin Chang
- Shih-hao Liu
- Eric A. Woodcock

#### ❖ **Professor Alex K-Y. Jen**

Number of PI(s) and Co-PI(s) Involved: 1

Number of Post Docs Supported: 4

Number of Graduate Students Supported: 5

Other Researchers Supported: 0

Postdoctoral Fellows Supported:

- Jingdong Luo
- Shi Liu
- Baoquan Chen
- Qingmin Xu

Graduate Students Supported:

- Petra Herguth
- Tae Dong Kim

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- Sen Liu
- Richard Schofield
- Lixin Zheng

### ❖ **Professor Younan Xia**

Number of PI(s) and Co-PI(s) Involved: 1

Number of Post Docs Supported: 7

Number of Graduate Students Supported: 2

Other Researchers Supported: 0

Postdoctoral Fellows Supported:

- Sang Hyuk Im
- Unyong Jeong
- Xuchuan Jiang
- Kaori Kamata
- Xianmao Lu
- Yugang Sun
- Yuliang Wang

Graduate Students Supported:

- Byron Gates
- Jesse McCann

### ❖ **Professor Alan Heeger**

Number of PI(s) and Co-PI(s) Involved: 1

Number of Post Docs Supported: 9

Number of Graduate Students Supported: 1

Other Researchers Supported: 2

Postdoctoral Fellows Supported:

- Glenn Bartholomew
- Giovanni Bellomi
- Anoop Dhoot
- Xiong Gong
- Youngjin Kim
- Raluca Negres
- Cesare Soci
- Cuiying Yang
- Qinghua Xu

Graduate Students Supported:

- Glenn Bartholomew

Other Researchers Supported:

- Kwanghee Lee
- Daniel Moses

# Polymeric Smart Skin Materials: Concepts, Materials, and Devices

## Statistical Report

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### ❖ **Professor Jean Frechet**

Number of PI(s) and Co-PI(s) Involved: 1  
Number of Post Docs Supported: 5  
Number of Graduate Students Supported: 8  
Other Researchers Supported: 0  
Postdoctoral Fellows Supported:

- Zachary Ball
- Katya Kadnikova
- Christine Luscombe
- Claire Pitois
- Xavier Schultze

Graduate Students Supported:

- Paul Armstrong
- Lan Deng
- Paul Furuta
- Stefan Hecht
- David Kavulak
- Justin Mynar
- Jason Serin
- Kevin Sivula

### ❖ **Professor Aaron Harper**

Number of PI(s) and Co-PI(s) Involved: 1  
Number of Post Docs Supported: 0  
Number of Graduate Students Supported: 4  
Other Researchers Supported: 0  
Graduate Students Supported:

- Patrick J. Case
- Michael D. Julian
- Cory G. Miller
- Asanga B. Padmaperuma

### ❖ **Professor S.A. Jenekhe**

Number of PI(s) and Co-PI(s) Involved: 1  
Number of Post Docs Supported: 2  
Number of Graduate Students Supported: 1  
Other Researchers Supported: 1  
Postdoctoral Fellows Supported:

- M. M.(Faruk) Alam
- T. W. Kwon

Graduate Students Supported:

- Jessica Schendel

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#### ❖ **Professor James M. Tour**

Number of PI(s) and Co-PI(s) Involved: 2  
Number of Post Docs Supported: 4  
Number of Graduate Students Supported: 8  
Other Researchers Supported: 2

PIs Supported:

- James M. Tour
- James Roberts

Postdoctoral Fellows Supported:

- Christopher Dyke
- Bo Chen
- Yubao Li
- Yuxing Yao

Graduate Students Supported:

- Dell Doyle
- Jared Hudson
- Tim Imholt (UNT)
- Joshua Jurs
- David Price
- Katherine Price
- Arnab Mukerjee
- Jason Stephenson

Other Researchers Supported:

- Christy Steger
- Adilah Guiseppi-Wilson

#### ❖ **Professor William Steier**

Number of PI(s) and Co-PI(s) Involved: 1  
Number of Post Docs Supported: 4  
Number of Graduate Students Supported: 2  
Other Researchers Supported: 0

Postdoctoral Fellows Supported:

- She-Won Ahn
- H-C Song
- C. Wang
- C. Zhang

Graduate Students Supported:

- Y-H Kuo
- Reem Song

#### ❖ **Professor Surya Prakash**

Number of PI(s) and Co-PI(s) Involved: 1  
Number of Post Docs Supported: 0  
Number of Graduate Students Supported: 2

# Polymeric Smart Skin Materials: Concepts, Materials, and Devices

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Other Researchers Supported: 0

Graduate Students Supported:

- Ryan DeSousa
- Sujith Chacko

❖ **Professors Martin Gouterman and Gamal Khalil**

Number of PI(s) and Co-PI(s) Involved: 2

Number of Post Docs Supported: 0

Number of Graduate Students Supported: 3

Other Researchers Supported: 0

Graduate Students Supported:

- Kimberly Lau
- Fletcher Kimura
- Wayne Shinoki

### Publications:

#### Summary all years

Total number of publications in refereed journals: 771

Total number of publications which acknowledge AFOSR support: 274

❖ **Professor Larry Dalton**

Number of Publications in Refereed Journals: 148

Number of Publications Which Acknowledge AFOSR Support: 94

#### Publications Which Acknowledge MURI Support

1. Ma, H.; Chen, B.; Sassa, T.; Dalton, L. R.; Jen, A. K-Y. Highly efficient and thermally stable nonlinear optical dendrimer for electro-optics. *J. Am. Chem. Soc.*, (2001), 123(5), 986-987.
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### Statistical Report

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  8. Jen, A. K-Y.; Luo, Jingdong; Ma, Hong; Liu, Sen; Liu, Lu; Haller, M.; Sassa, T.; Kang, .; Dalton, L. R. Nanoscale tailoring of dendrimers and polymers for photonic and opto electronic applications. *Proceedings of SPIE-The International Society for Optical Engineering* (2002), 4798 (Linear and Nonlinear Optics of Organic Materials II), (in press).
  9. Zelelow, B.; Phelan, G.; Carlson, B.; Khalil, G.; Gouterman, S. M.; Dalton, L. R. A lifetime-based pressure and temperature measuring paint with a europium complex as temperature sensor & a platinum porpholactone as pressure sensor 9<sup>th</sup> Annual PSP Workshop, Washington DC, April 6, 2002.
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  12. L. R. Dalton, B. H. Robinson, A. K. Y. Jen, W. H. Steier, and R. Neilsen "Systematic Development of High Bandwidth, Low Drive Voltage Organic Electro-Optic Devices and Their Applications," *Opt. Mater.*, 21, 19-28 (2003).
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  14. S. Liu, M. A. Haller, H. Ma, L. R. Dalton, S. H. Jang, and A. K. Y. Jen, "Focused Microwave-Assisted Synthesis of 2,5-Dihydrofuran Derivatives as Electron Acceptors for Highly Efficient Nonlinear Optical Chromophores," *Adv. Mater.*, 15, 603-7 (2003).
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20. J. Luo, S. Liu, M. Haller, H. Li, T. D. Kim, K. S. Kim, H. Z. Tang, S. H. Kang, S. H. Jang, H. Ma, L. R. Dalton, and A. K. Y. Jen "Recent Progress in Developing Highly Efficient Nonlinear Optical Chromophores and Side-Chain Dendronized Polymers for Electro-Optics," *Proc. SPIE*, 4991, 520-9 (2003).
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23. L. R. Dalton and D. H. Bale, "Nonlinear Optical Materials," *Kirk-Othmer Encyclopedia of Chemical Technology*, Fifth Addition, published 1993 (available through Wiley, New York).
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25. B. Maune, R. Lawson, C. Gunn, A. Scherer, and L. Dalton, "Electrically Tunable Ring Resonators Incorporating Nematic Liquid Crystals as Cladding Layers," *Appl. Phys. Lett.*, 83, 4689-91 (2003).
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### ❖ **Professor Alex K-Y. Jen**

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#### ❖ **Professor Younan Xia**

Number of Publications in Refereed Journals: 91

Number of Publications Which Acknowledge AFOSR Support: 19

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5. Electrospun Nanofibers of Blends of Conjugated Polymers: Morphology, Optical Properties, and Field-Effect Transistors Babel, A.; Li, D.; Xia, Y. and Jenekhe, S. A. *Macromolecules*, 2005, 38, 4705-4711.
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### ❖ **Professor Alan Heeger**

Number of Publications in Refereed Journals: 55

Number of Publications Which Acknowledge AFOSR Support: 23

### **Publications Which Acknowledge MURI Support**

1. "Electrophosphorescence from a conjugated copolymer doped with an iridium complex: high brightness and improved operational stability" *Adv. Mater.*, 2003, 15, 45. X. Gong, J. C. Ostrowski, G. C. Bazan, D. Moses, A.J. Heeger, M. S. Liu and A. K.-Y. Jen
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### ❖ **Professor Samson A. Jenekhe**

Number of Publications in Refereed Journals: 45

Number of Publications Which Acknowledge AFOSR Support: 9

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1. Babel, A.; Jenekhe, S. A. "Charge Carrier Mobility in Blends of Poly(9,9-dioctylfluorene) and Poly(3-hexylthiophene)," *Macromolecules* **2003**, *36*, 7759-7764.
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### ❖ **Professor Jean Frechet**

Number of Publications in Refereed Journals: 158

Number of Publications Which Acknowledge AFOSR Support: 34

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11. Chang, P.C.; Lee, J.; Huang, D.; Subramanian, V.; Murphy, A. R.; Fréchet, J.M.J. Film Morphology and Thin Film Transistor Performance of Solution Processed Oligothiophenes. *Chem. Mater.* 2004 ASAP edition.

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### ❖ **Professor James M. Tour**

Number of Publications in Refereed Journals: 60

Number of Publications Which Acknowledge AFOSR Support: 19

### **Publications Which Acknowledge MURI Support**

1. Dyke, C. A.; Tour, J. M. "Solvent-free Functionalization of Carbon Nanotubes" *J. Am. Chem. Soc.* 2003, 125, 1156 -1157.

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2. Strano, Michael S.; Dyke, Christopher A.; Usrey, Monica L.; Barone, Paul W.; Allen, Mathew J.; Shan, Hongwei; Kittrell, Carter; Hauge, Robert H.; Tour, James M.; Smalley, Richard E. "Electronic Structure Control of Single-Walled Carbon Nanotube Functionalization" *Science* Sep 12 2003: 1519-1522.
3. H-C Song, M-C Oh, S-W Ahn, W. H. Steier, H. R. Fetterman, C. Zhang, "Flexible Low Voltage Electro-optic Polymer Modulators", *Appl. Phys. Lett.* **82**, 4432-4, June 23, 2003
4. P. Rabiei, W. H. Steier, "Tunable Polymer Double Micro-ring (DMR) Filters", *IEEE Phot. Tech. Lett.*, **15**, 1255-7, (2003)
5. Dyke, C. A.; Tour, J. M. "Unbundled and Highly Functionalized Carbon Nanotubes from Aqueous Reactions," *Nano Lett.* 2003, 3, 1215-1218.
6. Imholt, T. J.; Dyke, C. A.; Hasslacher, B.; Perez, J. M.; Price, D. W.; Roberts, J. A.; Scott, J. B.; Wadhawan, A.; Ye, Z.; Tour, J. M. "Nanotubes in Microwave Fields: Light Emission, Intense Heat, Out-Gassing and Reconstruction," *Chem. Mater.* 2003, 15, 3969-3970.
7. Pham, J. Q.; Mitchell, C. A.; Bahr, J. L.; Tour, J. M.; Krishnamoorti, R.; Green, P. F.; "Glass Transition of Polymer/Single-Walled Carbon Nanotube Composite Films," *J. Polym. Sci. Part B: Polym. Phys.* 2003, 41, 3339-3345.
8. Dyke, C. A.; Stewart, M. P.; Maya, F.; Tour, J. M., "Diazonium-Based Functionalization of Carbon Nanotubes: XPS and GC-MS Analysis and Mechanistic Implications," *SynLett* 2004, 155-160.
9. Dyke, C. A.; Tour, J. M. "Overcoming the Insolubility of Carbon Nanotubes through High Degrees of Sidewall Functionalization," *Chem. Eur. J.* 2004, 10, 812-817.
10. Roberts, J. A.; Imholt, T.; Ye, Z.; Dyke, C. A.; Price, D. W., Jr.; Tour, J. M. "Electromagnetic Wave Properties of Polymer Blends of Single Wall Carbon Nanotubes Using a Resonant Microwave Cavity as a Probe," *J. App. Phys.* 2004, 95, 4352-4356.

# Polymeric Smart Skin Materials: Concepts, Materials, and Devices

## Statistical Report

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11. Flatt, A.K.; Chen, B. Tour, J.M. 'Fabrication of Carbon Nanotube-Molecule-Silicon Junctions," *J. Am. Chem. Soc.* **2005**, 127, 8918-8919.
12. Shi, X.; , Hudson, J. L.; Spicer, P. P.; Tour, J. M.; Krishnamoorti, R.; Mikos, A. G. "Rheological Behavior and Mechanical Characterization of Injectable Poly(propylene fumarate)/Single-Walled Carbon Nanotube Composites for Bone Tissue Engineering," *Nanotechnology* **2005**, 16, S531-S538.
13. Hadjiev, V. G.; Mitchell, C. A.; Arepalli, S.; Bahr, J. L.; Tour, J. M.; Krishnamoorti, R., "Thermal Mismatch Strains in Sidewall Functionalized Carbon Nanotubes/Polystyrene Nanocomposite," *J. Chem. Phys.* **2005**, 122, 124708.
14. Dyke, C. A.; Stewart, M. P.; Tour, J. M. "Separation of Single-Walled Carbon Nanotubes on Silica Gel. Materials Morphology and Raman Excitation Wavelength Affect Data Interpretation," *J. Am. Chem. Soc.* **2005**, 127, 4497-4509.
15. Zhou, C.; Kumar, S.; Doyle, C. D.; Tour, J. M. "Functionalized Single Wall Carbon Nanotubes Treated with Pyrrole for Electrochemical Supercapacitor Membranes," *Chem. Mater.* **2005**, 17, 1997-2002.
16. Hudson, J. L.; Casavant, M. J.; Tour, J. M. "Water-Soluble, Exfoliated, Nonroping Single-Wall Carbon Nanotubes," *J. Am. Chem. Soc.* **2004**, 126, 11158-11159.
17. Roberts, J. A.; Imholt, T.; Ye, Z.; Dyke, C. A.; Price, D. W., Jr.; Tour, J. M. "Electromagnetic Wave Properties of Polymer Blends of Single Wall Carbon Nanotubes Using a Resonant Microwave Cavity as a Probe," *J. App. Phys.* **2004**, 95, 4352-4356.
18. Dyke, C. A.; Tour, J. M. "Overcoming the Insolubility of Carbon Nanotubes through High Degrees of Sidewall Functionalization," *Chem. Eur. J.* **2004**, 10, 812-817.
19. Dyke, C. A.; Stewart, M. P.; Maya, F.; Tour, J. M., "Diazonium-Based Functionalization of Carbon Nanotubes: XPS and GC-MS Analysis and Mechanistic Implications," *SynLett* **2004**, 155-160.

### ❖ **Professor William Steier**

Number of Publications in Refereed Journals: 55

Number of Publications Which Acknowledge AFOSR Support: 13

### **Publications Which Acknowledge MURI Support**

1. S-W Ahn, W. H. Steier, Y-H Kuo, M-C Oh, H-J Lee, C. Zhang, H. R. Fetterman, "Integration of electro-optic polymer modulators with low-loss fluorinated polymer waveguides" Accepted for publication in Optics Letters
2. H-C Song, M-C Oh, S-W Ahn, W. H. Steier, H. R. Fetterman, C. Zhang, "Flexible Low Voltage Electro-optic Polymer Modulators", *Appl. Phys. Lett.* 82, 4432-4, June 23, 2003
3. P. Rabiei, W. H. Steier, "Tunable Polymer Double Micro-ring (DMR) Filters", *IEEE Phot. Tech. Lett.*, 15, 1255-7, (2003)

# Polymeric Smart Skin Materials: Concepts, Materials, and Devices

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4. "Polymer Microring Resonators", with P. Rabiei, *Optical Microcavities*, K. Vahala editor, World Scientific Co., 2004
5. B. Bohla, H-C Song, H. Tazawa, and W. H. Steier, "Polymer Micro-Resonator Strain Sensors", *Phot. Tech. Lett.* 17, 867-9, (2005)
6. P. Rabiei, W. H. Steier, "Lithium niobate ridge waveguides and modulators fabricated using smart guide", *Appl. Phys. Lett.* 86, 1, (2005)
7. H. Tazawa, W. H. Steier, "Bandwidth of linearized ring resonator assisted Mach-Zehnder modulator", accepted in *Phot. Tech. Lett.*
8. Hidehisa Tazawa and William H. Steier, "Analysis of Ring Resonator based Traveling Wave Modulators", *Photonic Technology Letters*, 18, 211-213, (2006) Erratum to "Analysis of Ring Resonator-Based Traveling-Wave Modulations" *Photonics Technology Letters*, IEEE, Volume 18, Issue 5, 1 Mar 2006 Page(s):727 – 727
9. S. Dubovitsky and W. H. Steier "Relationship between the slowing and the loss in optical delay lines" *IEEE J. Quant. Electr.* Volume 42, Issue 4, April 2006 Page(s):372 – 373
10. Hidehisa Tazawa and William H. Steier, "Linearity of Ring Resonator based Electro-optic Polymer Modulator" *IEE Electronic Letter*, Volume 41, Issue 23, 10 Nov. 2005 Page(s):1297 – 1298
11. Thanh Le, Anatoliy A. Savchenkov, Hidehisa Tazawa, William H. Steier and Lute Maleki, "Polymer optical waveguide vertically coupled to high Q whispering gallery resonators", *IEEE Photonic Technology Lett.* Volume 18, Issue 7, April 1 2006 Page(s):859 – 861
12. Bartosz Bortnik, Yu-Chueh Hung, Hidehisa Tazawa, Byoung-Joon Seo, Jingdong Luo, Alex K.-Y. Jen, William H. Steier, Harold R. Fetterman, "Electrooptic Polymer Ring Resonator Modulation up to 165 GHz", submitted to *IEEE J. Sel. Topics in Quant. Electr.*
13. Hidehisa Tazawa, Ying-Hao Kuo, Ilya Dunayevskiy, Jingdong Luo, Alex K.-Y. Jen, Harold R. Fetterman, and William H. Steier, "Ring Resonator-Based Electro-Optic Polymer Traveling-Wave Modulator", *IEEE J. Lightwave Tech.* Jan. 2006

❖ **Professor Surya Prakash**

Number of Publications in Refereed Journals: 44

Number of Publications Which Acknowledge AFOSR Support: 0

❖ **Professor Aaron W. Harper**

Number of Publications in Refereed Journals: 4

Number of Publications Which Acknowledge AFOSR Support: 8

**Publications Which Acknowledge MURI Support**

1. Collette, J.C.; Harper, A.W., "Chemically Responsive Fluorophores Exhibiting Large Color Changes," *Proc. SPIE* 4809, *in press*.

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2. Padmaperuma, A.B.; Case, P.J.; Harper, A.W., "Triplet Energy Harvesting by Organolanthanide Complexes in Conjugated Polymers," *Proc. SPIE* 4809, *in press*.
3. Miller, C.G.; Harper, A.W., "Synthesis of Poly(*p*-Phenylene Vinylene) via Acyclic Diene Metathesis (ADMET) Polymerization," *J. Am. Chem. Soc.*, *submitted*.
4. "Efficient energy harvesting of conjugated polymers by direct coordination to novel low energy complexes of europium," Padmaperuma, A.B.; Harper, A.W., *Nanoscale Opt. Photon.* 2003, *in press*.
5. "Photophysics of novel conjugated polymers with alternating heteroaromatic rings: synthesis and applications," Padmaperuma, A.B.; Harper, A.W., *Nanoscale Opt. Photon.* 2003, *in press*.
6. "Photonic crystals for energy transfer experiments," Julian, M.D.; Desousa, R.; Prakash, G.K.S.; Harper, A.W., *Nanoscale Opt. Photon.* 2003, *in press*.
7. "Synthesis and applications of polymers with pendant groups for efficiency energy transfer applications," Padmaperuma, A.B.; Case, P.J.; Harper, A.W., *submitted to Chem. Mater.*
8. "Harvesting Triplet Energy from conjugated polymers by europium ternary complexes: The Effect of Mixed Ligand Systems on Tuning the Energy of Complexes to Achieve Efficient Energy Transfer," Padmaperuma, A.B.; Harper, A.W., *submitted to Adv. Funct. Mater.*

#### ❖ **Professors Martin Gouterman and Gamal Khalil**

Number of Publications in Refereed Journals: 16

Number of Publications Which Acknowledge AFOSR Support: 17

#### **Publications Which Acknowledge MURI Support**

1. Gamal Khalil, Severin Grenoble, Stephen Ching, Martin Gouterman, James B. Callis "Concentration Effects on PSP Performance" 9<sup>th</sup> Annual PSP Workshop, Washington DC, April 6, 2002.
3. Biniam Zelelew, Greg Phelan, Brendon Carlson, Gamal Khalil, Severin Martin Gouterman, Larry Dalton "A Lifetime-Based Pressure and Temperature Measuring Paint with a Europium Complex as Temperature Sensor & a Platinum Porpholactone as Pressure Sensor" 9<sup>th</sup> Annual PSP Workshop, Washington DC, April 6, 2002.
5. Gamal Khalil, Gerg Phelan, Kim Lau, Brendon Carlson, Larry Dalton, Martin Gouterman, Jim Callis "EU-Beta-Diketonate Temperature Sensors: Effects of Ligands, Matrix and Concentration" ACS, NORM 2002, Spokane, Washington, June 20-21 (2002).
6. Gamal Khalil "Porphyrin as Chemical Sensors" invited talk, 2<sup>nd</sup> International Conference on Porphyrin and Phthalocynines, Kyoto, Japan, June 30 – July 5 (2002).
7. "Dual Luminophor Pressure Sensitive Paint II: Lifetime Based Measurement of Pressure and Temperature," Biniam Zelelew, Gamal E.

