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6. AUTHORS
Natalia Litchinitser

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Michigan - Ann Arbor
Regents of the University of Michigan
3003 S. State St
Ann Arbor, MI 48109 -1274

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14. ABSTRACT
Our research was focused on the development of theoretical and numerical models for understanding, modeling and controlling linear and nonlinear interactions of light with graded-index photonic metamaterials (MMs) and their device applications.In particular, we predicted and investigated the resonant enhancement of electromagnetic waves propagating at oblique incidence in MMs near a point where the real part of the refractive index is zero. This effect occurs for both TE and TM polarizations near the point where the refractive index changes its sign at it transitions

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Report Title

Final Report: Nonlinear Optics of Negative Index Metamaterials

ABSTRACT

Our research was focused on the development of theoretical and numerical models for understanding, modeling and controlling linear and nonlinear interactions of light with graded-index photonic metamaterials (MMs) and their device applications.In particular, we predicted and investigated the resonant enhancement of electromagnetic waves propagating at oblique incidence in MMs near a point where the real part of the refractive index is zero. This effect occurs for both TE and TM polarizations near the point where the refractive index changes its sign at it transitions through zero. Our model elucidates the unique features of the resonant enhancement in “positive-to-negative transition” MMs for a broad frequency range from microwaves to optics. These results are likely to have several applications for low-intensity nonlinear optical devices, optical buffers, and antenna applications.

Also, we investigated the effects of bi-stabilities, multi-stabilities and gap solitons in positive-negative index based nonlinear optical couplers.

We found that although nonlinear optical couplers made of conventional positive index materials are not bistable (unless some additional components such as Bragg gratings or mirrors are introduced), in metamaterials-based couplers, bistability results from the effective feedback mechanism enabled by opposing directionality of the wave vector and the Poynting vector in negative index materials. These unusual properties of MM directional couplers form a basis for the development all-optical processing applications, including wavelength converters, flip-flops, and mirrorless lasers. Moreover, MMs allow for ultra-compact (subwavelength) design of such couplers.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

1. Title: Metamaterials: electromagnetic enhancement at zero-index transition
Author(s): Litchinitser NM, Maimistov AI, Gabitov IR, et al.
Source: OPTICS LETTERS Volume: 33 Issue: 20 Pages: 2350-2352 Published: OCT 15 2008
2. Title: Photonic metamaterials
Author(s): Litchinitser NM, Shalaev VM
Source: LASER PHYSICS LETTERS Volume: 5 Issue: 6 Pages: 411-420 Published: JUN 2008
3. Title: Solitary waves in a nonlinear oppositely directed coupler
Author(s): Maimistov AI, Gabitov IR, Litchinitser NM
Source: OPTICS AND SPECTROSCOPY Volume: 104 Issue: 2 Pages: 253-257 Published: FEB 2008
4. Title: Optical bistability in a nonlinear optical coupler with a negative index channel
Author(s): Litchinitser NM, Gabitov IR, Maimistov AI,
Source: Phys. Rev. Lett. Volume: 99 Pages: 113902 (4) Published: SEP. 2007

Number of Papers published in peer-reviewed journals: 4.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Title: Metamaterials move beyond nature's limits
Author(s): Litchinitser N M, Shalaev VM
Source: Optics & Laser Europe Issue 161 Pages: 14–16, Published MAY 2008

Number of Papers published in non peer-reviewed journals: 1.00

(c) Presentations

1. N. M. Litchinitser, Invited Lecture at The Nonlinear Waves School, Nizhnii Novgorod, Russia (2008).
2. N. M. Litchinitser, I. R. Gabitov, and A. I. Maimistov, Electromagnetic waves propagation in inhomogeneous metamaterials, SPIE Optics & Photonics Conference, Photonic Metamaterials Workshop, San Diego, California (2008).
3. N. M. Litchinitser, From positive- to negative-index materials: Transitional Phenomena, The 38th Winter Colloquium on the Physics of Quantum Electronics, Snowbird, Utah (2008).
4. N. M. Litchinitser, I. R. Gabitov, A. I. Maimistov, and V. M. Shalaev, Ambidextrous light in a nonlinear left-handed world, SPIE Optics & Photonics Conference, Photonic Metamaterials Workshop, San Diego, California (2007).