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- Khalil<sup>\*\*</sup>, Greg Phelan, Brenden Carlson, Martin Gouterman, James B. Callis, Larry R. Dalton, *Sensors and Actuators B*, In Press (2003).
8. G. Khalil<sup>\*</sup>, C. Costin, J. Crafton, S. Grenoble, M. Gouterman, J. Callis, L. R. Dalton, "Dual Luminophor Pressure Sensitive Paint I: Ratio of Reference to Sensor Giving a Small Temperature Dependency" *Sensors and Actuators*, 97, 13-21 (2004).
  9. Gamal E. Khalil<sup>1)</sup>, Kimberly Lau, Greg Phelan, Brenden Carlson, Martin Gouterman, James B. Callis, Larry R. Dalton. "Eu beta-diketonate temperature sensors: Effects of Ligands, Matrix, and Concentration", *Rev. Sci. Instruments*, 75, pp. 192-206 (2004).
  10. Martin Gouterman, James Callis, Larry Dalton, Gamal Khalil<sup>\*</sup>, Youssef Mébarki<sup>1</sup>, Kevin R. Cooper<sup>1</sup> and Michel Grenier<sup>1</sup> "Dual Luminophor Pressure Sensitive Paint III: Application to Automotive Model Testing", *Measurement Science and Technology* (2004), in press
  11. Severin Grenoble, Martin Gouterman, Gamal Khalil<sup>\*</sup>, James Callis, Larry Dalton, "Pressure Sensitive Paint (PSP): Concentration Quenching of Platinum and Magnesium Porphyrin Dyes in Polymeric Films", *Journal of Luminescence* (2004), accepted for publication.
  12. G. Khalil, A. Chang, M. Gouterman, J. B. Callis, L. R. Dalton, N. J. Turro and S. Jockusch, "Oxygen Pressure Measurement Using Singlet Oxygen Emission", *Rev. Sci. Instruments*, 76, 054101 (2005).
  13. G. Khalil, F. Kimura, A. Chin, M. Gandahari, R. Wan, W. Shinoki, M. Gouterman, J. B. Callis and L. R. Dalton, "Continuous Monitoring of Gas Leaks in the Subsurface Environment", *Research in Nondestructive Evaluation*, in press (2005).
  14. Masoud Ghandehari, Gamal Khalil, "Materials Health Management by In-Situ Chemical Analysis" *Journal of Materials Evaluation*, 63, 724-730 (2005).
  15. C. M. McGraw, J. H. Bell, G. Khalil and J. B. Callis, "Dynamic surface pressure measurements on a square cylinder with pressure sensitive paint", *Experiments in Fluids* in press (2005).
  16. Sang Hyuk Ima, †, Gamal E. Khalil, †, James Callis, Byung Hyun Ahn, and Younan Xia "Synthesis of polystyrene beads loaded with dual luminophors for self referenced oxygen sensing" *Talanta*, in press (2005).
  17. Kimberly S. F. Lau, Martin Sadilek, Gamal E. Khalil, Martin P. Gouterman, and Christian Brückner, "Tandem ESI Mass Spectrometric Analysis of meso-Tetrakis(heptafluoropropyl)porphyrin" *Journal of Am. Mass Spectrometry*, in press (2005).

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### Interactions/Transitions:

### Participation/Presentations:

❖ *Professor Larry Dalton*

1. March 1, 2002—Dinner meeting and presentation with Seattle Mayor Greg Nichols, community leaders, and UW President McCormick.
2. March 4-5, 2002--NSF Review Panel: Nanoscale Science and Engineering (NSE), Nanoscale Interdisciplinary Research Team (NIRT), NSF Headquarters, Arlington, VA
3. March 6-7, 2002--DARPA/MTO Molecular Photonics Workshop--Invited presentation. "Organic Electro-Optics: Past, Present, and Future".
4. *Conference*--March 11-15, 2002-- Government Microcircuit Applications & Critical Technology (GOMAC)-02 Conference, "The Rational Design and Production of Organic Electro-Optic Materials and Devices".
5. *Conference*--April 17, 2002--Invited Lecture for New Horizons in Polymer Chemistry Conference, Los Angeles, CA. "Realization of the Promise of Electro-Optic Polymers."
6. April 29, 2002—Invited Seminar, Washington State University, Pullman, WA. "Electro-Optic Materials and Devices".
7. June 10, 2002--3 presentations in the Palo Alto, CA area
8. Presentation 1. Invited presentation before the Select Committee on Science & Technology of the British House of Lords. Published in "Chips for Everything: Britain's Opportunities in a Key Global Market", Session 2002-02, 2nd Report, The Stationery Office Limited, London.
9. Presentation 2. EE Seminar Stanford University.
10. Presentation 3. Seminar at Agilent (Both American and British Agilent researchers attending).
11. *Conference*--June 20, 2002--Invited presentation at the IBM Workshop on Organic Electronic and Photonic Materials (T. J. Watson Research Center, Yorktown Heights, NY)
12. June 28, 2002--Lumera Corporation Board of Directors Meeting. Invited Presentation.
13. *Conference*--July 10, 2002—SPIE Seattle National Meeting, Conference 4798: Linear and Nonlinear Optics and Organic Materials II. Invited Lecture: "Organic Electro Optics: From Molecules to Devices".
14. *Conference*--July 11, 2002—SPIE Seattle National Meeting, SPIE Workshop on the Nanotechnology of Polymeric Smart Materials. Invited Lecture: "Electro-Optic Polymers".
15. *Conference*--July 12, 2002—Semiconductor Research Corporation-IFC Topical Workshop on Optical Interconnects, Seattle, WA. Invited Presentation: "Modulators".
16. August 12-13, 2002--PNNL Nanoscience and Technology Advisory Committee Meeting, Richland, WA.

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17. August 14-16, 2002--Defense Advanced Research Projects Agency (DARPA) Microsystems Technology Office (MTO) CS-WDM Program Kickoff, Whitefish, MT.
18. August 19-29, 2002—STC Director's Meeting, Atlanta, GA. Overview of UW STC.
19. August 26, 2002—Invited presentation to U.S. Congressman (D-7<sup>th</sup>, Washington State) James McDermott, Seattle. The STC and electro-optic materials research.
20. September 13, 2002—Technology Alliance Presentation, Seattle, WA. Invited Lecture: "Information Technology in the 21<sup>st</sup> Century: Exploiting the Best of Electronics and Photonics".
21. September 17, 2002--Washington Roundtable Invited Presentation, Washington Athletic Club. "The New Information Technology Age: Exploiting the Best of Photonics and Electronics".
22. September 30, 2002--National Science Foundation Distinguished Lecturer, Inaugural Lecture 2002-2003 NSF Distinguished Lecture Series, NSF Headquarters, Arlington, VA, "The New Information Age: Exploiting the Best of Electronics and Photonics."
23. October 3, 2002—Invited Seminary, California Institute of Technology. "Organic Electro-Optics".
24. October 9, 2002—Seminar, Norfolk State University, Norfolk Virginia. "Implementing the New Information Technology Age: Exploiting the Best of Photonics and Electronics".
25. *Conference*--October 10-13, 2002--10th Annual Foresight Conference on Molecular Nanotechnology Two invited presentations (one Scientific Tutorial and one Invited Conference Presentation) Bethesda, Maryland. Title of invited lecture:"Breaking the Bandwidth Bottleneck in Telecommunications & Information Processing: New Electro-Optic Materials."
26. October 23, 2002—Presentation before National Reconnaissance Office Site Visit to the University of Washington. "Organic Electro-Optic Materials: Past, Present, and Future".
27. November 11-13, 2002—DoD DDR&E Nanophotonics & Nanoelectronics Review, University of Buffalo, Buffalo, NY. Invited Presentation: "Nanophotonic Electro-Optic and Opto-Electronic Materials".
28. November 26, 2002—Seminar, Department of Electrical Engineering, University of Washington. "Preparation and Utilization of Organic Electro-Optic Materials".
29. December 5, 2002—Seminar, Applied Physics Laboratory, University of Washington. "Materials for Next Generation Telecommunications".
30. December 6, 2002—UW Science Forum Lecture, University of Washington. "Implementing the New Information Technology Age: Exploiting the Best of Photonics & Electronics".
31. *Conference*--December 11-13, 2002--NSF Nanoscale Science and Engineering, NSF Grantees Conference, Arlington, VA, Invited

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- Presentation: "Nanostructured Optoelectronic Materials: New Concepts in Theoretical Design, Synthesis, and Processing."
32. *Conference*--January 16-17, 2003--NSF Workshop on Technological Challenges for Flexible, Light-weight, Low-cost and Scalable Organic Electronics and Photonics. Arlington Hilton Hotel & Towers, Arlington, VA--Invited Presentation: Organic Electro-Optic Materials: Present and Future.
  33. January 24, 2003--DoD DDR&E Review of Polymeric Smart Skin Materials, Seattle, WA. Presentation: "An Overview of Polymeric Smart Skins Materials Research".
  34. *Conference*--January 30, 2003--Photonics West Symposium on Organic Photonic Materials and Devices VI, San Jose, CA. Invited Lecture: "Organic Electro Optics: Exploiting the Best of Electronics and Photonics".
  35. February 13, 2003--Florida International University, Miami, FL. Invited Seminar: "Technology for the 21<sup>st</sup> Century: Exploiting the Best of Photonics and Electronics".
  36. February 14, 2004--University of Miami, Miami, FL. Invited Seminar: "Technology for the 21<sup>st</sup> Century: Exploiting the Best of Photonics and Electronics".
  37. *Conference*--March 25, 2003--American Chemical Society National Meeting, New Orleans, Award Symposium on Organic Electro-Optic and Optoelectronic Materials Honoring the Chemistry of Materials Award Recipient Larry Dalton, Invited Lecture: Organic Electro-Optic Materials: Past, Present, and Future".
  38. March 31, 2003--Government Microcircuit Applications & Critical Technology (GOMAC)-03 Conference, Tampa, FL. Invited Lecture: "New Organic Electro-Optic Materials for Time and Wavelength Division Multiplexing Applications".
  39. April 8, 2003--Science Forum Lecture, University of Washington. "Lighting the Way in the New Information Technology Age."
  40. April 23, 2003--DARPA/MTO: CS-WDM "Nanophotonics for Mobile Platforms" Review, Boeing, Seattle. Invited Presentation: "Electro-Optic Polymers: Roadmap".
  41. April 24, 2003--Frontiers in Nanotechnology Lecture, BIOE599/CHEM650, University of Washington, Seattle. "Nanotechnology and Information Technology"
  42. May 5-7, 2003--PNNL Nanoscience and Technology Advisory Committee Meeting, Richland, WA
  43. May 17-18, 2003--NSF "Chemical Bonding Centers" Workshop, NSF Headquarters, Arlington, VA
  44. *Conference*--June 18-25, 2003--NSF/ACS Workshop Conference on the Chemistry of Information Technology/Electrical, Magnetic, and Optical Properties of Organic and Hybrid Materials, multiple presentations.
  45. *NASA Space Grant Program on Research for Undergraduates*--July 3,

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- 2003--Delivered Education Component including lecture on Space Based Applications of Organic Electro-Optic Modulators.
46. July 28-29, 2003—Panel Review of the Nanoscience and Nanotechnology Initiative at PNNL, Richland, WA
  47. *Conference*—August 10-15, 2003—Keynote Lecture, 39<sup>th</sup> IUPAC Congress and 86<sup>th</sup> Conference of the Canadian Society of Chemistry, Symposium MS05-Polymers in Electronics and Photonics, Ottawa, Canada. Invited Presentation: "Organic Electro-Optic Materials".
  48. *Conference*—September 21-25, 2003—Keynote Lecture, 29<sup>th</sup> European Conference on Optical Communications-14<sup>th</sup> International Conference on Integrated Optics and Optical Fibre Communication, Rimini, Italy. Invited Presentation: "Novel Polymer Based High-Speed Electro-Optic Devices"
  49. September 26, 2003—Provided day long Orientation for the incoming Freshman Class at the University of Washington under the auspices of a new program developed by the Dean of Undergraduate Education to introduce students to unique educational opportunities at UW.
  50. October 1, 2003—Presentation to the National Reconnaissance Office on the status of organic electro-optic materials, Univ. of Washington, Seattle.
  51. *Conference*—October 18-25, 2003—Invited Lecture, The Enrico Fermi and Galileo Galilei Celebrations, International School of Quantum Electronics, Erice, Sicily. "Microresonators as Building Blocks for VLSI Photonics"
  52. October 27-31, 2003--•AFRL/Materials and Manufacturing Directorate (ML) Scientific Advisory Board (SAB) Science and Technology (S&T) Quality Review
  53. November 4, 2003—Eastman Lecture at the Department of Chemistry, University of Akron
  54. September 14-15, 2004 — 2 Lectures, DARPA MORPH Review, Redmond, WA
  55. September 22-24, 2004 — Invited Lecture, Frontiers of Polymer Science, Leuven, Belgium
  56. September 29, 2004 — Invited Lecture, Universite Pierre & Marie Curie, Paris France
  57. October 4-6, 2004 — Invited Lecture, MWP 2004 International Topical Meeting on Microwave Photonics, Qgunguit, Maine
  58. October 21, 2004 — Invited Lecture, Air Force Research Laboratory (AFRL) Materials and Manufacturing Technology Lecture Series, Dayton, OH
  59. October 22-26, 2004 — Invited Lecture, Symposium on Organic Thin Film for Photonic Applications, 228<sup>th</sup> ACS National Meeting, Philadelphia, PA
  60. October 25-27, 2004 — Invited Lecture, SPIE Optical Materials in Defense System Technology, London, England
  61. November 6-7, 2004 — Invited Lecture, Tobinstock, Northwestern University, Evanston, IL
  62. November 18-20, 2004, 2 Lectures, DARPA MORPH Review, Atlanta, GA

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63. November 30-December 2, 2004 — Invited Lecture, 2004 DARPA MTO Photonics Symposium, San Francisco, CA
64. January 22-27, 2005 — Invited Lecture, SPIE Photonics West, San Jose, CA
65. March 7-11, 2005 — Invited Lecture, International Conference on Organic Photonics and Electronics 2005 (ICOPE2005) & The 8<sup>th</sup> International Conferences on Organic Nonlinear Optics (ICONO'8), Matsushima, Japan
66. March 13-17, 2005 — Invited Lectures, 229<sup>th</sup> American Chemical Society National Meeting, San Diego, CA
67. May 14, 2005 — Invited Lecture, Stanford Photonics Research Center Annual Symposium, Stanford, CA
68. May 22-27, 2005 — 1 Tutorial and 1 Invited Lecture, CLEO/QELS/PhAST Conference, Baltimore, MD
69. March 31-April 2, 2005, Invited Lecture, Spring Materials Research Society Meeting, San Francisco, CA
70. April 5-7, 2005 — 2 Lectures, Graduate Course: Introduction to Advanced Photonic Materials and Devices, Norfolk State University, Norfolk, VA
71. June 3-5, 2005 — Unconventional Magnetic and Electronic Materials Conference, Columbus, OH
72. June 5-8, 2005 — Invited Lecture, Photonics 2005: Nanophotonics, Biophotonics and Optoelectronic Polymer Systems, Orlando, FL
73. July 11-14, 2005 — Invited Lecture, IQEC and CLEO-PR Conference, Tokyo, Japan
74. July 15, 2005 — Invited Lecture, 2005 IEEE Conference on Nuclear and Space Radiation Effects (NSREC), Seattle, WA
75. July 27-28, 2005 — 2 Lectures, DARPA MORPH Review, Arlington, VA
76. July 31-August 4, 2005 — 3 Invited Lectures, SPIE Optics & Photonics Conference, San Diego, CA
77. August 8-13, 2005 — Air Force Office of Scientific Research, Chemistry & Life Sciences Directorate, Polymer Chemistry & Polymer Matrix Composites Program Review, San Diego, CA
78. September 24, 2005, the Dow/Karabatosos & Distinguished Alumni Lectureship, Michigan State University, East Lansing, MI
79. November 7, 2005, Invited Lecture, Symposium on Exploratory Research for Advanced Technology (ERATO)—Koike Photonics Polymer Project, Japan Science Technology Agency (JST), Tokyo, Japan
80. December 15, 2005, Invited Lecture, PACIFICHEM 2005: Symposium on Macromolecules for Photonic Applications, Honolulu, Hawaii
81. January 15-20, 2006, Invited Lecutre, 3<sup>rd</sup> ICPOP and 2<sup>nd</sup> KF-PMD, Val Thorens, France
82. March 8, 2006, Corporate-wide invited seminar, Intel Corporation
83. March 13, 2006, Invited seminar, Corning Corporation, Corning, NY
84. March 14, 2006, Invited seminar, CIBA Corporation, Tarrytown, NY
85. March 20-23, 2006, Invited Tutorial on Nanosensor Technologies (Institute for Defense Analyses), GOMAC-06, San Diego, CA

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86. May 2-4, 2006, Invited Lecture, 7<sup>th</sup> International Symposium on Technology and the Mine Problem, Naval Postgraduate School, Monterey, CA
87. June 16, 2006, Keynote Lecture, 2007 IEEE-MTT-S International Microwave Symposium Workshop on "Low-cost Microwave Photonic Component Technologies to Address Emerging Applications", San Francisco, CA

#### Invited Presentations and Seminars by Alex Jen:

1. "Nanoscale Architectural Control of Organic Functional Materials for Photonics & Molecular Electronics", Lawrence Berkeley Lab., Univ. of California, Berkeley, CA, 8/03.
2. "Nanoscale Architectural Control of Organic Functional Materials for Photonics & Molecular Electronics", Department of Chemistry, Washington State University, WA, 8/03.
3. "Nanoscale Architectural Control of Organic Functional Materials for Photonics & Molecular Electronics", International Workshop on Nanotechnology of Polymeric Smart Materials, SPIE's 48<sup>th</sup> Annual Meeting, San Diego, CA, 8/03.
4. "Self-Assemble Organic Functional Materials for Opto-electronics", Conference 5224, Nanomaterials and Their Optical applications", SPIE's 48<sup>th</sup> Annual Meeting, San Diego, CA, 8/03.
5. "Functional Self-Assemblies with Nanoscale Ordering for Molecular Electronics and Biomaterials", in the Symposium of "Organic and Polymeric Materials for Plastic and Molecular Electronics", ACS Annual Meeting, New York, NY, 9/03.
6. Effects of Molecular Architecture, Functional Groups, and Hydrogen Bonding on the Macroscopic Features of Highly Ordered Self-Assemblies", in the Symposium of "Polymer Chemistry in Nanotechnology-Polymers and Surfaces", ACS Annual Meeting, New York, NY, 9/03.
7. "Nanoscale tailoring of dendrimers and polymers for electro-optic devices", in the International Symposium on "Fluoropolymers 2002", Revena, GA, 10/02.
8. "Nanoscale architectural control of dendrimers and polymers for photonics and molecular electronics", Institute of Chemistry, Academia Sinica, Taiwan, 12/02.
9. "Nanoscale architectural control of dendrimers and polymers for photonics and molecular electronics", National Tsing Hua University, Taiwan, 12/02.
10. "Recent progress in developing highly efficient nonlinear optical chromophores and side-chain dendronized polymers for electro-optics", in the Symposium on "Organic Photonic Materials and Devices VI", Photonics- West: Optoelectronics San Jose, CA, 1/03.

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11. "Nanoscale tailoring of dendrimers and polymers for electro-optic devices" in the Photonics Initiative Workshop, University of Arizona, Tucson, AZ, 1/03.
12. "Nanoscale tailoring of organic functional materials for photonics and molecular electronics", Chinese University of Hong Kong, Hong Kong, 2/03.
13. "Nanoscale tailoring of organic functional materials for photonics and molecular electronics", Department of Chemistry, University of Texas, Arlington, TX, 3/02.
14. "Nanoscale tailoring of organic functional materials for photonics and molecular electronics" in the "Chemistry of Materials Award Symposium", ACS National Meeting, New Orleans, 3/03.

#### Invited Presentations and Seminars by Younan Xia

1. "Shape-Controlled Synthesis of Nanostructures", the Alvin L. Kwiram Symposium on the Electrical, Optical, and Magnetic Properties of Organic and Hybrid Materials, University of Washington, Seattle, WA, June, 2003.
2. "Tutorial Introduction on Nanostructured Materials", the ACS/PRF Summer School on Photonics, University of Washington, Seattle, WA, June, 2003.
3. "Shape-Controlled Synthesis of Nanostructures", the 77th ACS Colloid and Surface Science Symposium, Atlanta, GA, June, 2003.
4. Physical Chemistry Seminar, Department of Chemistry, University of British Columbia, Vancouver, BC, Canada, March, 2003.
5. Materials Science Seminar, Department of Chemical Engineering and Materials Science, University of Minnesota, Minneapolis, MN, March, 2003.
6. "Self-Assembly Approaches to Photonic Devices", the Knowledge Foundation's International Conference on Photonic Nanostructures, San Diego, CA, October, 2002.
7. Inorganic Chemistry Seminar, Department of Chemistry, University of California, Santa Barbara, CA, October, 2002.
8. Physical Chemistry Seminar, Department of Chemistry, Stanford University, Palo Alto, CA, October, 2002.
9. "Self-Assembly Approaches to Photonic Structures and Devices", the Society of Photo-Optical Instrumentation Engineers (SPIE) Annual Meeting, Seattle, WA, July, 2002.
10. "The Chemistry and Art of Synthesizing Nanowires", the Society of Photo-Optical Instrumentation Engineers (SPIE) Annual Meeting, Seattle, WA, July, 2002.

#### Invited Presentations and Seminars by Alan Heeger

1. "Progress in "plastic" electronics," Kwiram International Conference on Optical, Electrical, and Magnetic Properties of Organic and Hybrid Materials, University of Washington, Seattle, WA, June 24, 2003.

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2. "Progress in "plastic" electronics," Conference: Advancing Frontiers of Condensed Matter Physics, International Center for Theoretical Physics, Trieste, Italy, August 11-15, 2003.
3. X. Gong, "Conjugated polymer composites for use in electrophosphorescent light-emitting diodes," Conference presentation, SPIE, San Diego, CA, August 2003.
4. "Progress in "plastic" electronics," Conference on Electroactive polymers, DuPont, Chesapeake Farms, Sept 30-Oct 3, 2002.
5. "Progress in "plastic" electronics," Conference Presentation: Advanced Materials and Technology, Wellington, NZ, Feb 9-13, 2003.
6. "Progress in "plastic" electronics," MRS Conference, San Francisco, CA, April 21-25, 2003.
7. "Progress in "plastic" electronics," DOE Workshop; DOE Basic Energy Sciences Personnel, Salt Lake City, UT.

#### Invited Presentations and Seminars by Aaron W. Harper

1. "Photophysics of europium(III)  $\beta$ -diketone complexes that can be excited at lower energies," Presentation at 2002 Materials Research Society Meeting, San Francisco, CA, April 21-25, 2003.
2. "Synthesis and photophysical properties of poly(p-phenylene vinylene) via thermal decomposition of a polyazine precursor," Presentation at 2003 Materials Research Society Meeting, San Francisco, CA, April 21-25, 2003.
3. "Energy transfer studies of polyphenylene-type polymers to a series of dyes," 2003 Materials Research Society Meeting, San Francisco, CA, April 21-25, 2003.
4. "Energy transfer from polyphenylene-type polymers to a series of coumarins and other acceptors," SPIE National Meeting, San Diego, July 2003.
5. "Structure-optical property studies of two-photon engineered alkylamino-substituted styryl pyrazine dyes," American Chemical Society National Meeting, New York, 2003.
6. "Chemical environment effects on the photophysical behavior of two-photon materials," SPIE National Meeting, San Diego, July 2003.
7. "Photonic crystals for energy transfer experiments," SPIE National Meeting, San Diego, July 2003.
8. "The structure-property relationship of conjugated polymers: the effect of heteroaromatic rings on photophysical properties," American Chemical Society National Meeting, New Orleans, March 2003.
9. "Harvesting triplet energy from conjugated polymers by europium ternary complexes: tuning the energy of complexes to achieve higher energy transfer efficiencies," American Chemical Society National Meeting, New Orleans, March 2003.
10. Efficient energy harvesting of conjugated polymers by direct coordination

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to novel low energy complexes of europium," SPIE National Meeting, San Diego, CA, Aug 2003.

11. "Photophysics of novel conjugated polymers with alternating heteroaromatic rings: synthesis and applications," SPIE National Meeting, San Diego, CA, Aug 2003.
12. "Synthesis of novel conjugated high-energy polymers with terpyridine and  $\beta$ -diketonate type pendant groups to facilitate energy transfer to lanthanides," American Chemical Society National Meeting, New Orleans, March 2003.

#### Invited Presentations and Seminars by S.A. Jenekhe:

1. Jenekhe, S. A., "Speeding up electrons in polymer semiconductors," NSF workshop on organic electronics, Arlington, VA, Jan 16-17, 2003.
2. Jenekhe, S. A., "High performance n- and p-channel polymer thin film transistors," Invited Talk, MRS Spring Meeting 2003, San Francisco, CA, April 21-25.
3. Jenekhe, S. A., "Conjugated polymer nanowires for nanoelectronics and nanophotonics," Invited Talk, MRS Spring Meeting 2003, San Francisco, CA, April 21-25.
4. Jenekhe, S. A., "Polymer electronics and nanoelectronics," Seminar, University of Victoria, Victoria, BC, March 24, 2003.
5. Jenekhe, S. A., "Polymer electronics and nanoelectronics," Seminar, Georgia Tech, Atlanta, Georgia, April 3, 2003.
6. Jenekhe, S. A., "Conjugated polymer nanowires," Invited Talk, ACS Fall National Meeting 2003, New York, NY, September 7-11, 2003.
7. Jenekhe, S. A., "Conjugated ladder polymers for thin film transistors," Invited Talk, ACS Fall National Meeting 2003, New York, NY, September 7-11, 2003.

#### Invited Presentations and Seminars by William Steier:

1. "Application of Organic Materials in Photonics," Presentation at Alvin L. Kwiram Symposium, Seattle WA, June 24, 2003.
2. "Application of Organic Materials in Photonics," Presentation at Microwave Photonics Conference, Japan, November 6, 2002.
3. "Polymer Micro-resonator Technology," Presentation at PECIO'03 Conference, Prague, Italy.

#### Invited Presentations and Seminars by Gamal Khalil and Martin Gouterman

1. Khalil, Gamal; Phelan, Gregory D.; Lau, Kimberly S. F.; Carlson, Brenden; Dalton, Larry R.; Gouterman, Martin; Callis, Jim. Eu  $\beta$ -diketonate temperature sensors: effects of ligands, matrix, and concentration. Abstracts of Papers, 225th ACS National Meeting, New Orleans, LA, March 23-27, 2003.

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2. Grenoble, Severin; Khalil, Gamal; Gouterman, Martin; Callis, Jim; Dalton, Larry R., Concentration Quenching of Platinum & Magnesium Porphyrin Dyes in Polymeric Films Abstracts of Papers, 58th ACS Northwest Regional Meeting (NORM), Bozeman, MO, June 12-14, 2003.
3. Khalil, Gamal; Chang, Alvin; Gouterman, Martin; Callis, Jim; Lau, Kimberly S. F., Simulation and Spectroscopic Studies on Singlet Oxygen and its Interaction with platinum porphyrin: Abstracts of Papers, 58th ACS Northwest Regional Meeting (NORM), Bozeman, MO, June 12-14, 2003.
4. Carlson, Brenden; Khalil, Gamal; Gouterman, Martin; Dalton, Larry. Novel pressure/oxygen sensing coatings based upon iridium complexes and fluorinated polymers. Abstracts of Papers, 224th ACS National Meeting, Boston, MA, United States, August 18-22, 2002.

#### **Consultative/Advisory Functions:**

❖ *Professor Larry Dalton*

#### ***Recent Representative Advisory Positions, Non-Federal***

- Member, Editorial Board, Materials Today (2002-)
- Chairman/Member, External Advisory Committee, Center for Research and Education on Advanced Materials, Norfolk State University, (2002-)
- Member, External Advisory Committee, NSF RISE Center, Alabama A&M University (2005-)
- Member, Scientific American 50 Awards Advisory Committee (2003)
- Board of Visitors, Chemistry Department, University of Alabama (98-2002)
- Guest Editor, Special Issue of the Journal of Physical Chemistry (2003-2004)
- Academic Technology Advisory Committee, University of Washington (2003-)

#### ***Recent Representative Recent Federal and State Advisory Panel Service***

- Member, NSF ACGPA (Advisory Committee for the Government Performance and Results Act) (2006-)
- Member, Advisory Committee, Mathematical and Physical Science Directorate, National Science Foundation (2005- 2008)
- Member, Advisory Group on Electron Devices (AGED), Office of the Undersecretary of Defense (2006-)
- Member, Committee of Visitors, Division of Materials Research, National Science Foundation (2005)
- Member, MPS/EHR (Education Human Resources) Subcommittee on Broadening Participation, National Science Foundation (2005)
- Member, Engineering and Physical Sciences Research Council (EPSRC), England
- Chairman, Arizona Biomedical Research Commission (formerly, Arizona Disease Control Research Commission) Review Panel for Biomedical Engineering, Imaging, and Sensing (2005-)

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- Member, National Science Foundation Panel on the Technological Challenges of Organic Electronic and Photonic Materials (2004)
- Member, National Science Foundation Panel on Sensors and Sensor Systems (2003)
- Member, National Science Foundation Workshop on Chemical Bonding Centers (2003)
- Member, National Science Foundation "Grand Challenges Workshops" for the National Nanotechnology Initiative (2003)
- Member, Air Force Scientific Advisory Board (2003)
- Member, Department of Energy Peer Review Panel for the Energy Science and Technology Directorate (2003-)
- Oversight Reviewer of the National Research Council Report on Implications of Emerging Micro- and Nanotechnologies (2002)
- Member, Department of Energy Peer Review Panel for the Nanotechnology Initiative (2002-2004)
- Member, National Science Foundation NIRT Review Panel (2002)
- Member, National Science Foundation Panel on Information Technology Research (ITR)
- Member, National Science Foundation SBIR/STTR Peer Review Panel (2001)
- Member, National Science Foundation IGERT Review Panel (2001, 2006)
- Member, National Science Foundation Nanotechnology Review Panel (2001)
- Reviewer, Arizona Biomedical Research Commission (formerly, Arizona Disease Control Research Commission) for Annual Review of Proposals (1995-present)

#### ***Recent Invited Lectures at Federal, British Government, and Corporate Workshops***

- Institute for Defense Analyses Nanosensor Technology Tutorial (Gomac Tech 06, San Diego, March 20, 2006)
- NSF Workshop on the Technology Challenges of Organic Electronic and Photonic Materials (2003)
- NSF Nanotechnology Review (2002, 2003)
- DARPA Workshop on Molecular Photonics/Engineering (2002)
- DARPA/Semiconductor Research Corporation Workshop on Optical Interconnects (2002) URL address:  
[http://www.src.org/member/sa/nis/E002117\\_Opto\\_wksp.asp](http://www.src.org/member/sa/nis/E002117_Opto_wksp.asp)
- IBM Corporate Workshop on Organic Electronic and Photonic Materials (2002)
- Corning Corporate-wide Workshop on Organic Electro-Optic Materials (2001)
- British House of Lords Workshop on Next Generation Computing (2002)
- 2006 Corporate-wide lectures at Intel, CIBA, GE, and Corning

#### Other Knowledge/Technology Transitions:

Transition 1

a. Dalton, UW, b. Data for organic electro-optic materials, c. William Krug/Boeing

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Phantom Works., 253-657-8018 d. For a development of a research program for handling both digital and analog data exploiting WDM techniques and explicitly wavelength selective filter and beam steering concepts.

#### Transition 2

a. Dalton, UW, b. Data relating to polymeric electro-optic materials and processing protocols, c. Susan Ermer/Lockheed Martin Corporation, 650-424-3131 d. For prototyping high frequency, low drive voltage modulators.

#### Transition 3

a. Dalton, UW, b. Polymeric electro-optic materials and processing protocols, c. Abraham Gross/Microvision, 425-415-6642 d. For prototyping electro-optic modulator devices for telecommunication and display applications.

#### Transition 4

a. Dalton, UW, b. Polymeric electro-optic materials and processing protocols, c. Todd McIntyre/Lumera Corporation, 425-415-6616 d. For electro-optic device fabrication and consideration for establishing an electro-optic materials production facility.

#### Transition 5

a. Dalton, UW, b. Polymeric electro-optic materials and processing protocols, c. Ray Chen/UT-Austin Microelectronics Center and Radiant Photonics, 512-338-4942 d. For electro-optic device fabrication and evaluation.

#### Transition 6

a. Dalton, UW, b. Polymeric electro-optic materials and processing protocols, c. James G. Grote/AFRL/MLPO, 937-255-4474 ext 3263 d. For use with conducting cladding materials developed by AFRL.

#### Transition 7

a. Dalton, UW, b. Polymeric electro-optic materials and processing protocols, c. James Bechtel/TACAN Corporation, 760-438-1010 ext 3278 d. Polymeric electro-optic materials for device fabrication.

#### Transition 8

a. Dalton, UW, b. Polymeric electro-optic materials and processing protocols, c. G. A. Lindsey/NAWCWD, 760-939-1396 d. Polymeric electro-optic materials for optical gyro development.

#### Transition 9

a. Dalton, UW, b. Polymeric electro-optic materials and processing protocols, c. Paul Ashley/Army Missile Command, Redstone Arsenal, 205-876-7484 d. Polymeric electro-optic materials for gyro development.

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#### Transition 10

a. Dalton, UW, b. Polymeric electro-optic materials and processing protocols, c. Howard Katz/Bell Labs Lucent Technologies, 908-582-6968 d. Polymeric electro-optic materials for evaluation and to repeat syntheses.

#### Transition 11

a. Dalton, UW, b. Light harvesting solar cell coatings, c. Paul Hausgen/Kirtland AFB, [paul.hausgen@kirtland.af.mil](mailto:paul.hausgen@kirtland.af.mil) d. Improved solar cell technology.

#### Transition 12

a. Dalton, UW, b. Pressure sensitive paints, c. Rush Queen/Boeing, 206-655-7761; Tim Rieger/Boeing, 206-655-7769; Doug McLean/Boeing, 206-234-1106; John Harris/Boeing, 206-655-7794 d. Pressure sensitive paints for wind tunnel evaluation of airframes.

#### Transition 13

a. Dalton, UW, b. Photonic Bandgap Sensors, c. Alex Dickinson/Luxtera, 626-390-0380 d. Development of photonic bandgap devices including sensors.

#### Transition 14

a. Tour, Rice, b. Stealth Skins, c. Charles Liang/Lockheed Martin, 817-763-7302 d. Development of thin film materials with stealth capabilities.

#### Transition 15

a. Tour, Rice, b. Nanotube Blending, c. Jeffrey Bahr/Carbon Nanotechnologies, Inc., 281-492-5795 d. Development of materials blending carbon nanotubes in plastics.

#### Transition 16

a) Tour, Rice University, b) Functionalization of single wall carbon nanotubes, c) Morley Stone, Program Manager, DARPA, 571-218-4504, d) For preparation of new polymer composites.

#### Transition 17

a) Tour, Rice University, b) Functionalization of single wall carbon nanotubes, c) MURI Smart Skin Review at University of Washington d) For preparation of new polymer composites.

#### Transition 18

a) Tour, Rice University, b) Functionalization of single wall carbon nanotubes, c) TiIMS URETI meeting, NASA Langley, d) For preparation of new polymer composites.

#### Transition 19

a. Younan Xia, U. Washington, b. Thin film photonic crystals, c. Ted Rupp,

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Honeywell FM&T, 505-661-1207, d. For improving the damage threshold of optical devices.

#### Transition 20

a) Xia, U. Wash., b) Electrospinning with co-axial capillaries, c) M. Marquez, Kraft Foods, 847-646-3357, d) For fabrication of hierarchically, multifunctional materials related to drug delivery and controlled release.

#### Transition 21

a) PI. Jen, Univ. of Washington, b) highly efficient E-O polymers and NLO chromophores, c) Professors Steier (USC) and Yariv (CalTech), and Dr. Bill Krug (Boeing), d) for the fabrication of low  $V_{\pi}$  modulators and active ring resonators. We have already supplied both the high  $r_{33}$  guest/host polymers and Diels-Alder reversibly crosslinkable polymers to Bill Steier's group (USC) for evaluation of making E-O devices. Their initial approach will be to fabricate stripline Mach-Zehnder modulators and also micro ring resonator because the latter devices can tolerate higher loss. In addition, we have worked with Amnon Yariv's groups (Caltech) and Bill Krug (Boeing) to incorporate these newly developed reversibly crosslinkable polymers into their ring-resonator device structures and photonic bandgap structures using soft lithography or nanoimprinting.

#### Transition 22

a) PI. Jen, Univ. of Washington, b) highly efficient E-O polymers and NLO chromophores, c) Professors Steier (USC), Peyghambarian and Fallahi (UA), and Scherer (CalTech), and Dr. Bill Krug (Boeing), d) for the fabrication of low  $V_{\pi}$  modulators and active ring resonators. We have already supplied both the high  $r_{33}$  guest/host polymers and Diels-Alder reversibly crosslinkable polymers to Bill Steier's and Fallahi/Peyghambarian groups for evaluation of device fabrication. They have fabricated low drive voltage ( $V_{\pi}=1.7$  V) stripline Mach-Zehnder modulators and very low insertion loss sol-gel/polymer hybrid modulators (~7 dB fiber-to-fiber which is the lowest among all polymer-based E-O devices). In addition, we have worked with Axel Scherer's groups (Caltech) and Bill Krug (Boeing) to incorporate these newly developed reversibly crosslinkable polymers into their ring-resonator device structures, nano slot waveguide structures, and photonic bandgap structures using nanoimprinting.

#### Transition 23

a. Jen, U. Washington, b. new E-O materials, c. Dr. Geoffrey Linday (NAVY), d. to provide detailed synthetic schemes and procedures for them to develop new E-O materials for DoD's applications.

#### Transition 24

a. Khalil & Gouterman, UW, b. Pressure Sensitive Films, c. James Bell /NASA Ames, [jhbell@mail.arc.nasa.gov](mailto:jhbell@mail.arc.nasa.gov) d. Performance of low speed pressure steady measurements.

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#### Transition 25

a. Khalil & Gouterman, UW, b. Pressure Sensitive Films, c. Youssef Mebarki /The Institute for Aerospace Research, [Youssef.Mebarki@nrc-cnrc.gc.ca](mailto:Youssef.Mebarki@nrc-cnrc.gc.ca) d. Performance of automotive model pressure measurement.

#### Transition 26

a. Khalil & Gouterman, UW, b. Pressure Sensitive Films, c. Jim Crafton/ISSI, [jwcrafton@innssi.com](mailto:jwcrafton@innssi.com) d. Successful evaluation of the "dual paint".

#### Transition 27

a. Khalil & Gouterman, UW, b. Fiber-optic Sensors, c. Roger Wolthuis/RJC Enterprises, [roger@ricenterprises.net](mailto:roger@ricenterprises.net) d. Development of fiber optic oxygen sensor - medical application.

#### Transition 28

a. Khalil & Gouterman, UW, b. Pressure Sensitive Films, c. Timothy Bencic/NASA Glenn, [Timothy.J.Bencic@grc.nasa.gov](mailto:Timothy.J.Bencic@grc.nasa.gov) d. Research into ice wind tunnel performance.

#### Transition 29

a. Khalil & Gouterman, UW, b. Dual luminophor Pressure Sensitive Paint c. James Bell /NASA Ames, [jhbell@mail.arc.nasa.gov](mailto:jhbell@mail.arc.nasa.gov) d. Applications in wind tunnel testing

#### Transition 30

a. Khalil & Gouterman, UW, b. Dual luminophore Pressure Sensitive Paint, c. Youssef Mebarki /The Institute for Aerospace Research, [Youssef.Mebarki@nrc-cnrc.gc.ca](mailto:Youssef.Mebarki@nrc-cnrc.gc.ca), d. For low speed wind tunnel testing for automotive designs.