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Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

1. A. I. Maimistov, I. R. Gabitov, R. Z. Sagdeev, and V. M. Shalaev, Transition metamaterials, 2nd International Congress on Advanced Electromagnetic Materials in Microwaves and Optics, Pamplona, Spain (2008).
2. N. M. Litchinitser, A. I. Maimistov, I. R. Gabitov, V. M. Shalaev, From positive- to negative-index materials: Transitional Phenomena, Lasers and Electro-Optics, 2008 and Conference on Quantum Electronics and Laser Science, CLEO/QELS 2008, pp. 1 – 2.
3. N. M. Litchinitser, I. R. Gabitov, A. I. Maimistov, and V. M. Shalaev, Bistability and multistability in negative index metamaterial structures, Laser Physics Workshop, Leon, Mexico (2007).
4. N. M. Litchinitser, I. R. Gabitov, A. I. Maimistov, and V. M. Shalaev, Nonlinear optics in negative index materials, ICONO/LAT 2007, Minsk, Belarus (2007).

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 4

(d) Manuscripts

N. M. Litchinitser and V. M. Shalaev, Optical Metamaterials: Invisibility in Visible and Nonlinearities in Reverse, in Nonlinearities in Periodic Structures and Metamaterials: Springer Series in Optical Sciences, Vol. 150, edited by C. Denz, S. Flach, and Yu. S. Kivshar (to be published by Springer in 2009).

Number of Manuscripts: 1.00

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Natalia Litchinitser	0.25	No
Andrei Maymistov	0.10	No
FTE Equivalent:	**0.35**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

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The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

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Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See attachment

Technology Transfer

Research Summary

1. ***Transition Metamaterials***

While the optical properties and potential applications of uniform metamaterials with constant refractive indices have been studied in detail and are quite well understood, graded-index metamaterials – artificial materials with refractive indices gradually varying in space in a wide range from positive to zero to negative values – have received significantly less attention so far. The enormous potential of refractive index engineering in metamaterial structures was recently exemplified by the first experimental demonstration of an invisibility (cloaking) device. Nevertheless, no fundamental physical models, design and optimization numerical tools, and experimental platforms exist to date to fully explore their unique properties.

We developed simplified analytical and numerical models to study the EM wave propagation from a

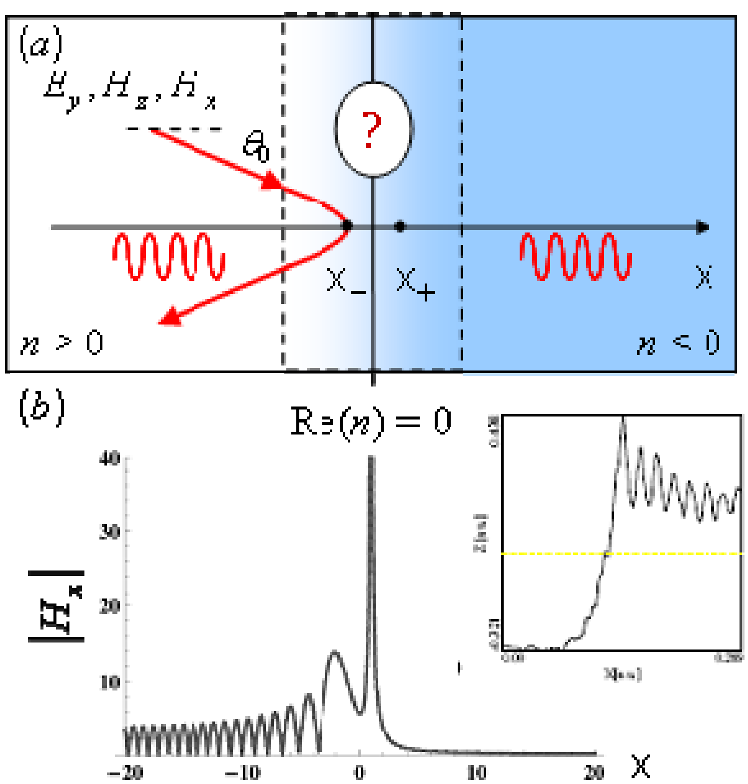

Figure 1 (a) The real parts of the dielectric permittivity and magnetic susceptibility as functions of a longitudinal coordinate, (b) The absolute value of the normalized magnetic field component as a function of normalized longitudinal coordinate. The inset shows preliminary experimental demonstration of the predicted effect obtained by our collaborators.

homogeneous positive index material (PIM) to a homogeneous negative index material (NIM) separated by a graded-index (transition) metamaterial layer with and gradually changing from positive to negative values as shown in Fig. 1(a) [1]. We found exact analytical solutions and asymptotics for the field components near the zero-index point and discovered resonant field enhancement occurring near the zero-refractive-index point under oblique incidence of both TE and TM polarized electromagnetic (EM) waves on a graded-index metamaterial layer such as shown in Fig. 1(b). The inset shows preliminary experimental demonstration of the predicted effect obtained by our collaborators.