#### Transition 31

a. Khalil & Gouterman, UW, b. Dual luminophor Pressure Sensitive Paint, c. Jim Crafton/ISSI, [jwcrafton@innssi.com](mailto:jwcrafton@innssi.com), d. For licensing evaluation

#### Transition 32

a. Khalil & Gouterman, UW, b. Oxygen sensor material, c. Roger Wolthuis/RJC Enterprises, [roger@ricenterprises.net](mailto:roger@ricenterprises.net), d. For fiber optic oxygen sensor, medical application

#### Transition 33

a. Khalil & Gouterman, UW, b. Temperature sensitive dye c. Donald Oglesby, NASA Langley, Hampton, Virginia d. For cryogenic wind tunnel testing.

#### Transition 34

a. Khalil & Gouterman, UW, b. Pressure and Temperature Sensitive Paints c.

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Jim Callis, UW, d. For insect flight research

### Transition 35

a. Khalil & Gouterman, UW, b. Oxygen sensitive dye c. Ian Sweet, UW, d. For islets viability research

### Transition 36

a. Khalil & Gouterman, UW, b. Oxygen, zinc, pH sensitive dyes c. Masoud Ghandehari, Polytechnic University, d. For infrastructure corrossions sensing and gaseous leak detections.

### Transition 37

a) Khalil, University of Washington, b) "Highly Stable NIR Dyes for Photonic Applications: Tetra(pentafluorophenyl)porphodilactone and trilactone" 3<sup>rd</sup>, c) International Conference on Porphyrins and Phthalocynines, New Orleans, LA, July 11-16, 2004, d) presented findings

### Transition 38

a) Lau, University of Washington, b) "Highly Stable NIR Dyes for Photonic Applications: effects of light and oxygen on the synthesis of Tetra(pentafluorophenyl)porphodilactone", c) 3<sup>rd</sup> International Conference on Porphyrins and Phthalocynines, New Orleans, LA, July 11-16, 2004, d) presented findings

### Transition 39

a) Gouterman, University of Washington, b) "Platinum Porphyrin Luminescence: Oxygen Sensing and Pressure Sensitive Paint (PSP)", c) Chemistry Department, LSU, Baton Rouge, LA, July 19, 2004, d) presented findings

### Transition 40

a) Khalil, University of Washington, b) "Dynamic surface pressure measurements, Pressure measurement in fluid phase Shear stress measurement, oxygen lung physiology", c) James Callis, Department of Chemistry, University of Washington  
(206) 543 1208

### Transition 41

a) Khalil, University of Washington, b) "Instrumentation for shear stress measurement", c) Werner Kaminsky, Department of Chemistry, University of Washington (206) 543 7585

### Transition 42

a) Khalil, University of Washington, b) "Lung oxygen physiology studies", c) Michael P Hlastala, Department of Physiology and Biophysics University of Washington (206) 543-3166

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#### Transition 43

a) Khalil, University of Washington, b) "Pressure measurement in fluid phase", c) Dana Dabiri, Department of Aeronautics, University of Washington (206) 543 6067

#### Transition 44

a) Khalil, University of Washington, b) "Synthesis of porpholactones NIR dyes", c) Christian Bruckner, Department of Chemistry, University of Connecticut, Storrs, Connecticut (860) 486-2743

#### Transition 45

a) Khalil, University of Washington, b) "Sensors for insitu monitoring of geo-environmental and infrastructure materials, Gas leak detection", c) Masoud Ghandehari, Department of Civil Engineering, Polytechnic University, Brooklyn, New York (718) 260 3441

#### Transition 46

a) Khalil, University of Washington, b) "Optical Measurements in Wind Tunnel Testing: application to delta wings", c) Mebarki, Youssef, The Institute for Aerospace Research, National Research Council, Ontario, Canada (613) 998 8994

#### Transition 47

a) Khalil, University of Washington, b) "Improved Pressure- and Temperature-Sensitive Paint, Shear stress measurement" c) Jim Crafton, ISSI, Dayton, Ohio, (937) 429 4980

#### Transition 48

a) G. Khalil, Univ. of Washington, b) Developed and transferred a leak detection system to Professor Masoud Gandahari of Civil Engineering Department, Polytechnic University, Brooklyn, New York, c) Collaborating with the New York Gas Institute the leak detection system can be used to capture and measure in real time gas leaks from refineries as well as oil, gas and chemical processing equipment.

#### Transition 49

a) G. Khalil, Univ. of Washington, b) Developed and transferred pressure sensitive particles production system for fluid flow measurement to Professor Dana Dabiri, Department of Aeronautics, University of Washington. The system is capable of producing airborne polystyrene beads. The beads are small enough to follow fluid flow accurately and function as pressure-sensitive air-born micro-particles.

#### Transition 50

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a) Jenekhe, S. A., "Polymer thin film transistors: high electron mobility and ambipolar charge transport," APS March Meeting 2004, Montreal, Canada, March 22-26.

#### Transition 51

a) Jenekhe, S. A., "Conducting polymers symposium," co-organizer, ACS Spring National Meeting 2004, Anaheim, CA, March 28-April 2.

#### Transition 52

a) Prakash, University of Southern California, b) Functionalization of Crosslinked Polystyrene Nanospheres, c) 227<sup>th</sup> National American Chemical Society Meeting, Anaheim CA, March 28-April 1, 2004, d) Presented findings to organic division

#### Transition 53

a) Frechet, University of California, Berkeley, b) electroactive copolymers and terpolymers for highly efficient solution processible light emitting diodes, c) transition to Prof Mark Thompson, University of Southern California, (213) 740-6402, d) application: highly efficient solution processed light emitting diodes.

#### Transition 54

a) J.M.J. Frechet, University of California, Berkeley. b) electroactive copolymers and terpolymers for highly efficient solution processible light emitting diodes c) transition to Prof Mark Thompson, University of Southern California, (213) 740-6402 d) application: highly efficient solution processed light emitting diodes.

#### Transition 55

a) J.M.J. Frechet, University of California, Berkeley. b) Low bandgap polymers c) Transition to Nanosolar Inc. d) application in photovoltaics

#### Transition 56

a. Heeger, UC Santa Barbara, b. Light Emitting Diodes, c. /UNIAX, d. Development of polymer LED technology.

#### Transition 57

a. Heeger, UC Santa Barbara, b. Light Emitting Diodes, c. /DuPont Displays, d. Development of polymer LED technology.

#### Transition 58

a. Heeger, UC Santa Barbara, b. Light Emitting Diodes, c. John Langan/ Computational Sensors Inc, d. "Plastic Retina" project.

#### Transition 59

a. Heeger, UC Santa Barbara, b. New hole injection layer for polymer LEDs, c. DuPont Displays, Dalen Keyes and Ian Parker d. Polymer LED displays

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#### Transition 60

a. Heeger, UC Santa Barbara, b. New hole injection layer for polymer LEDs, c. Ritdisplay (Taiwan), D.C. Wang CEO, Note: Ritdisplay is a joint venture with DuPont to manufacture polymer LED displays, d. Polymer LED displays

#### Transition 61

a. Heeger, UC Santa Barbara, b. Polymer solar cell technology transfer, c. Board of Directors and consultant to Konarka Technologies, d. Polymer solar cell technology

#### Transition 62

a. Heeger, UC Santa Barbara, b. Goodyear; Contact: Dr. A Saleem, c. May 9, 2003, d. Progress in "plastic" electronics

#### Transition 63

a. Heeger, UC Santa Barbara, b. VEECO, Dr. C. Prater, CTO, c. May 29, 2003, d. Progress in "plastic" electronics

#### Transition 64

a) Heeger, University of California, Santa Barbara, b) polymer LEDs, c) Dalen Keys and Ian Parker, DuPont Displays, d) Polymer LED displays

#### Transition 65

a) Heeger, University of California, Santa Barbara, b) Polymer LEDs, c) Ritdisplay (Taiwan), D.C. Wang CEO (Ritdisplay is a joint venture with DuPont to manufacture polymer LED displays), d) Polymer LED displays

#### Transition 66

a) Heeger, University of California, Santa Barbara, b) Polymer solar cell technology transfer, c) Board of Directors and consultant to Konarka Technologies (Howard Berke, CEO), d) Polymer solar cell technology

#### Transition 67

a) Heeger, University of California, Santa Barbara, b) Polymer diodes and polymer Field effect transistors, c) B. Nilsson ([b.nilsson@ieee.org](mailto:b.nilsson@ieee.org)) d) Formation of a new start-up company to develop "plastic electronics"

#### Transition 68

a) Heeger, University of California, Santa Barbara, b) Venture Partner for evaluation of new materials concepts, c) NGEN (Santa Barbara), d) Peter Grubstein, (805) 896-4614

#### Transition 69

a) Heeger, UC Santa Barbara, b) The solar cell technology (see B under Accomplishments/Findings section) has been licensed by Konarka Technologies,

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headquarters in Lowell MASS. Konarka is developing the technology for plastic solar cells for commercialization. Konarka recently announced a commercialization plan that schedules Pilot Plant production in 2007 with the manufacturing of commercial products in 2008.

#### Transition 70

a. Steier, USC, b. Device Techniques, c. Boris Tsap/Pacific Wave Industries, 310-229-0099 d. Development of device fabrication, poling, and measurement techniques.

#### Transition 71

a. Steier, USC, b. Modulators, c. Serge Dubovitsky/Jet Propulsion Laboratory, 818-354-9796 d. Development of 40 GHz EO polymer phase modulators for use in laser range sensing for space applications.

#### Transition 72

a. Steier, USC, b. Materials and Devices, c. Paul Payson/Air Force Research Laboratory, Rome, NY, [Paul.Payson@rl.af.mil](mailto:Paul.Payson@rl.af.mil) d. A materials and device collaboration has been established. A recent graduate of my group has now joined the Air Force Research Laboratory.

#### Transition 73

a. Steier, USC, b. Resonators, c. Mike Morse/Intel, [mike.morse@intel.com](mailto:mike.morse@intel.com) d. Development of polymer ring resonators for computer backplane interconnections.

#### Transition 74

a. Steier, U. South. Calif. b. polymer device technology. c. A. Szep, F. Haas, P. Payson, AFRL, 315-330-4069 d. visit on 7/31/03 to discuss linearization of EO modulators

#### Transition 75

a. Steier, U. South. Calif. b. polymer device technology. c. J. Grote, AFRL, (937) 255-4474 x3263 d. visit 5/20/03 to review waveguide technology and present seminar

#### Transition 76

a. Steier, U. South. Calif. b. polymer device and material technology. c Timothy Parker, R. Dinu, T. Mino, Lumera Corp. (425) 398-6526 d. visit on 8/28/03 to review EO modulator work and several materials and device exchanges.

#### Transition 77

a. Steier, U. South. Calif. b. polymer device and material technology. c. G. Lindsay Naval Weapons Ctr. China Lake, 760-939-1630 d. Exchange information on materials and waveguide fabrication.

## **Polymeric Smart Skin Materials: Concepts, Materials, and Devices**

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#### Transition 78

a. Steier, U. South. Calif. b. polymer resonator technology and applications, c. M. Morris, Intel Corp., 408 545 6403 d. Visit on 5/22/03 to review polymer micro-resonator technology and applications of interest to Intel.

#### Transition 79

a. Steier, U. South. Calif. b. polymer device and material technology. c. Lockheed Martin, W. Anderson, 650 424 2224, d. Flexible polymer modulator technology and applications to Lockheed systems.

#### Transition 80

a. Steier, U. South. Calif. b. polymer device and material technology. c. Photonic Systems, Inc. C. Cox, 780 272 1819, d. Review integration of polymer components and discuss joint programs.

#### Transition 81

a. Steier, U. South. Calif. b. polymer device and material technology. c. PWI, Inc., J. Michael, 310 229 0099, d. High speed modulators and new polymer materials.

#### Transition 82

a. Steier, U. South. Calif. b. polymer device and material technology, c. JPL, Dr. Serge Dubovitsky 818 354 9796 d. Integration of polymer devices with high speed electronics.

#### Transition 83

a) Steier, University of Southern California, b) Polymer device technology, c) M. Morris, B. Block, Intel, 408-455-6403, d) Discuss integration of polymer devices.

#### Transition 84

a) Steier, University of Southern California, b) Polymer device technology, c) L. Maleki, JPL, 818-354-3688, d) Review polymer resonator technology.

#### Transition 85

a) Steier, University of Southern California, b) Polymer device and material technology, c) Timothy Parker, R. Dinu, Lumera Corp., 425-398-6526, d) Review EO modulator work and several materials and device exchanges.

#### Transition 86

a) Steier, University of Southern California, b) Polymer device and material technology, c) G. Lindsay Naval Weapons Ctr. China Lake, 760-939-1630, d) Exchange information on materials and waveguide fabrication.

#### Transition 87

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a) Steier, University of Southern California, b) Polymer device and material technology, c) Lockheed Martin, W. Anderson, 650-424-2224, d) Flexible polymer modulator technology and applications to Lockheed systems.

#### Transition 88

a) Steier, University of Southern California, b) Polymer device and material technology, c) photonic Systems, Inc., C. Cox, 780-272-1819, d) Review integration of polymer components and discuss joint programs.

#### Transition 89

a) Steier, U. South. California b) Polymer device and material technology c) Presentation at AAAS Symposium, Seattle WA, 2/15/04, d) Review status of high speed modulator technology and polymer micro-resonator technology.

#### Transition 90

a) Steier, U. South. California b) Polymer device and material technology c) Presentation at SPIE Conference, San Jose, 1/28/04, d) Review technology for polymer photonic devices

#### Transition 91

a) Steier, U. South. California b) Polymer micro-resonator technology c) OSA Topical Meeting, San Diego, 6/28/04, d) Presented status of polymer micro-resonators devices.

#### Transition 92

a) Steier, U. South. California b) Polymer device and material technology, c) LEOS meeting, Tucson, 10/29/03, d) reviewed polymer photonic device program

#### Transition 93

a) Steier, U. South. Calif. b) polymer device technology. c) M. Morris, B. Block, Intel, (408) 455 6403 d. program review during the year to discuss integration of polymer devices.

#### Transition 94

a) Steier, U. South. Calif. b) polymer device technology. c) L. Maleki, JPL, 818-354-3688 d. established cooperative program on polymer resonator technology

#### Transition 95

a) Steier, U. South. Calif. b) polymer device and material technology. c) Timothy Parker, R. Dinu, Lumera Corp. (425) 398-6526 d. continued collaboration on EO modulator work using Lumera materials.

#### Transition 96

a) Steier, U. South. Calif. b) polymer device and material technology. c) G. Lindsay Naval Weapons Ctr. China Lake, 760-939-1630 d. Exchange

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information on materials and waveguide fabrication.

#### Transition 97

a) Steier, U. South. Calif. b) polymer device and material technology. c) Lockheed Martin, W. Anderson, 650 424 2224, d. Reviewed bias technology and flexible polymer modulator technology and applications to Lockheed systems.

#### Transition 98

a) Steier, U. of Southern California, b) Applications of polymers to tunable filters, c) LightSmyth Technologies, Dr. C. M. Greiner, d. Submitted joint STTR proposal.

#### Transition 99

a) Steier, U. of Southern California, b) Applications of polymers to rf links, c) Regolux Technologies, Dr. Kanti Jain, d. Submitted joint STTR proposal.

#### Transition 100

a. Steier, U. South. Calif. b. polymer device technology. c. M. Morris, B. Block, Intel, (408) 455 6403 d. program review during the year to discuss integration of polymer devices.

#### Transition 101

a. Steier, U. South. Calif. b. polymer device technology. c. L. Maleki, JPL, 818-354-3688 d. established cooperative program on polymer resonator technology

#### Transition 102

a. Steier, U. South. Calif. b. polymer device and material technology. c Timothy Parker, R. Dinu, Lumera Corp. (425) 398-6526 d. continued collaboration on EO modulator work using Lumera materials.

#### Transition 103

a. Steier, U. South. Calif. b. polymer device and material technology. c. G. Lindsay Naval Weapons Ctr. China Lake, 760-939-1630 d. Exchange information on materials and waveguide fabrication.

#### Transition 104

a. Steier, U. South. Calif. b. polymer device and material technology. c. Lockheed Martin, W. Anderson, 650 424 2224, d. Reviewed bias technology and flexible polymer modulator technology and applications to Lockheed systems.

#### Transition 105

a. Steier, U. of Southern California, b. Applications of polymers to tunable filters, c. LightSmyth Technologies, Dr. C. M. Greiner, d. Submitted joint STTR

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proposal.

Transition 106

a. Steier, U. of Southern California, b. Applications of polymers to rf links, c. Regolux Technologies, Dr. Kanti Jain, d. Submitted joint STTR proposal.

#### **New Discoveries, inventions, or patent disclosures:**

- OTL Ref #: 2636-3380  
Inventor(s): Larry R. Dalton  
Title of Work: Hyperpolarizable Organic Chromophores and Electro-optic Materials  
Patent Title: Hyperpolarizable Organic Chromophores  
Patent App. Filed: 7/24/2001  
Provisional Filed: 7/24/2000  
PCT App. Filed: 7/24/2001  
Elect title: Yes  
Lics. to the Gov: 8/24/2001
- OTL Ref#: 2727-3487  
Inventor(s): L. R. Dalton, W. B. Carlson, Gamal-Eddin, Khalil, M. Gouterman  
Title of Work: Fouorinated Acrylic Polymer based upon 2-[ethyl(heptadecafluorooctyl)-sulfonyl]amino]ethyl methyacrylate (FAB)  
Date Disclosed: 5/1/2001
- OTL Ref: 2765-3533  
Inventor(s): Larry R. Dalton, W. Brenden Carlson, Gamal-Eddin Khalil, Gregor D. Phelan  
Title of Work: Temperature sensing europium chelates  
Date Disclosed: 8/13/2001
- OTL Ref: 2766-3534  
Inventor(s): Larry R. Dalton, W. Brenden Carlson, Gamal-Eddin Khalil, Martin Gouterman  
Title of Work: Novel iridium luminophores for use as oxygen sensors and pressure sensing paint based upon FAB, FTB, acrylic polymers, acrylic/silicone polymers, polydimethylsiloxane, and trimethylsiliyl-1-propyne  
Date Disclosed: 8/13/2001
- OTL Ref: 2790-3581  
Inventor(s): Larry R. Dalton, W. Brenden Carlson, Alex Kwan-yue Jen, Xuezhong Jiang

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Title of Work: Osmium based Organic Light Emitting Diodes (OLEDs). New ligands for osmium based OLEDs.

Date Disclosed: 6/11/2002

• OTL Ref: 2636-3859

Inventor(s): Larry R. Dalton, Jindong Luo, Marnie Haller, Alex Kwan-yue Jen

Title of Work: "Highly efficient and thermally stable electro-optic polymers from reversibly crosslinkable process"

Date Disclosed: 12/27/2002

• OTL Ref: 2799-3935

Inventor(s): Younan Xia, Yugang Sun, Brian Mayers

Title of Work: "Hollow nanostructures of Palladium and Applications"

Date Disclosed: 4/14/2003

• OTL Ref: 3020-3868

Inventor(s): Younan Xia, Hiroshi Fudoji

Title of Work: "Photonic papers and inks"

Date Disclosed: 12/23/2002

• OTL Ref: 4098DL

Inventor(s): Larry R. Dalton, Alex Kwan-yue Jen

Title of Work: "Highly efficient and thermally stable electro-optic polymers from reversibly crosslinkable process"

Date Disclosed: 01/09/2004

• OTL Ref: 7027DL

Inventor(s): Khalil, Callis, Kaminsky, Kimura

Title of Work: Shear Sensitive Paint for High-resolution 2-Dimensional Shear Stress Measurements Over Dynamic Surfaces

Date Disclosed: 4/7/2004

• OTL Ref: 7061DL

Inventor(s): Khalil, Callis, Gouterman, Hankins

Title of Work: Simple Visual Test for Packaging Integrity

Date Disclosed: 5/27/2004

• OTL Ref: 7062DL

Inventor(s): Khalil, Callis, Chang, Dalton, Gouterman

Title of Work: Surface Pressure Measurements Using Singlet Oxygen Emission

Date Disclosed: 5/28/2004

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- OTL Ref: 7184D  
Inventor(s): Gregory D. Phelan, William Brenden Carlson, Larry R. Dalton  
Title of Work: Rhodium Based Luminescent Materials  
Date Disclosed: 03/15/2005
  
- OTL Ref: 7185D  
Inventor(s): William Brenden Carlson, Gregory D. Phelan, Larry R. Dalton  
Title of Work: Platinum Luminescent Materials for Use as an Emission Source  
Date Disclosed: 03/14/2005
  
- OTL Ref: 7186D  
Inventor(s): William Brenden Carlson, Gregory D. Phelan, Larry R. Dalton  
Title of Work: Osmium Based Oxygen Sensors and Pressure Sensing Paint (PSP)  
Date Disclosed: 03/14/2005
  
- OTL Ref: 7191D  
Inventor(s): William Brenden Carlson, Gregory D. Phelan  
Title of Work: Polymeric Host Materials for Use in Organic Light Emitting Devices  
Date Disclosed: 03/25/2005
  
- OTL Ref: 7217D  
Inventor(s): William Brenden Carlson, Gregory D. Phelan  
Title of Work: Platinum based near infrared emitters for use in organic light emitting devices  
Date Disclosed: 04/14/2005
  
- OTL Ref: 7261D  
Inventor(s): Younan Xia, Sang-Hyuk Im  
Title of Work: Polystyrene Hollow Particles with Deliberate Holes in Their Surface  
Date Disclosed: 06/20/2005
  
- OTL Ref: 7272D  
Inventor(s): Younan Xia, James B. Callis, Gamal-Eddin Khalil  
Title of Work: Polystyrene beads loaded with dual luminophors for self referenced optical sensing  
Date Disclosed: 07/13/2005
  
- Patent No: 3426P.1US

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Inventor(s): Xia, Callis, Dalton, Khalil, Gouterman, Costin, Im  
Title of Work: Dual-Luminophor Compositions and Related Methods  
Date Disclosed: 07/19/2005

• OTL Ref: 7352D  
Inventor(s): Alex Kwan-yue Jen, Shi Michelle Liu, Yuhua Niu  
Title of Work: Crosslinkable Hole-transport Layer on p-doped Hole-injection Layer for High Efficiency Polymer Light-emitting Diodes  
Date Disclosed: 11/29/2005

• OTL Ref: 7353D  
Inventor(s): Alex Kwan-yue Jen, Yuhua Niu  
Title of Work: High-efficiency Light-emitting Diodes Using Neutral Surfactants and Aluminum Cathode  
Date Disclosed: 11/29/2005  
Provisional Filed: 5/25/06  
Provisional no.: 60/808,920

• OTL Ref: 7419D  
Inventor(s): Brendan Carlson, Larry R. Dalton, Gregory D. Phelan  
Title of Work: Phosphorescent Osmium Complexes as Oxygen Sensors and Pressure Sensing Paint (PSP)  
Date Disclosed: 3/10/2006

• OTL Ref: 7501D  
Inventor(s): Brendan Carlson, Larry R. Dalton, Gregory D. Phelan  
Title of Work: Luminescent Metal Complexes Synthesized from Bidentate Mixed Ligand Systems New Ligand Design for the Creation of Luminescent Metal Complexes for Use in Sensors and Organic Electronics that Emit Light.  
Date Disclosed: 6/27/2006

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### RICE UNIVERSITY

Tech ID#: 24044  
Inventor(s): James Tour, Christopher Dyke, Francisco Maya, Michael Stewart, Bo Chen, Austen Flatt  
Title of Work: Use of Functionalized Carbon Nanotubes for Covalent Attachment of Nanotubes to Silicon  
Date Disclosed: 05/10/2005

Tech ID#: 24040  
Inventor(s): James Tour, Christopher Dyke, Jared Hudson  
Title of Work: Functionalization of Carbon Nanotubes in Super Acid Medium  
Date Disclosed: 03/01/2004

### POLYTECHNIC UNIVERSITY / CITY UNIVERSITY OF NEW YORK, NEW YORK

Inventor(s): Khalil, Callis, Gouterman, Ghandehari, Spellane  
Title of Work: Porphyrin Compound Based Corrosion Sensors  
Date Disclosed: 7/9/2003

### **Honors/Awards:**

#### Awards and Honors Received by Larry Dalton:

- 2006 IEEE/LEOS William Streifer Scientific Achievement Award
- Fellow, American Association for the Advancement of Science (2006)
- Senior Member, IEEE (2006)
- QEM (Quality Education for Minorities)/MSE (Mathematics, Science, and Engineering) Network 2005 Giants in Science Award
- Dow/Karabatsos Lecture Series and the Alumni Distinguished Lectureship, Michigan State University, 2005
- AFRL Materials, Manufacturing & Enabling Technologies Lecture Series, Dayton, 2004
- 2003 Chemistry of Materials Award of the American Chemical Society
- 2003 Eastman Lecturer, University of Akron
- 2002 Lecturer, Distinguished Lecture Series of the National Science Foundation
- 2000 Distinguished Alumni Award of Michigan State University
- 1996 Richard C. Tolman Medal of the American Chemical Society
- Paul C. Cross Lectureship, University of Washington, Seattle, WA (1996)
- NASA Lecturer, Fifty-Fourth Frontiers in Chemistry Lecture Series (1995),

# **Polymeric Smart Skin Materials: Concepts, Materials, and Devices**

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Case Western Reserve University

- The 1990 University of Southern California Associates Award for Creativity in Research and Scholarship
- 1986 Burlington Northern Foundation Faculty Achievement Award
- NIH Research Career Development Awards (Two Awards, one at Stony Brook, one at Vanderbilt, 76-81)
- Camille and Henry Dreyfus Teacher-Scholar Award (75-77)
- Alfred P. Sloan Fellowship (74-77)

### Awards and Honors Received by A. K-Y Jen

- Fellow, American Association for the Advancement of Science (2006)
- Boeing-Johnson Endowed Chair University of Washington, 1999-
- Industrial fellow (rank as full professor) Northwestern University, 1995-2000
- Founder's Award ROITech, 1995
- Outstanding Achievement Award EniChem America, 1994
- President's Award EniChem America, 1989
- Rohm & Hass Research Fellowship Dept. of Chemistry, U. of Pennsylvania, 1981

### Awards and Honors Received by Y. Xia:

- Camille Dreyfus Teacher Scholar, the Camille and Henry Dreyfus Foundation, 2002
- Fellow in Science and Engineering, the David and Lucile Packard Foundation, 2000
- Research Fellow, the Alfred P. Sloan Foundation, 2000
- Faculty Early Career Development Award, the National Science Foundation, 2000
- Victor K. LaMer Award, the American Chemical Society (ACS), 1999
- Oversea Young Investigator Award, the Chinese Natural Science Foundation, 1999
- New Faculty Award, the Camille and Henry Dreyfus Foundation, 1997
- ICI Student Award Finalist, the American Chemical Society (ACS), 1997

### Awards and Honors Received by Alan Heeger:

- Presidential Chair, UC Santa Barbara, 2003
- Doctor of Philosophy (h.c.) Bar-Ilan University, Israel, 2002
- National Academy of Engineering (USA), 2002
- Korean Academy of Science (Foreign Member), 2001
- University of California, Santa Barbara, Chancellor's Medal, 2001
- University of Pennsylvania, President's Medal for Distinguished Achievement, 2001
- National Academy of Sciences (USA), 2001
- Doctor of Science (h.c) South China Institute of Science and Technology, 2001

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- Doctor of Science (h.c.) Japan Advanced Institute for Science and Technology, 2001
- Nobel Prize in Chemistry, 2000
- Doctor of Science (h.c.), Univ. of Nebraska, 2000
- Doctor of Humane Letters (h.c.), Univ. of Mass-Lowell, 1999
- Doctor of Technology (h.c.) Abo Akademi University, Finland, 1999
- Doctor of Technology (h.c.) University of Linköping, Sweden, 1996
- Balzan Prize, "Science of New Materials", Bern, Switzerland, 1995
- Doctor of Science (h.c.) Université d'Etat a Mons, Belgium, 1992
- John Scott Award for 1989
- Oliver E. Buckley Prize for Condensed Matter Physics, 1983
- Fellow, American Physical Society, 1968
- John Simon Guggenheim Foundation Fellow, 1968-1969
- Alfred P. Sloan Foundation Fellow, 1963-1965

#### Awards and Honors Received by Samson Jenekhe

- Tau Beta Pi, National Engineering Honor Society, 1976.
- Honeywell Star Inventor Award, 1986.
- 21<sup>ST</sup> Annual New Horizons in Physics Lecturer, SUNY – New Paltz, Fall 1990.
- Distinguished Lecturer, Materials Directorate, Air Force Materials Laboratory, Dayton, OH, June 1994.
- The Weissberger-Williams Lecturer, Eastman Kodak Research Laboratories, Rochester, NY, Nov., 1996.
- Macromolecules, Editorial Advisory Board, 1994 - 1996.
- Chemistry of Materials, Editorial Advisory Board, 1997 - 2002.
- Boeing-Martin Professor of Engineering, University of Washington, 2000.
- Fellow, American Physical Society, 2003
- Fellow, American Association for the Advancement of Science, 2003
- Chemistry of Materials, Editor of Special Issue on *Organic Electronics*, 2004.

#### Awards and Honors Received by Jean Frechet:

- IUPAC Canadian National Committee Award, 1983.
- Polymer Society of Japan Lecture Award, 1986.
- American Chemical Society, Doolittle Award in Polymer Materials Science & Eng., 1986.
- American Chemical Society, Cooperative Research Award in Polymer Science 1994.
- American Chemical Society, ACS Award in Applied Polymer Science, 1996
- Society of Imaging Science and Technology, Kosar Memorial Award, 1999
- American Chemical Society, ACS Award in Polymer Chemistry, 2000
- Elected Member of the National Academy of Sciences, 2000
- Elected Fellow of the American Association for the Advancement of Science,

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2000

- Elected Fellow of the PMSE Division of the American Chemical Society, 2000
- Elected Member National Academy of Engineering, 2000
- Elected Fellow of the American Academy of Art and Sciences, 2000
- American Chemical Society, Cope Scholar Award, 2001
- American Chemical Society, 2001 Salute to Excellence Award.
- Honorary doctorate, University of Lyon (France) 2002
- Honorary Doctorate, University of Ottawa (Canada) 2004
- *(b) Honors and major Lectures & Series (2001-2004 only)*
- The John Stauffer Lectures, Stanford University 2001
- The Bayer Lectures, University of Pittsburgh 2001
- The George Fisher Baker Lectures in Chemistry, Cornell University 2001
- The Walter J. Chute Distinguished Lectures in Chemistry, Dalhousie University 2002
- The Merk-Frosst Lecture, University of Alberta, 2002
- The Chambers Lectures, University of Rochester, 2002
- Opening Lecture, International Symposium on Nanobiochemistry, Taiwan, 2002
- Plenary lecture: International Symposium of the Molecules of the Future, Lyon, 2002
- Plenary Lecture "Polymeric Nanomaterials 2002", California 2002
- Keynote Lecturer IUPAC conference on mission and Challenges of Polymer Science & Technology Kyoto 2002
- Plenary Lecture International Symposium on Soft Materials, Tokyo 2002
- The Xerox Distinguished Lectures, Xerox Corp. and McMaster Univ. 2003
- Opening Plenary Lecturer International Dendrimer Symposium, Berlin 2003
- Opening Plenary Lecturer Australian Polymer Symposium, 2003
- Plenary Lecturer IUPAC World Congress, Ottawa, 2003
- Plenary Lecturer Nanotechnology Symposium Yokohama Japan, 2003
- Plenary Lecturer Okamoto Symposium 2004 Nagoya
- Plenary Lecturer Fpi-6 Ithaca, 2004
- Plenary Lecturer POC-2004 Prague
- Plenary Lecturer IUPAC Macro-2004 Paris

### Awards and Honors Received by James M. Tour:

- Advisory Board, NIRT at U. South Carolina Philosophical and Social Dimensions of Nanoscale Research, 2003-present.
- Distinguished Faculty Associate, Hanszen College, Rice University, 1999-2000.
- Chemical Reviews, American Chemical Society, Editorial Advisory Board, September 1999 to 2003.
- Russell Research Award in Science, Mathematics and Engineering, Univ. South Carolina, 1997.

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- Abbott Distinguished Lecturer, Colorado State Univ., March 1997
- National Defense Science Study Group, 1997-1999.
- Governor's Mathematics and Science Advisory Board for South Carolina, September 1996-98.
- National Science Foundation, Materials Research Centers Advisory Committee, April 1996.
- National Science Foundation, CAREER Program Advisory Committee, March 1995.
- Weissberger-Williams Lecturer, Eastman Kodak Corporation, Rochester, NY, November 1995.
- Exxon Educational Foundation Research and Training Award, 1994.
- National Science Foundation Presidential Young Investigator Award in Polymer Chem., 1991-96.
- Office of Naval Research Young Investigator Award in Polymer Chemistry, 1989-92.
- IBM Corp. One Week Visiting Lecturer, Polymer Division, Almaden Research Center, June 1988.
- National Institutes of Health Postdoctoral Fellow, 1987-88.
- IBM Corporation Full Graduate Fellowship in Polymer Chem., Purdue Univ. 1985-86.
- Celanese Corporation Graduate Fellowship in Chemistry, Purdue Univ., 1981-82.
- American Institute of Chemists Award, 1981.
- George Wiley Award in Organic Chemistry, 1979.

#### Awards and Honors Received by William Steier:

- School of Engineering Faculty Service Award
- School of Engineering Senior Research Award
- Fellow IEEE
- Fellow Optical Society of America
- William M. Hogue Professor of Electrical Engineering
- USC Associates Award for Creativity in Research and Scholarship
- Distinguished Alumnus Award, University of Illinois Department of Electrical and Computer Engineering

#### Awards and Honors Received by Surya Prakash:

- 2004, Elected Member, Phi Kappa Phi Honor Society
- 2004, NASA Space Act Board Award for NTR no. 19227, New Fuels For Direct Oxidation Fuel Cells
- 2004 American Chemical Society Award for Creative Work in Fluorine Chemistry.
- Appointed Member of the Editorial Board, The Journal of Nanoscience and Nanotechnology, American Scientific Publishers, 2001.
- Appointed Member of the Editorial Board, The Journal of Organic Chemistry,

## **Polymeric Smart Skin Materials: Concepts, Materials, and Devices**

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- American Chemical Society, 2001.
- USC Associates Award for Creativity in Research and Scholarship, University of Southern California, 2000.
- Appointed Member of the Editorial Board, Indian Journal of Chemistry, Section B, 1999.
- JPL/TAP Group Achievement Award for Low Crossover Membranes for Methanol Fuel Cells, December 1998.
- Visiting Professor, University of Pierre et Marie Curie, Paris 6, France, April - May 1998.
- First Holder of the George A. & Judith A. Olah Nobel Laureate Chair in Hydrocarbon Chemistry.
- Advisory Editor, International Journal of Porphyrins and Pthalocyanines, 1997-2000.
- Guest Editor, Research on Chemical Intermediates, Issues 7, 8 and 9, 1996.
- Visiting Researcher, National Institute for Resources and Environment (MITI), Tsukuba, Japan, January 16-26, 1996.
- JPL/TAP Group Achievement Award for Direct Oxidation Methanol Fuel Cells, November 1994.
- AIST Guest Researcher, Osaka National Research Inst.(MITI), Japan, December 1993.
- Phi Kappa Phi Faculty Recognition Award for Research and Scholarship, University of Southern California, 1986.
- Research Excellence Award by the University of Southern California, 1984.
- University of Southern California Research Assistantship, 1977-1978.
- Case Western Reserve University Graduate Fellowship, 1974-1978.
- Subject Scholar, 1971-1972; Government of India Merit Scholar, 1972-1974.

#### Awards and Honors Received by Martin Gouterman:

- Liberal Arts Professor, 1993-94
- Faculty Excellence Award, Minority Science and Engineering Program, 1991
- Received an award certificate for "creative and enduring theoretical contributions to the chemistry of porphyrins..." presented by an indebted porphyrin community, assembled in Los Angeles, California, Sept., 1988.
- NSF Pre-Doctoral Fellow, 1954-58
- PhD student, Roald Hoffmann shared the 1981 Nobel Prize in Chemistry

*Awards Received by Under-Graduate Students Working on This Project: 1*

# **Polymeric Smart Skin Materials: Concepts, Materials, and Devices**

*Individual PI: Dr. Alex Jen, University of Washington*

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## **Status of Effort:**

In the past year, we have made major breakthrough in electro-optic (E-O) materials and polymer light-emitting diodes (PLEDs). Both ultrahigh electro-optic coefficient ( $> 180 \text{ pm/V @ } 1300\text{nm}$ ) and highly efficient red-emitting LEDs (maximum external quantum efficiency of 7.9% and a maximum brightness of  $15800 \text{ cd/m}^2$ ) have been demonstrated for potential applications in ultrahigh-speed modulation/signal processing and flat panel displays.

## **Highly efficient electro-optic materials development**

(1) Materials exhibiting electro-optic activity ( $r_{33}$ ) of greater than  $180 \text{ pm/V}$  have been achieved. Moreover, new chromophores have been prepared that possess improved molecular hyperpolarizability that should be capable of being translated into even higher electro-optic activity. Efficient synthetic techniques, including microwave-assisted synthesis, have also been used to improve reaction yields and reduce reaction times in the production of new materials. The chromophore development include the following:

- (a) Replacement of methyl groups on the tricyanodihydrofuran (TCF) acceptor with one trifluoromethyl group and one alkyl-phenyl-substituted group leads to a factor of 1.5-2.0 in improving molecular hyperpolarizability ( $\beta$ ).
- (b) Development of new acceptors (e.g., replacement of the TCF acceptor with a tricyanopyrrolinevinylene (TCP) or a dicyanopyrrolineketone (DCPK) acceptor leads to significantly improved (a factor of 2 improvement) molecular first hyperpolarizability.

The above advances have already led to record EO activity ( $>180 \text{ pm/V}$  at 1.3 micron telecommunication wavelength). When implemented together with supramolecular assembly, these chromophore modifications may lead to further improvement in E-O activities. Long-term stability at  $85^\circ\text{C}$  has also been demonstrated for these chromophores in a high glass transition polycarbonate host polymer. Future research will focus on combining the above-mentioned strategies together with synthesizing of more efficient conjugating bridges. This activity should lead to further improvements in molecular first hyperpolarizability. Chromophores will be incorporated into a variety of hardened lattice structures and the resulting materials will be transitioned to device prototyping after synthetic production has been optimized.

(2) We have developed a novel lattice-hardening method using the Diels-Alder reaction. To overcome the nonlinearity-stability trade-off in poled polymers, the lattice-hardening process should ideally be separated from the poling process that requires high rotation freedom of chromophores. In addition, since most of the highly efficient NLO chromophores possess only moderate chemical and thermal stability, very mild conditions should be employed for

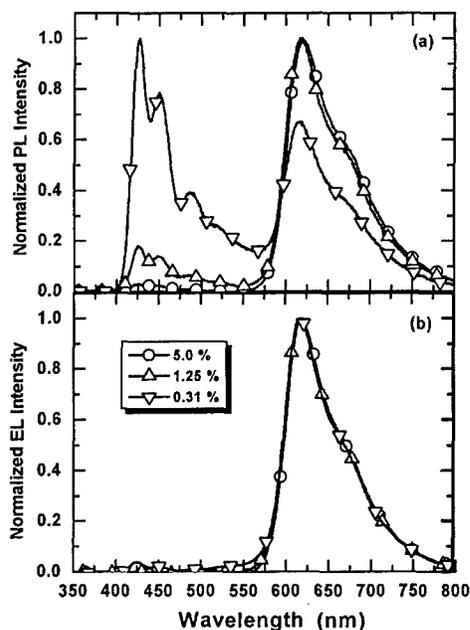
# Polymeric Smart Skin Materials: Concepts, Materials, and Devices

Individual PI: Dr. Alex Jen, University of Washington

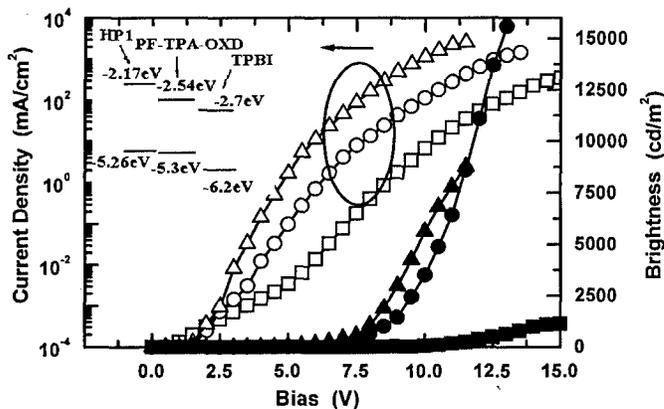
lattice hardening. Taking into account all of these requirements, we have developed an efficient crosslinking method using the Diels-Alder [4+2] cycloaddition reaction. The Diels-Alder (DA) reaction generally involves the coupling between a "diene" with a "dienophile". Among many features of the DA reaction is that the resultant adducts can be reversibly thermally cleaved to give back the starting materials. By taking these process advantages in hardening NLO polymers, it allows us to achieve both very high nonlinearity (76 pm/V at 1.3  $\mu\text{m}$ ) and thermal stability at 70 °C.