While we have not assumed any specific structure of the metamaterial, in a simplified way the origin of the anomalous field enhancement shown in Fig. 1(b) can be understood as a spatial analog of the well-known resonance occurring in a spectral domain when, for example, light interacts with a harmonic oscillator. It is noteworthy that because the wavelength of light becomes very large in the vicinity of the $=0$ (and $=0$) point, the system can effectively be considered as static-like. In the case of the TM wave, the thin layer near the $=0$ point can be considered as a very thin capacitor that accumulates infinitely large electric field energy if we neglect the effects of dissipation and spatial dispersion. Note that such energy accumulation occurs only for obliquely incident waves since the electric field at the oblique incidence has a non-zero component in the direction of propagation. Since electric displacement, D, must be continuous, the electric field, E, anomalously increases as tends to zero. Likewise, for the TE wave considered herein, the magnetic field has a non-zero component in the direction of propagation, and the magnetic field energy accumulates in the vicinity of the $=0$ point in space. Such a thin layer near the $=0$ point can be considered as a short solenoid that stores the magnetic field energy. In this case, H anomalously increases as tends to zero. Finally, owing to the singularities of the magnetic field components, the x- and z-components of the Poynting vector are also singular at $\varsigma=1$. In addition, the z-component of the Poynting vector, given by $S_z = -(c/4\ )E_y H_x$, changes sign while passing the point $\varsigma=1$. This corresponds to a change of sign of the refraction angle at $\varsigma=1$.

It is noteworthy that this phenomenon appears to have an analog in plasma physics, where it is referred to as resonant absorption. However, it was found that the dynamics of wave propagation in graded-index metamaterials as compared to that in plasma is more elaborate and possesses several unique features: 1) the field enhancement effect occurs in both TE and TM polarizations; 2) there are two "reflection" points on either side of the resonance; and 3) propagating waves are allowed past the resonant point. These initial results suggest that metamaterials provide a superior environment for further studies of fundamental and applied aspects of resonant effects in graded-index media. Moreover, these findings indicate that graded-index metamaterials with the material parameters changing from positive to negative values might form a basis for a variety of applications in microwave, terahertz, and optical spectral ranges including sub-wavelength transmission, wave concentrators, and low-intensity nonlinear optical devices.

2. *Nonlinear positive-negative index couplers*

As a first step toward designing practical metamaterials-based guided-wave components, we proposed and investigated a novel kind of nonlinear coupler with one channel filled with a negative index metamaterial as shown in Fig. 2 and developed a model based on the nonlinear coupled-mode equations to describe continuous wave (cw) propagation in such couplers [2]. Making several simplifications including the assumption of identical coupling and nonlinear coefficients in both channels, we found two constants of motion and exact analytical solutions cw light transmission in these

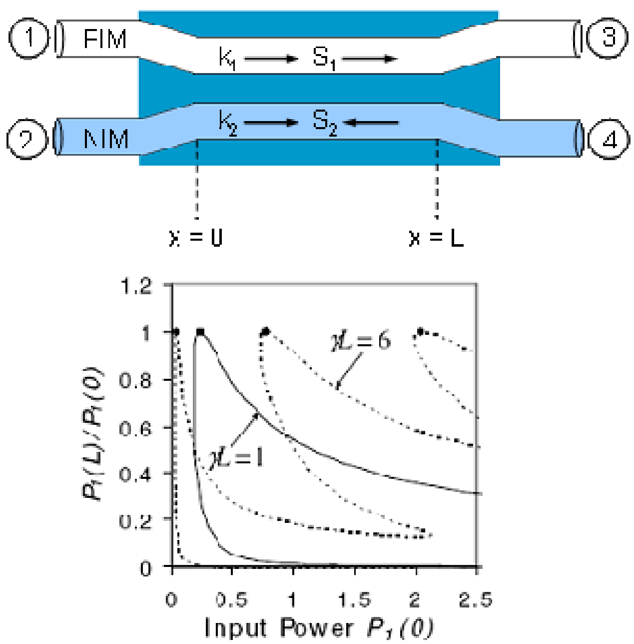

Figure 2. Schematic of a nonlinear PIM-NIM coupler. Light is initially launched into channel 1 (PIM). A wave vector k and a Poynting vector S are parallel in the PIM channel and antiparallel in the NIM channel, enabling a new backward-coupling mechanism.