## Highly efficient red light-emitting diodes

Highly efficient red-emitting electrophosphorescent devices were fabricated by doping a novel Iridium (Ir)-complex containing trifluoromethyl ( $\text{CF}_3$ )-substituted pyrimidine ligand into a conjugated bipolar polyfluorene with triphenylamine and oxadiazole as side chains. The device efficiency was enhanced through effective exciton confinement using a layer of 1,3,5-tris(*N*-phenylbenzimidazol-2-yl)benzene on the cathode side and a layer of *in-situ* polymerized tetraphenyldiamine-perfluorocyclobutane on the anode side. For a blend with 5 wt % of the Ir-complex, a maximum external quantum efficiency of 7.9 photon/electron % and a maximum brightness of 15800  $\text{cd}/\text{m}^2$  are reached with Commission Internationale de L'Eclairage chromaticity coordinates of  $x = 0.65$ ,  $y = 0.34$ . To our knowledge, these results are among the best for red LEDs using a phosphorescent emitter as dopant in conjugated polymer.



(a) PL spectra of the spin-coated films of the PF-TPA-OXD:Ir-1 blends with different Ir-1 content. (b) EL spectra from corresponding LEDs with the blends as EL layer



Current density-voltage (open) and brightness-voltage (solid) characteristics of the LEDs based on blend of 5% Ir-1 in PF-TPA-OXD. The rectangle corresponds to LED with structure ITO/PEDOT:PSS/EM/TPBI/CsF/Al, the circle to ITO/HP1/EM/TPBI/CsF/Al while the triangle to ITO/HP1/EM/CsF/Al. Inset: energy levels of HP1, PF-TPA-OXD and TPBI.

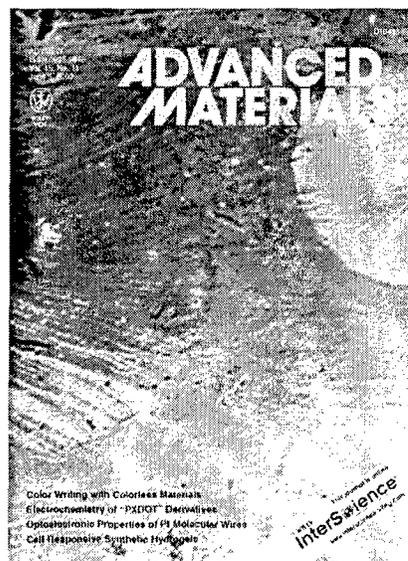
**Accomplishments/New Findings:**

**MURI Final Report, Xia Group (UW), 8/2006**

In the last five years (5/1/2001-4/30/2006), my group has extensively explored a broad range of approaches related to the design and fabrication of smart skin materials capable of detecting, amplifying, and responding to external stimuli. In most of these studies, our efforts were focused on the ability to tune the optical properties of nanostructured materials, and thus to demonstrate the "smart skin" concept. Three accomplishments are highlighted below.

**1. Colloidal Crystals with Tunable Stop Bands and Colors**

*Colloidal crystals whose stop bands could be tuned through the application of a liquid have been fabricated and demonstrated for use as smart photonic coatings. Such a colloidal crystal was generated by infiltrating the voids within an opaline lattice of polystyrene beads with a liquid prepolymer to poly(dimethylsiloxane), followed by thermal curing. When a liquid (e.g., a silicone fluid, hexane, or octane) capable of swelling the elastomer matrix was applied to the surface of this crystal, the lattice constant and thus the wavelength of Bragg-diffracted light was increased. For instance, the color of light diffracted from a colloidal crystal made of 175-nm polystyrene beads could be varied from violet through green and orange to red by swelling it with different solvents. Based on this mechanism, we further demonstrated a photonic paper/ink system where colored patterns could be conveniently generated on the surface of such a colloidal crystal by writing with a Pilot pen, by screen printing, or by microcontact printing with an elastomer stamp. To fully illustrate the potential of this paper/ink system, we have demonstrated the fabrication of photonic papers as large as 75 cm<sup>2</sup> in area, both supported on rigid substrates and flexible Mylar films. By judiciously choosing the size of the polystyrene beads, it was possible to adjust the color initially displayed by a photonic paper to any wavelength within the spectral region from the ultraviolet to the near infrared. These photonic papers can be fabricated to appear colorless while the regions patterned with the inks will display a shiny color, or vice versa. Such thin films coating are also potentially useful for color coding. For more details, see the publications in *Advanced Materials* (2003, 15, 892-896) and *Langmuir* (2003, 19, 9653-9658)*



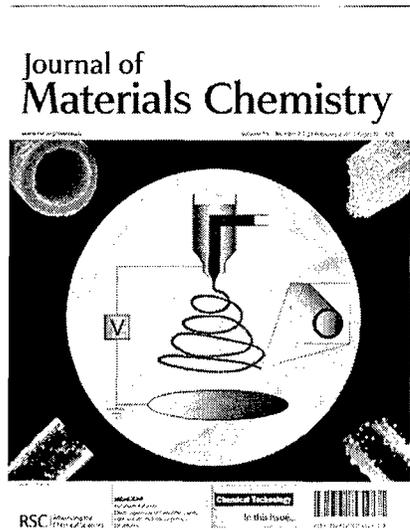
**2. Multifunctional Nanofibers by Electrospinning**

Electrospinning is a simple and inexpensive technique for the production of fibers with nanoscale

# Polymeric Smart Skin Materials: Concepts, Materials, and Devices

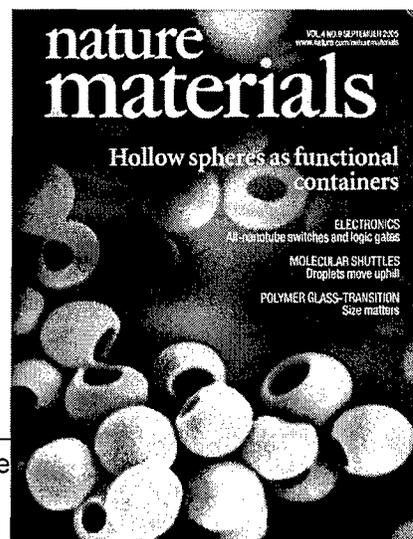
Individual PI: Dr. Younan Xia, University of Washington

diameters and long lengths. Traditionally this method is used to create randomly-oriented non-woven mats of organic fibers from polymer solutions or melts. By co-spinning sol-gel precursors with an ethanol soluble polymer, we have extended this system to spin composite fibers with excellent size control down to tens of nanometers. Additionally, we have made two important modifications to the electrospinning setup. Using a coaxial spinneret, we have been able to manufacture porous, hollow, and core-sheath nanofibers and control the surface chemistry of resultant fibers by tuning the core and sheath solutions. We have also used patterned collectors to uniaxially align nanofibers into parallel arrays. These arrays could be readily assembled into structures for device fabrication. In a recent study, we have directly fabricated porous nanofibers by immersing the collector in a bath of liquid nitrogen. As a result of thermally induced phase separation, between solvent-rich and solvent-poor regions in the fiber, porous nanofibers were obtained when the solvent was removed *in vacuo*. This method is versatile in that it can be readily used with non-volatile solvents and does not require selective dissolution of phase-separated polymers. The porosity and resultant morphology of the fibers can be controlled by altering the collection distance and freeze-drying protocol. As this method is dependent on the presence of residual solvent to induce phase separation, it is also applicable to electrospray in order to generate hollow and/or porous particles in a simple and inexpensive fashion. In addition, the fibers are porous throughout, thus making them suitable for encapsulation of active substances or catalysts. By altering the surface properties of the fibers, it is possible to control the adhesion and growth of cells to the fibers, thus enhancing the properties of nanofiber assemblies for applications such as smart fabrics. In addition, the increased surface area of the fibers can be used to create superhydrophobic coatings. For details, see a comprehensive review on this subject published in *Advanced Materials* (2004, 16, 1151-1170), as well as a recent communication in *Journal of the American Chemical Society* (2006, 128, 1436-1437).



### 3. Polymeric Capsules with Controllable Holes in the Surface

Polymer hollow particles with deliberate holes in their surfaces were prepared by swelling solid beads with a good solvent, followed by freeze-drying with liquid nitrogen. The void size of such a hollow particle is controlled by the solubility parameter of the solvent while the hole diameter is determined by the flux of solvent evaporation. This novel class of hollow particles can serve as mesoscale containers to encapsulate various types of functional materials that include organic chromophores, fluorescent proteins, superparamagnetic iron oxide nanoparticles, and spherical polymer beads. As a major advantage of this system, the functional material to be encapsulated can be directly loaded



**Polymeric Smart Skin Materials: Concepts, Materials, and Devices**  
*Individual PI:* Dr. Younan Xia, University of Washington

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through the holes, which will then be closed by heating the sample above the glass transition temperature of the polymer. This novel class of capsules is immediately useful in the fabrication of self-healing composites as well as other types of smart materials. A report on this finding was published as a cover article in *Nature Materials* (2005, 4, 672-675).

# **Polymeric Smart Skin Materials: Concepts, Materials, and Devices**

*Individual PI: Dr. Alan Heeger, University of California, Santa Barbara*

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## **Status of Effort:**

We have continued to focus on the achievement of improved performance for light emitting diodes fabricated from semiconducting polymers (polymer based electroluminescent devices) and from blends of semiconducting polymers with Ir-based metal-organic complexes (electrophosphorescent devices). A number of specific steps forward were demonstrated including the following:

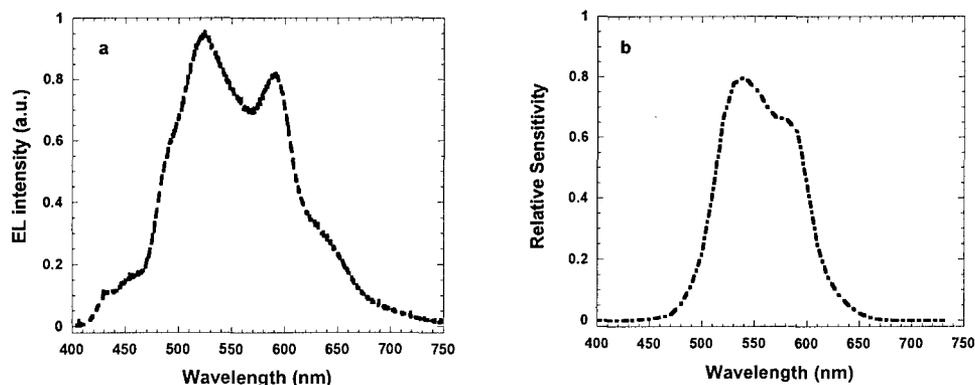
- Demonstration that end-capping could be used to introduce localized impurity levels that function to improve carrier injection
- Demonstration of white emitting electrophosphorescent devices in which the color coordinates, color temperature and color rendering index are insensitive to the brightness
- Demonstration of "printable" --- water soluble conjugated polymer layer --- electron-transporting in polymer LEDs.

A continuing theme was that the energy transfer from the semiconducting polymer host to the emitting moiety (e.g. the Ir-complex, or the fluorenone defect) occurs by sequential charge trapping and not by Förster resonance energy transfer (FRET).

## **Accomplishments/New Findings:**

### **White Light Electrophosphorescence from Polyfluorene-based Light-Emitting Diodes: Utilization of Fluorenone Defects**

Poly(9,9-dioctylfluorene-co-fluorenone) with 1 % fluorenone, (PFO-F(1%)), was synthesized as a model compound in order to investigate the optical and electrical effects of fluorenone defects in poly(9,9-dioctylfluorenyl-2,7-diyl), PFO. Photoluminescence (PL) and electroluminescence (EL) measurements demonstrate that PFO-F(1%) emits stable green light. PL and EL studies indicate that Förster energy transfer to and charge carrier trapping on fluorenone defects (with subsequent fluorenone emission) are responsible for the color degradation typically observed with the polyfluorenes. By utilization of "fluorenone defects" in PFO - fluorenone copolymers (PFO-F), white electrophosphorescent light-emitting diodes were fabricated. Polymer blends were spin-cast from solution containing PFO, PFO-F (1%) and tris[2,5-bis-2'-(9',9'-dihexylfluorene)pyridine- $\kappa^2$ NC<sub>3</sub>]Iridium(III), Ir(HFP)<sub>3</sub>. The white emission turns on at approximately 5V, with a luminance (L) of 6100 cd/m<sup>2</sup> at 17 V. The luminous efficiency is 3 cd/A at current density of 8.5 mA/cm<sup>2</sup> (L= 255 cd/m<sup>2</sup>).



(a) EL spectrum obtained from white emitting electrophosphorescent PLEDs and (b) the same spectrum as in (a) but renormalized to the sensitivity of the human eye. The white light exhibits stable color coordinates, stable color temperature and has a high color rendering index.

*Authors: Xiong Gong, D. Moses and Alan J. Heeger and Steven Xiao*

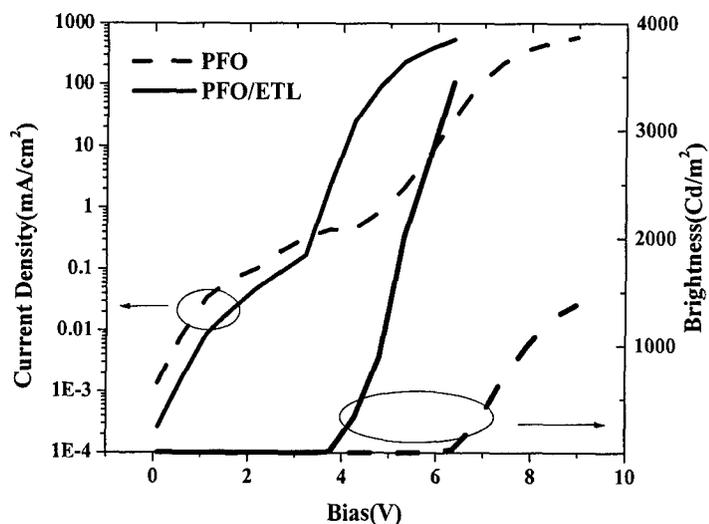
### **Water Soluble Conjugated Copolymer as Electron-Transport Layer in Polymer Light Emitting Diodes**

The principal criteria for a polymer based electron transport layer (ETL) for use in polymer light-emitting diodes (PLEDs) are the following: (1) The lowest unoccupied molecular orbital (LUMO) of the ETL must be at an energy close to, or even within the  $\pi^*$ -band of the emissive semiconducting polymer; and (2) The solvent used for casting the electron injection material must not dissolve the underlying emissive polymer. Although a few attempts to satisfy these criteria have been reported, <sup>[11,12]</sup> none has succeeded in avoiding interfacial mixing in multi-layer PLEDs.

In this study, we reported the fabrication of multi-layer PLEDs using a semiconducting polymer (red, green or blue emitting), cast from solution in an organic solvent, as the emissive layer and a water-soluble (or methanol-soluble) conjugated copolymer as electron-transport layer (ETL) in the device configuration: ITO/PEDOT/emissive polymers/ETL/Ba/Al. To our knowledge, there are no previous reports on the fabrication of multi-layer PLEDs using a water-soluble conjugated polymer as ETL to solve the interfacial mixing problem. The results demonstrate that devices with the ETL have significantly lower turn-on voltage, high brightness and improved luminous efficiency.

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*Individual PI: Dr. Alan Heeger, University of California, Santa Barbara*

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The current density ( $\text{mA}/\text{cm}^2$ ), applied voltage (V) and luminance ( $\text{cd}/\text{m}^2$ ) vs. applied voltage (V) for devices made using blue-emitting PFO with and without the ETL. Note that with the ETL, the devices turn on at a significantly lower voltage and the brightness at all voltages is increased by orders of magnitude.

*Authors: W. Ma, X. Gong, P. Iyer, B. Liu, G. C. Bazan<sup>1</sup>\*, D. Moses\* and A. J. Heeger<sup>1</sup>*

**Status of Effort:**

Double heterojunction photovoltaic cells were prepared from the acceptor polymer poly(benzimidazobenzophenanthroline ladder) (BBL) and the donor poly(*p*-phenylenevinylene) (PPV) or poly(2-methoxy-5(2'-ethyl-hexyloxy)-1,4-phenylenevinylene) (MEH-PPV). Although the photovoltage was almost doubled as expected, the photocurrent and fill factor were low and thus photovoltaic power conversion efficiencies of only up to 1.35 % were achieved. This power conversion efficiency is significantly lower than the single heterojunction solar cells, suggesting that there is a major problem in coupling the two cells. This is believed to be due to the poor conductivity of the conducting polymer used as a metallic electrode between the two heterojunction cells. A new class of n-type fullerodendrimers with high electron affinity (4.0 eV) were synthesized and explored in photovoltaic devices. A maximum fill factor of 42 % and a power conversion efficiency of 0.15 % were obtained at 10 mW/cm<sup>2</sup> illumination for initial ITO/C<sub>60</sub>-G1:MEH-PPV/Al photovoltaic cells. In collaboration with Younan Xia we have prepared a mesh of conjugated polymer nanofibers by electrospinning as an approach to control the interface of polymer solar cells.

**Accomplishments/New Findings:**

**1. Double Heterojunction Polymer Photovoltaic Cells.** It has been recognized that photoinduced electron transfer between donor and acceptor polymers with significantly different energy levels leads to the most efficient exciton dissociation at a donor/acceptor interface. As we reported last year, layered donor/acceptor heterojunctions of poly(*p*-phenylenevinylene) (PPV) and poly(benzimidazobenzophenanthroline ladder) (BBL) gave very promising photovoltaic conversion efficiencies of about 1.5-4.6 %. One limitation of this layered architecture is the small interface between the donor and acceptor polymers. A double heterojunction device of the type ITO/PPV/BBL//conductor//PPV/BBL/Al represents a potential improvement by doubling the interfacial area. In this case, the individual cells are sufficiently thin to allow for a large fraction of the photogenerated excitons to reach a donor/acceptor interface, while the complete stack is sufficiently thick to absorb most of

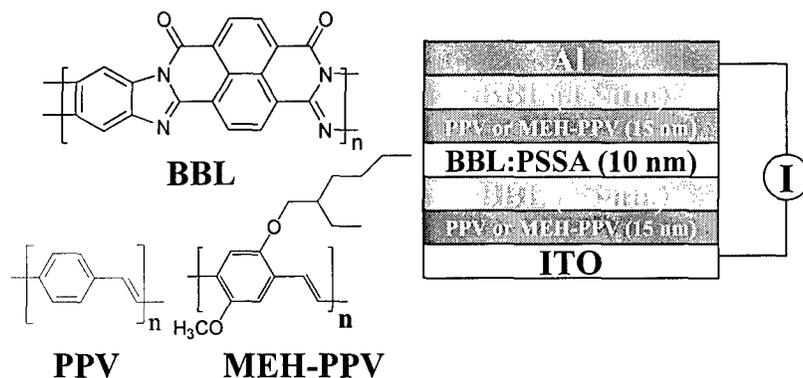


Figure 1. Molecular structures of conjugated polymers and schematic diagram of double heterojunction photovoltaic device.

the incident photons. Furthermore, the photovoltage of a double heterojunction cell should, in principle, be equal to the sum of the photovoltages of the individual heterojunction cells and thus result in an increased open-circuit voltage. We used a conducting polymer thin layer (BBL:PSSA) as the conductor between adjacent

cells to serve as efficient recombination sites for electrons and holes generated in the neighboring cells and ensuring a minimal loss of photovoltage.

The current density-voltage ( $J$ - $V$ ) curves of the PPV/BBL double heterojunction devices in the dark and under AM1.5 simulated solar light illumination are shown in Figure 2a. Under dark condition, the  $J$ - $V$  curve revealed excellent rectifying semiconductor diode characteristics. Upon illumination, a larger photocurrent was observed in this device. Short-circuit current density ( $J_{SC}$ ) and open-circuit voltage ( $V_{OC}$ ) of the photodiode were  $0.045 \text{ mA/cm}^2$  and  $1.11 \text{ V}$  at the  $10 \text{ mW/cm}^2$  illumination, whereas  $J_{SC} = 0.97 \text{ mA/cm}^2$  and  $V_{OC} = 1.35 \text{ V}$  at  $80 \text{ mW/cm}^2$  light illumination. A maximum fill factor of 27 % and power conversion efficiency ( $\eta_p$ ) of 1.35 % were obtained at  $10 \text{ mW/cm}^2$  illumination. The open-circuit voltage ( $1.11 \text{ V}$ ) was much greater than that of single heterojunction cell ( $0.74 \text{ V}$ ) as expected. However, the photocurrent and fill factor were much lower and thus the photovoltaic power conversion efficiency was significantly lower than that of the single heterojunction devices. The MEH-PPV/BBL double heterojunction photocell had a short-circuit current density ( $J_{sc}$ ) of  $0.172 \text{ mA/cm}^2$  and open-circuit voltage ( $V_{oc}$ ) of  $0.75 \text{ V}$  (Figure 2b) resulting in a fill factor of 29 % and power conversion efficiency of 0.37 % at  $10 \text{ mW/cm}^2$  illumination. The poor results are mainly attributed to the poor conductivity of the conducting polymer layer used as a metallic electrode between the two heterojunction cells. Further improvements of this architecture, e.g., optimization of the layer thickness for each cell and the contact layer and the use of other interlayers which are less optically absorptive and have better conductivity, are currently under investigation.

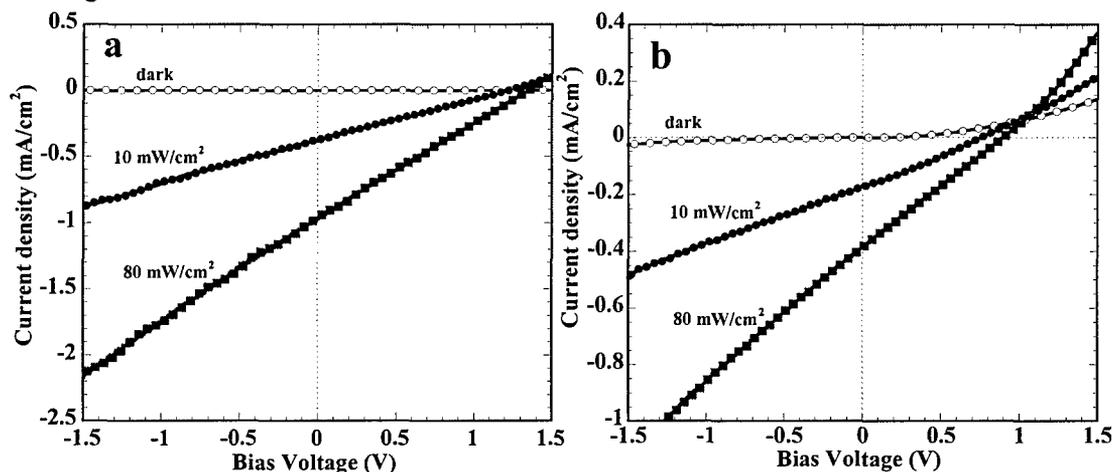


Figure 2. Current-voltage characteristics of double p/n heterojunction photocells; (a) ITO/PPV/BBL/BBL:PSSA/PPV/BBL/Al and (b) ITO/MEH-PPV/BBL/BBL:PSSA/MEH-PPV/BBL/Al.

**2. New Fullerodendrimers for Photovoltaic Devices.** Since  $C_{60}$  is a strong acceptor (n-type) with long exciton diffusion length and appears to be a versatile building block, fullerene-functionalized dendrimers which dramatically improve the solubility of the fullerenes have attracted much attention in photovoltaic applications. Here we have successfully prepared a new class of n-type quinoline-based fullerodendrimers (Figure 3) for use as good electron acceptors in photovoltaic cells.

# Polymeric Smart Skin Materials: Concepts, Materials, and Devices

Individual PI: Dr. Samson A. Jenekhe, University of Washington

We investigated the photovoltaic properties of these fullerodendrimers by blending with MEH-PPV. The photophysical and electrochemical properties of the dendrimers were reported last year. The molecular structures of two dendrimers and a schematic diagram of G1C<sub>60</sub>:MEH-PPV blend photovoltaic device are shown in Figure 3.

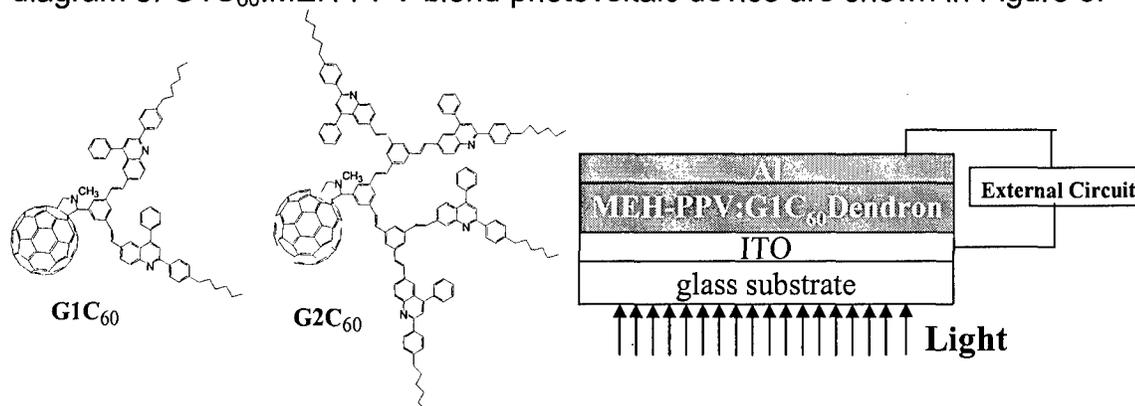


Figure 3. Molecular structures of fullerene based quinoline dendrons and schematic diagram of G1C<sub>60</sub>:MEH-PPV blend photovoltaic device.

The current density-voltage ( $J$ - $V$ ) curves of the photovoltaic device made from G1C<sub>60</sub>:MEH-PPV blend (ITO/G1C<sub>60</sub>:MEH-PPV/Al) in the dark and under AM1.5 simulated solar light illumination are shown in Figure 4. Short-circuit current density ( $J_{SC}$ ) and open-circuit voltage ( $V_{OC}$ ) of the photodiode were 62  $\mu\text{A}/\text{cm}^2$  and 0.58 V at the 10  $\text{mW}/\text{cm}^2$  illumination, whereas  $J_{SC} = 168 \mu\text{A}/\text{cm}^2$  and  $V_{OC} = 0.66$  V at 80  $\text{mW}/\text{cm}^2$  light illumination. A maximum fill factor of 42 % and power conversion efficiency of 0.15 % were obtained at 10  $\text{mW}/\text{cm}^2$  illumination. The power conversion efficiency is better than that of the single-layer PPV Schottky-barrier device ITO/PPV/Al which had a power conversion efficiency of 0.03 % at 10  $\text{mW}/\text{cm}^2$  illumination. These results demonstrate that the new quinoline-based fullerodendrimers are promising n-type (electron-transport) materials for polymer photovoltaic applications.

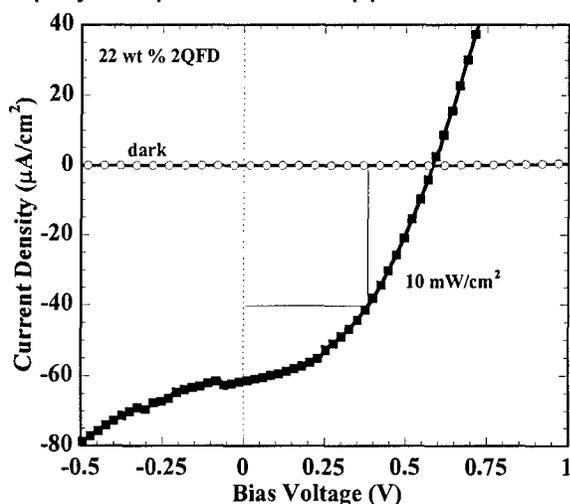


Figure 4. Current-voltage characteristics of ITO/G1C<sub>60</sub>:MEHPPV/Al photovoltaic cell.

**3. Polymer Blend Solar Cells via Electrospinning.** Charge recombination between the separated holes and electrons needs to be minimal to better utilize the photogenerated excitons in polymer-based solar cells. The exciton dissociation is most efficient at a donor-acceptor (p-type polymer/n-type polymer) interface, where a donor with a low IP and an acceptor with a high EA can drive the separation of the bound photogenerated exciton into free charges. The nanostructured interface heterojunctions (Figure 5) will increase the donor-acceptor interfacial area which will lead to better exciton dissociation and will alleviate the problems of generally small exciton diffusion lengths in organic materials. In collaboration with Younan Xia we propose to use electrospinning technique to make such nanostructured heterojunctions. Figure 6 shows an SEM micrograph of a mesh of nanofibers of MEH-PPV (p-type polymer) made via electrospinning. An n-type polymer layer can then be spin coated on top of this mesh to achieve large interfacial area heterojunction between the donor and acceptor polymers.

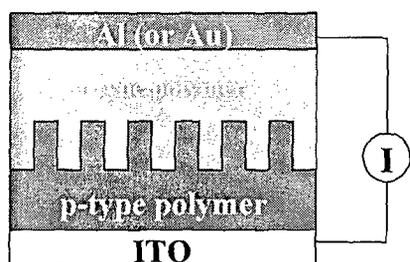


Figure 5. Nanostructured interface heterojunction polymer solar cell schematic

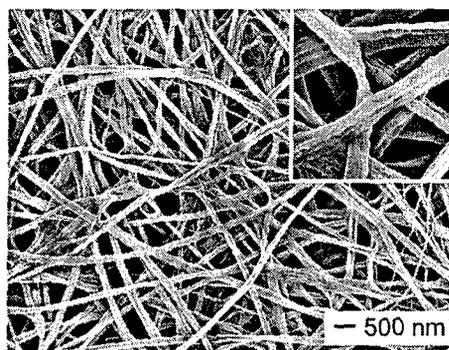


Figure 6. SEM Image of MEH -PPV Nanofibers by electrospinning .

# **Polymeric Smart Skin Materials: Concepts, Materials, and Devices**

*Individual PI: Dr. Jean Frechet, University of California, Berkeley*

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## **Status of Effort:**

We have focused on electroactive polymeric "smart skins" that fulfill functions of light emission and/or light absorption and/or charge transport for new generations of highly efficient polymer-based light emitting systems, photovoltaics, and organic field-effect transistors. While our polymer targets are based on fundamentally new molecular concepts, their designs are also user-friendly as they are solution processible: they can be applied by classical spin-coating, drop-casting, or ink-jetting techniques as opposed to more complex vacuum evaporation/deposition procedures. In addition to fundamental synthetic developments we have also demonstrated that the new smart skins can be incorporated into working polymer-based devices with state of the art efficiencies of over 10% in light emitting diode configuration and 2% in photovoltaic mode.

## **Accomplishments/New Findings:**

Novel copolymers incorporating both electron transport (ET) and hole transport (HT) moieties, or terpolymers containing emitter as well as ET and HT moieties, have been designed and their structure optimized for solubility and electronic properties from a small library of novel monomers with a variety of structures. The new polymers can be spin-coated onto appropriate substrates to produce highly efficient light emitting diode devices. Particularly noteworthy is the fact these polymers are highly soluble and can be handled in air to produce spin-coated OLED devices with efficiencies as high as 11% under unoptimized processing conditions.

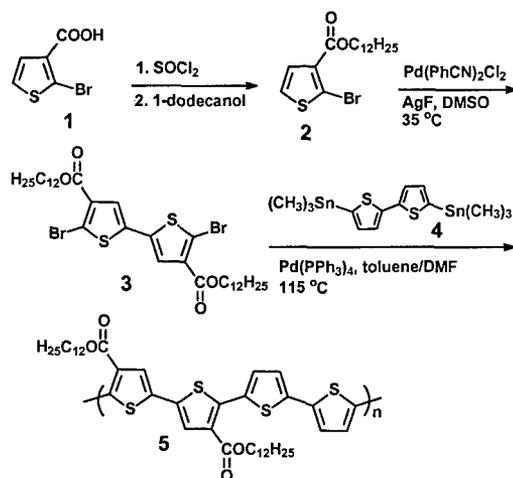
Similarly, we have designed novel functionalized electroactive polymers that provide excellent "electronic communication" with semiconducting inorganic components such as nanocrystals, nanowires, or bulk surfaces for the preparation of polymer-based photovoltaics. Once again the polymers are designed for their ease of use as their intrinsic solubility enables spin-coated for device preparation. In early tests, these novel polymers have demonstrated vastly improved photovoltaic performance over conventional electroactive polymers with efficiencies of 2% achieved in unoptimized devices.

**Most Recent Research: Design and applications of functionalized polythiophenes films as field effect transistor with increased air stability:** We have achieved the synthesis of new polythiophenes containing electron-withdrawing alkyl carboxylate substituents, which exhibit high charge mobility (Figure A). We have found that the regularity of the alkyl carboxylate substitution in our polythiophene can induce and facilitate molecular self-assembly in a fashion similar to that exhibited by regioregular poly(3-hexylthiophene) P3HT. Due to the electron-withdrawing properties of the carboxylate substituents, the new polymers have lower HOMO energy levels (by approximately 0.5 eV) than P3HT, and therefore provide better oxidative doping stability than conventional solution-processible polythiophenes such as P3HT. The new materials are highly crystalline and exhibit very small  $\pi$ - $\pi$  stacking distances

# Polymeric Smart Skin Materials: Concepts, Materials, and Devices

Individual PI: Dr. Jean Frechet, University of California, Berkeley

in the solid state. High charge mobilities are observed as a result of the close ordering of the polymer chains, and top-contact organic thin-film transistors (OTFTs) fabricated entirely in air had measured mobilities averaging  $0.06 \text{ cm}^2/\text{V}\cdot\text{s}$  with on/off ratios  $>105$ . Off currents in these devices remained low over a period of months demonstrating the low propensity of these materials towards p-doping by molecular oxygen. We have also prepared novel oligothiophenes with excellent solubility and electronic properties than can be used to print transistors using an ink-jet printer.



**Figure A.** Synthesis of the regioregular polythiophene 5 with low HOMO.

# **Polymeric Smart Skin Materials: Concepts, Materials, and Devices**

*Individual PI: Dr. James Tour, Rice University*

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## **Status of Effort:**

We have developed the covalent functionalization of single-wall carbon nanotubes (SWNTs) in fuming sulfuric acid to afford unbundled individual SWNT-arylsulfonic acids that are soluble in water; the process does not require surfactant or polymer-based pre-wrapping, centrifugation or sonication. SWNTs are promising building blocks for high performance composite materials. An obstacle to fully exploiting the materials properties of SWNTs is their tendency to spontaneously form bundles and/or flocculate in their unfunctionalized state due to the extraordinary 0.5 eV/nm intermolecular cohesive interaction between neighboring SWNTs.

It has recently been reported that SWNTs disperse as individuals in superacids with SWNT concentrations of up to 10 wt %. Exploiting the solubility of SWNTs in oleum, (H<sub>2</sub>SO<sub>4</sub>, 20% free SO<sub>3</sub>), we have modified our diazonium functionalization chemistry to produce efficient functionalizations of nanotubes in that solvent. The aryl rings sulfonate under the reaction conditions thereby imparting the unusual water solubility to the final compounds. We achieved the functionalization using sodium nitrite and diverse anilines to covalently attach arenes to the HiPco-produced SWNTs that had been oxidatively purified (p-SWNT). Previous diazonium functionalization methods required the presence of a radical source for functionalization to ensue. In superacids it is proposed that SWNTs are surrounded by a double layer of protons and counterions, thus the tube is unlikely to inject an electron into the diazonium salt. Interestingly, we found that the reaction in superacid does proceed in the presence of a radical initiator and affords a similar degree of functionalization when compared to previous diazonium methods. However, in the superacid process, the functionalization results in individual SWNTs, not bundles.

## **Accomplishments/New Findings:**

We have developed methods of functionalizing single wall carbon nanotubes (SWNTs) in SDS solution such that they do not rebundle once the SDS is removed. We have also developed methods of functionalized SWNTs in oleum, and have examined the physical characteristics of blends of nanotubes in various polymer matrixes (see publications). The functionalization of carbon nanotubes will allow the blending of the functionalized tubes into materials of aircraft construction, reducing weight and increasing strength.

**Status of Effort:**

We have been investigating optical waveguides made with ordered 3D arrays of polymer spheres (PBG) as the waveguide walls. By incorporating analytes in or on the spheres, the band gap properties of the arrays can become sensitive to numerous environmental components such as gasses, temperature, strain, moisture, etc. By combing this with the waveguide slow wave properties, a sensitive polymer detector could be realized. We have developed the technology of self alignment of the arrays and used the band gap properties for temperature detection. However the loss per reflection from the arrays is too large for an effective slow wave structure. We have therefore redirected our efforts. We are now preparing a theoretical paper that shows the trade off between slow wave velocity and loss in real media.

**Accomplishments/New Findings:**

As part of the "smart skins" program, we have analyzed and developed a new class of fiber based polymer micro-resonator strain sensors. The flexible sensors are fabricated using a lift off process and are based on the distortion of the micro-ring by strain and the subsequent shift of the resonant wavelength. For the demonstration, a controlled strain was achieved by flexing the sensor.

**A. Polymer Micro-Resonator Strain Sensors**

Fiber based sensors have been demonstrated and their advantages of EMI immunity, optical multiplexing, and relatively high sensitivity have been discussed widely in the literature. Fiber grating sensors have the added advantage that they can be used for distributed sensing and multiple sensors can be addressed in serial fashion over one fiber. We report here on a new type of fiber-based sensor that is based on the polymer micro-resonator technology and that has all of the advantages of fiber grating sensors including high sensitivity and wavelength multiplexing. These detectors are small (100-500  $\mu\text{m}$  dimensions) and could be embedded into materials for the detection of two-dimensional patterns for "smart structures". The sensors we report on here are strain sensors but the concepts can be expanded to real-time temperature, vibration, and load sensing. With the use of selected polymers, the micro-resonator sensors can also be used for chemical and environmental sensing.

Figure 1 shows a schematic of a waveguide coupled micro-ring resonator and the effect of strain on the ring. The resonant wavelength of the ring is given by

$$\lambda = \frac{n_{\text{eff}}L}{m} \quad (1)$$

and the free spectral range is given by

$$FSR = \frac{\lambda^2}{n_{\text{eff}}L}. \quad (2)$$

In these expressions L is the path length around the ring ( $L=2\pi R$  if the ring is a circle of radius R),  $n_{\text{eff}}$  is the effective index of refraction of the optical mode in the ring waveguide, and m is an integer. The unloaded Q is given by

$$Q_u = \frac{2.73 \times 10^5 n_{eff}}{\alpha \lambda} \quad (3)$$

where  $\alpha$  is the waveguide loss, including material, scattering, and bending loss in dB/cm and  $\lambda$  is in microns. At resonance, power is coupled from the input guide and the output drops. At critical coupling all of the power is removed from the input guide.

If the substrate upon which the polymer micro-resonator is fabricated is strained, the shape of the ring will be distorted and as  $L$  changes, the resonant wavelength shifts. Since these can be high  $Q$  devices ( $\sim 10^5$ ), small resonant shifts and small strains can be detected.

For small strain, the diameter becomes larger in the direction of the strain and smaller in the perpendicular direction and a circular ring becomes an ellipse. The change in path length around the ring can be written as

$$\frac{\Delta L}{L} \approx \frac{\varepsilon(1-\nu)}{2} \quad (4)$$

where  $\varepsilon$  is the strain and  $\nu$  is Poisson's ratio. For a circular ring, the direction of the strain does not matter.

The index of refraction of the polymer,  $n$ , is also affected by the strain through the strain-optic effect. For light propagating the direction of the strain, for either polarization

$$\frac{\Delta n}{n} = -\frac{n^2 \varepsilon}{2} [P_{12} - \nu(P_{11} + P_{12})] \quad (5)$$

For light propagating perpendicular to the strain with the polarization in the direction of the strain

$$\frac{\Delta n}{n} = -\frac{n^2 \varepsilon}{2} [P_{11} - 2\nu P_{12}] \quad (6)$$

For light polarization perpendicular to the strain the expression is the same as Equation (5). In these expressions  $P_{11}$  and  $P_{12}$  are the stress-optic coefficients. The calculation of the effect on the resonant wavelength due to  $\Delta n$  requires a weighted integral around the circular path but if the values for polystyrene, a typical polymer, ( $\nu=1.55$ ,  $P_{11}=0.3$ ,  $P_{12} = 0.31$ ,  $\nu=0.4$ ) are used in Equations 4, 5, and 6, we find  $\Delta n/n$  varies from  $-0.06$  to  $-0.085$ . This effect is smaller than  $\Delta L/L = 0.3\varepsilon$  and in this first demonstration we will therefore assume the average effect of the index change around the ring is the average value of  $-0.072\varepsilon$ . If we assume that  $\Delta n_{eff} \approx \Delta n$ , the change in the resonant wavelength,  $\Delta\lambda$ , due to strain is therefore

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta L}{L} + \frac{\Delta n}{n} = 0.228\varepsilon \quad (7)$$

The resonant wavelength is also temperature sensitive

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta L}{L} + \frac{\Delta n}{n} = \left[ \alpha + \left( \frac{dn}{dT} \right) \right] \Delta T \quad (8)$$

where  $\alpha$  is the coefficient of thermal expansion of the substrate and  $dn/dT$  is the thermal index coefficient of the core polymer. For typical polymers,  $dn/dT$  is approximately  $-10^{-4}$ . The thermal wavelength shift will therefore depend on the

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*Individual PI: Dr. William Steier, University of Southern California*

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substrate to which the ring is attached.

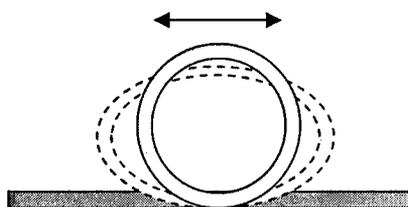
The fabrication of the micro-resonator strain sensor is based on a lift-off process used to fabricate flexible polymer electro-optic modulators. It is based on the low adhesion between Au films and SU-8, a photo-resist. The fabrication process is shown in Fig 2A and the cross-section and photograph of the sensor are shown in Fig.3A. The Si fabrication substrate is patterned with the Au lift-off pattern and the separation occurs at the SU-8/Au interface. After lift-off, the 150  $\mu\text{m}$  thick UV15-7 film becomes the device substrate. Si pads are left on each end of the device to serve as mounting pads for the coupling fibers.

To apply a controlled strain, the Si pads were mounted on separated movable micro-stages as shown in Fig 4A. When the pads are moved closer together, the flexible device bends upward and from the measured vertical displacement  $\Delta y$ , the radius of curvature,  $R$ , of the flexed device is calculated and from the radius and thickness,  $d$  of the film, the strain on the upper surface is calculated. The vertical displacement was measured optically using a CCD camera. The total length of the sensor,  $L$ , between the mounting pads was 11 mm. If the flexed shape is assumed to be a sigmoid and the horizontal movement,  $\Delta x$ , is much smaller than 11 mm, the radius of curvature  $R$  is approximately given by  $R \approx \frac{L^2}{16\Delta y} = \frac{7.6}{\Delta y}$  where  $R$  and  $\Delta y$  are in millimeters. If the Young's moduli of the various polymers used in the sensor are assumed equal, the strain on the upper surface where the micro-ring is located is approximately given by  $\epsilon \approx \frac{d}{2R}$ .

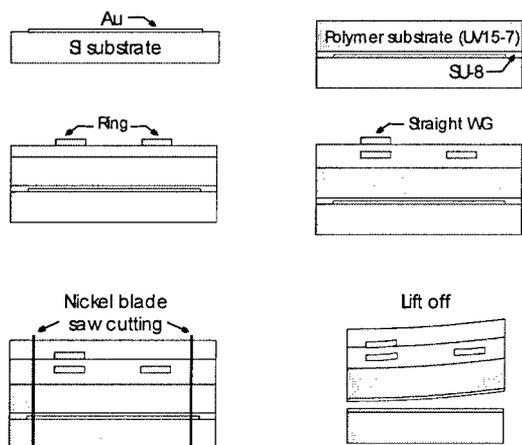
The measurements were done with a tunable 1310nm laser and the shift in the resonant wavelength of one of the modes of the ring was measured as a function of the bending of the ring. The measurements were done at room temperature and no attempts were made to closely control the temperature of the sensor. We believe the resonator was under coupled. The observed  $Q$  was  $4.5 \times 10^3$  and there was no observable change in the  $Q$  when the sensor was flexed.

Fig 5A shows the measured change in resonant wavelength compared to the calculated change given by Eq 7 as a function of the strain. The comparison is quite good; the measured slope is  $0.32 \times 10^{-3} \text{ nm}/\mu\epsilon$  and eq. (11) at 1310 nm gives  $0.30 \times 10^{-3} \text{ nm}/\mu\epsilon$ .

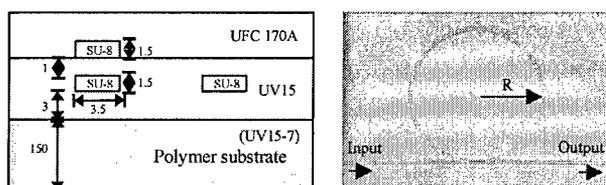
The sensitivity of the micro-resonator strain gauge is about 30% of that reported for fiber Bragg and fiber Fabry-Perot strain gauges. The micro-resonator strain gauge sensitivity can be increased to about the same as these sensors by using a race track design. In this design, the sensitivity is greatest for strain along the long axis of the resonator and by using two orthogonal race tracks, the direction of the strain can also be sensed. If two nominally identical race track resonators have their long axes perpendicular to each other and are coupled to the same waveguide, the difference between their resonant wavelengths is independent of temperature changes. The difference however is a function of the strain except in the special case where the strain is at  $45^\circ$  to the resonator axes. This is a possible way to eliminate the problem of these gauges being sensitive to both strain and temperature.



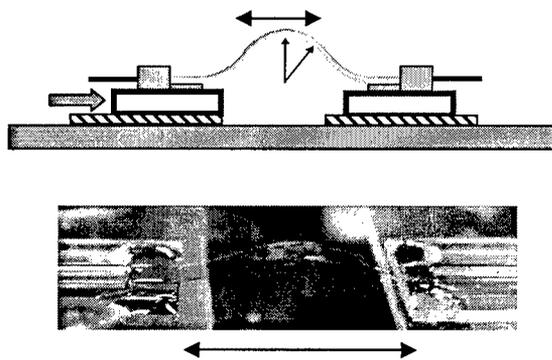
*Fig. 1A Schematic of the waveguide coupled micro-ring resonator and the effect of strain on the ring.*



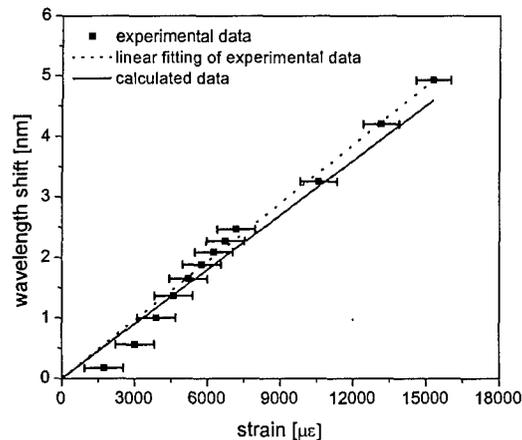
*Fig. 2A Fabrication process of the micro resonator strain sensor based on a lift-off process.*



*Fig. 3A Cross-section and photograph of the sensor.*



*Fig. 4A Application of controlled strain using a micrometer stage.*



*Fig.5A Measured change in resonant wavelength with applied strain. This is also compared with the calculated change*

B. Polymer optical waveguide vertically coupled to high Q Whispering-Gallery resonators.

In conjunction with JPL, we implemented a new approach to bringing very high Q disc resonators into an integrated circuit technology and smart skins based on polymer waveguides. The polymer optical waveguide is vertically coupled into the whispering gallery modes of a fused silica resonator disk. Vertical coupling between high Q WGM resonator disks with a polymer waveguide specially has potential benefits for many photonic applications such as: integrated circuits, power switching, wavelength selection, filters and modulator. This can potentially have a significant benefit for integrated photonic circuits and many other applications. We obtained the loaded quality factor  $Q \approx 3.43 \times 10^6$ .

Fused silica sphere and disc micro-resonators have been reported with Q's exceeding  $10^9$ . Tapered fibers, side polished fibers and frustrated total internal reflection prisms are typically used to couple to these whispering gallery modes. On the other hand, ring waveguide and disc micro-resonators have been integrated with coupling bus waveguides in several materials systems. The highest reported Q's in these integrated devices are  $\sim 10^5$  usually limited by scattering from side-walls.

In this work, the fused silica (Suprasil F300) disc, radius 1.7 mm, thickness 35  $\mu\text{m}$ , is fabricated with the sides optically flat and the edge optically polished. On a separate Si substrate

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*Individual PI: Dr. William Steier, University of Southern California*

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a group of straight polymer waveguides are fabricated. The waveguides are designed to have the same effective index of refraction at  $\lambda = 1550$  nm as the mode in the fused silica disc. One of the waveguides is vertically coupled to the mode of the disc by careful alignment of the waveguide near the perimeter of the disc and adjusting the vertical air gap between the disc and the waveguide as shown in Fig. 1B.

Efficient coupling from the polymer waveguide to the fused silica disc requires a velocity match between the waveguide mode and the whispering gallery mode of the disc. The effective index of the lowest order radial mode of the disc was estimated as using in and the results are shown in Fig. 2B for a wavelength of 1550 nm. The estimated effective index of a 1.7 mm radius disc is 1.4384.

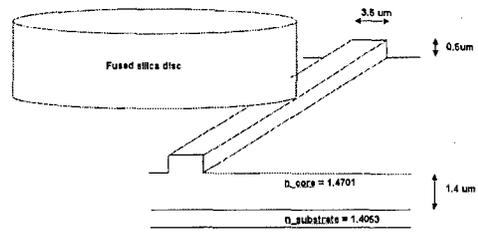
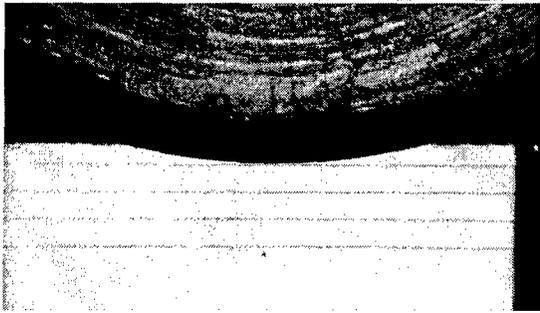
The single mode polymer waveguides were fabricated on a Si substrate using a 7  $\mu\text{m}$  thick lower cladding of ZPU13-R1 [3] with a refractive index of 1.4053 @ 1550 nm. The core material is ZPU12-R1 with a refractive index of 1.4701 @ 1550 nm. The upper cladding is air and a ridge waveguide is used for lateral confinement. The effective index method was used to design the waveguide with an effective index close to the effective index of the disc and with a width the same as our existing masks. With a waveguide width of 3.5  $\mu\text{m}$ , a ridge height of 0.5  $\mu\text{m}$  and a core width (outside the ridge) of 1.4  $\mu\text{m}$ , the calculated effective index is 1.4376. Over the estimated effective coupling length between the waveguide and the disc of  $\sim 150$   $\mu\text{m}$ , this index mismatch is negligible.

The disc was glued by wax on top of the brass holder post and the waveguides were mounted on a micro-manipulator for both horizontal and vertical adjustment. The waveguides were placed under the disc. One of the waveguides (as shown in Fig. 1B) was positioned near the perimeter of the disc and the lateral position fine tuned for maximum coupling. A tunable 1550 nm laser was fiber butt coupled into the correct waveguide and the waveguide output was fiber coupled to a photo-detector. The vertical coupling gap between the waveguide and the disc was adjusted with a micro-manipulator and piezo-electric movements to maximize the coupling.

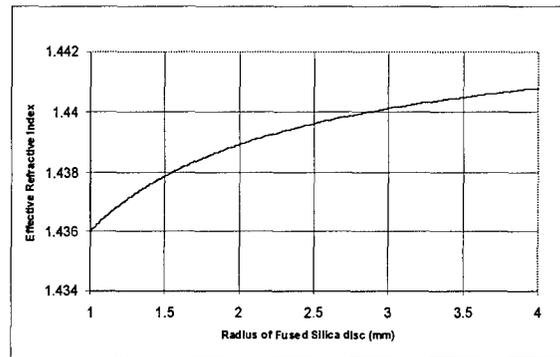
Fig 3Ba shows the output power vs. detuning frequency and shows coupling to two longitudinal modes and two different radial modes of the disc. The frequency spacing between the sets of the same radial modes is consistent with calculated free spectral range (FSR) of 19.5 GHz, where  $\text{FSR} = c/2\pi n_{\text{eff}}R$ . Figure 3Bb shows one mode on an expanded frequency scale. The measured loaded Q is  $3.43 \times 10^6$ . The coupling is near critical coupling. We calculate the percentage of power coupling from the waveguide into disc about 0.7 % [4]. The unloaded Q of  $6.86 \times 10^6$ , thus the total propagation loss (the sum of scattering loss due to roughness, absorption loss of material and radiation loss due to bending) is about  $8.5 \times 10^{-3} \text{ cm}^{-1}$  that leads to the roundtrip loss 0.9% in the disc.

We installed piezo-electric actuator with low drive voltage of 3 VDC per 100 nm displacement into the manipulator to control the air gap between disc and the waveguide. Through the microscope we can observe the contact fringes when we closely set the top of waveguide's ridge touching parallel with the bottom surface of the disc. The surface roughness of polished disc can be estimated about nm range [6]. The power coupled to one of the modes as measured and Fig 4B shows the transmission to the output guide as a function of the air gap when the wavelength is tuned to resonance. The critical coupling is obtained when the gap is about 0.45  $\mu\text{m}$  compare to the estimated gap of 0.5  $\mu\text{m}$  by using the coupled mode theory.

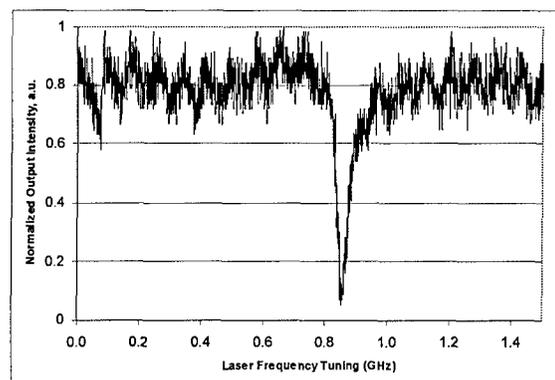
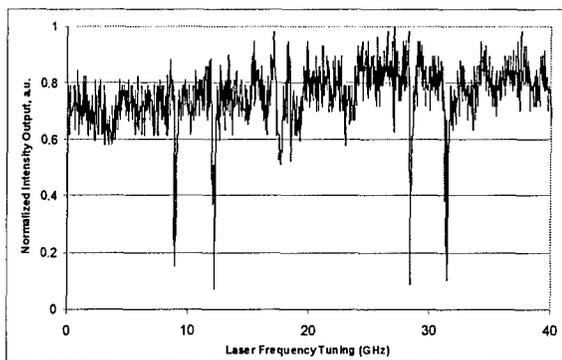
**Polymeric Smart Skin Materials: Concepts, Materials, and Devices**  
*Individual PI: Dr. William Steier, University of Southern California*



*Fig. 1B The top and cross section view of polymer waveguide vertically coupled to the WGM in resonator disk.*



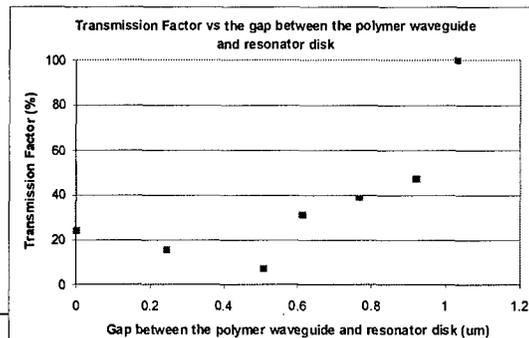
*Fig. 2B The effective refractive index of WGM in resonator disk as a function of its radius at wavelength of 1550 nm.*



*Fig. 3B The optical transmission spectrum for the polymer waveguide – fused silica resonator disk system at  $\lambda = 1550$  nm.*

- a) Output power vs Laser detuning frequency, FSR = 19.54GHz.
- b) Expanded frequency scale show that FWHM = 56.4 MHz, so the

$$Q_{\text{loaded}} = 3.43 \times 10^6$$



*Fig. 4B The transmission factor vs the gap between the polymer waveguide and resonator disk.*



# **Polymeric Smart Skin Materials: Concepts, Materials, and Devices**

*Individual PI: Dr. Surya Prakash, University of Southern California*

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## **Status of Effort:**

- Polystyrene nanospheres were doped with charged dyes.
- Poly(pentafluorostyrene) nanospheres and poly(pentafluorostyrene) grafted polystyrene nanospheres were surface functionalized by novel nucleophilic aromatic substitution chemistry.

## **Accomplishments/New Findings:**

### **Doping of polystyrene nanospheres with charged dyes**

The infrared region of the electromagnetic spectrum between 1300 nm and 1550 nm is in the telecommunication wavelength region. Many of the dyes emissive in the infrared region are either positively or negatively charged. The polystyrene nanospheres prepared by emulsifier free emulsion polymerization technique have overall surface negative charge. Positively charged Basic Fuchsin dye was found to attach to the surface of the nanospheres strongly by electrostatic interactions as indicated UV-Vis spectroscopy.

### **Functionalization poly(pentafluorostyrene) (PFS) nanospheres and poly PFS grafted polystyrene nanospheres.**

Monodispersed poly(pentafluorostyrene) nanospheres and poly(pentafluorostyrene) grafted polystyrene nanospheres fabricated in our previous work were functionalized by nucleophilic aromatic substitution chemistry. The nanospheres were surface functionalized with *para*-aminophenoxide and 2-(4-aminophenyl)ethoxide nucleophiles. The surface amino groups were diazotized and diazocoupled to interesting dye molecules. Furthermore, thiol group containing nucleophiles gave nanospheres that strongly complexed gold colloidal particles. Hydroxy as well as carboxylic acid group containing nanospheres were also prepared. All the surface functionalized nanospheres were characterized by DRIFT, XPS and diffuse reflectance UV spectroscopy.

# **Polymeric Smart Skin Materials: Concepts, Materials, and Devices**

*Individual PIs: Martin Gouterman, Gamil Khalil, and Larry R. Dalton,  
University of Washington*

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## **Status of Effort:**

### **(1) Highly Stable NIR Dyes for Photonic**

**Applications: Tetra(pentafluorophenyl)porphodilactone and trilactone.** *Kim Lau, 4<sup>th</sup> year graduate student*

The goal of this research is to synthesis and characterized stable NIR dyes from the porpholactones family. These photostable dyes will be used to develop oxygen, pressure, pH, CO<sub>2</sub>, temperature sensors and potential photovoltaic materials. Density Functional Theory calculations suggested that opposite porphodilactones should be significantly red shifted in comparison to the porphomonolactone and the porphotrilactone should have absorption bands greater than 1000 nm. We have varied the reaction conditions and observed that light and oxygen are critical factors. We have adopted a new synthetic approach, designed by Bruckner and Dolphin, to separately synthesize the dilactone isomers.

### **(2) High resolution, 2-dimensional shear stress measurements from imaging polarimetry.**

*Fletcher Kimura, 3<sup>rd</sup> year graduate student*

This project involves the development of a novel method for obtaining high-resolution, 2-dimensional shear stress measurements over aerodynamic surfaces, based upon the dynamic birefringence of a shear sensitive, liquid crystal coating. We developed a new imaging device that can make quantitative birefringence measurements at the rate of 30 Hz. The resolution of the resulting shear stress maps are limited only by the CCD imager. We made considerable progress fabricating liquid crystal coatings that are robust yet remain responsive to shear stress.

### **(3) Pressure Measurement Using Singlet Oxygen Emission.**

*Alvin Chang, 2<sup>nd</sup> year graduate student*

We are developing an alternative luminescence method to measure pressure / oxygen concentrations based on the 1270 nm singlet oxygen emission, which can be imaged with an InGaAs NIR camera. This direct measurement of oxygen emission complements and further validates the indirect oxygen measurement. Initial success at obtaining a high negative correlation between 650 nm and 1270 nm emissions under solution conditions has led us to additional two dimensional film studies. We are in the process of evaluating NIR cameras from different vendors.

### **(4) Continuous Gas Leak Detection System.**

*Alice Chin, senior, chemistry student*

A novel gas leak detector has been developed based on continuous monitoring of the oxygen concentration surrounding a natural gas pipeline. Any gas leaking from a pipeline and the associated displacement of oxygen by the

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*University of Washington*

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leaking gas can then be detected through fiber optic evanescent field spectroscopy via an oxygen sensitive based sensor. Once optimized, the detector system will capture and measure in real time large leaks from refineries and other oil and gas or chemical process equipment flanges, valves, and pump leaks. Grant proposal has been presented to the New York gas group for further development.

**Accomplishments/New Findings:**

- In collaboration with ISSI awarded phase I STTR Air Force grant to develop Pressure- and Temperature-Sensitive Paint.
- Developed a new imaging instrument for high resolution, 2-dimensional shear stress
- Progress has also been made towards the development of robust liquid crystal coating to adhere to an airfoil surface, yet remain responsive to shear stress.
- Successfully evaluated the gas leak detector system. Including > 30 days of continuous detection of methane gas leaks by the oxygen sensor embedded in wet sand.
- Identified a synthetic procedure to make the NIR dye dilactone at higher yield.

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*University of Washington*

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**ACCOMPLISHMENTS/FINDINGS:**

The Dalton research group has participated in many of the activities described by other individual investigators in the preceding paragraphs. Most particularly, they have been involved in the design and development of sensor paints (with Gouterman and Khalil). Activities of the final year resulted in development of chem./bio. thin film sensor paints and the integration of these materials into ring microresonator devices for enhanced sensitivity of detection. Another major theme of the Dalton research group has been the integration of multi-component diverse material technology into a single thin film (smart paint) format. This has included the integration of organic and silicon materials.

The Dalton research group has also actively collaborated with the Steier and Jen groups on the development of thin film materials with exceptional optoelectronic and sensor properties.

The Dalton research group helped pioneer the development of carbon nanotube actuators and other carbon nanotube based technologies.