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13. ABSTRACT (Maximum 200 words)

The primary purpose of the proposed program is to develop methods for controlling and synchronizing the behavior of optical and electronic systems that display complicated behavior such as high-dimensional chaos and turbulent-like behavior. The results of the program have potential applications in the area of increasing the coherence of high-power lasers and nonlinear optical devices, developing an entirely new class of high-speed digital communication system based on chaotic elements, devising ultra-high speed methods for generating random numbers for distributed communication networks, and in new techniques for computing with chaotic systems. We are especially interested in determining techniques for controlling systems that show complexity in both space and time. Specifically, we are trying to understand whether the behavior of such systems can be controlled by applying perturbations to the system at one or a few control locations, rather than at every spatial point of the device. From the results of this experiment, the number of controllers needed to stabilize the entire pattern will be determined. In addition, these results will determine how information spreads and is lost as it is injected into a complex system, with potential implications for communication and computation with chaotic devices.

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CONTROLLING HIGH-DIMENSIONAL CHAOS IN OPTICAL DEVICES

Final Report

Daniel J. Gauthier

Research Period Covered by Report:
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1. Forward

The primary purpose of the proposed program is to develop methods for controlling and synchronizing the behavior of optical and electronic systems that display complicated behavior such as high-dimensional chaos and turbulent-like behavior. The results of the program have potential applications in the area of increasing the coherence of high-power lasers and nonlinear optical devices, developing an entirely new class of high-speed digital communication system based on chaotic elements, devising ultra-high speed methods for generating random numbers for distributed communication networks, and in new techniques for computing with chaotic systems. We are especially interested in determining techniques for controlling systems that show complexity in both space and time. Specifically, we are trying to understand whether the behavior of such systems can be controlled by applying perturbations to the system at one or a few control locations, rather than at every spatial point of the device. From the results of this experiment, the number of controllers needed to stabilize the entire pattern will be determined. In addition, these results will determine how information spreads and is lost as it is injected into a complex system, with potential implications for communication and computation with chaotic devices.

2. Table of Contents

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4. Statement of the problem

One major area of research of the nonlinear dynamics community is the investigation of novel techniques for controlling and synchronizing the dynamics of systems using only small perturbations. The goals of this project include improving the performance of devices whose behavior is degraded by instabilities and chaos, and developing new devices that take advantage of the unique capabilities of the control and synchronization schemes.

The two primary research goals of the program are to: develop methods for controlling and synchronizing chaos in high-speed devices (time scale much less than one microsecond), and controlling the behavior of systems showing spatial as well as temporal complexity. I am motivated for studying the dynamics of fast systems because many potential applications (mentioned above) require high-speed response or processing capabilities. Through this research, I am attempting to push the field to consider true applications of the beautiful fundamental research that has taken place over the past decade. The area of controlling spatio-temporal complexity is the primary focus of many people in the field. The theoretical understanding of such systems lags far behind our understanding of systems displaying only temporal dynamics. Hence, experimental research on control and synchronizing spatio-temporal systems often pushes our basic understanding of such systems. In contrast, there was a firm theoretical foundation on the behavior of temporal systems at the time when people first devised methods for controlling their behavior.

5. Summary of the most important results

5.1. Ultra-low-light-level all-optical switching

We have developed an entirely new scheme for achieving ultra-low-light-level all-optical switching using spatial-temporal patterns in a nonlinear optical device. With future system optimization, we believe that it will be possible to develop a single-photon photon switch based on a collective instability that occurs when laser beams counterpropagate through a rubidium vapor. In most approaches for ultra-low-light level switching, researchers are exploring ways to enhance the nonlinear optical response of an atom to applied electromagnetic fields (*e.g.*, using electromagnetically-induced transparency and the resulting slow-light to enhance the interaction strength). The response of a collection of atoms is then proportional to the response of a single atom times the number of atoms in the interaction volume.

In our new approach, we take advantage of a collective instability that occurs when laser beams interact with a sample of atoms. The instability cannot be inferred from an analysis of a single atom interacting with the applied fields - it arises from the interaction of the applied fields and the entire sample of atoms. In our preliminary experiments (described in a recent publication appearing in *Science*), we find that the spatial patterns produced by the instability are extremely sensitive to the presence of a weak 'switching' beam, as shown in Fig. 5.1. We are able to switch a beam of light that is $>10^4$ times brighter than the switching beam. This is one of the few observations in nonlinear optics where a weak beam can be used to switch or modify a stronger beam of light. Also, we have demonstrated

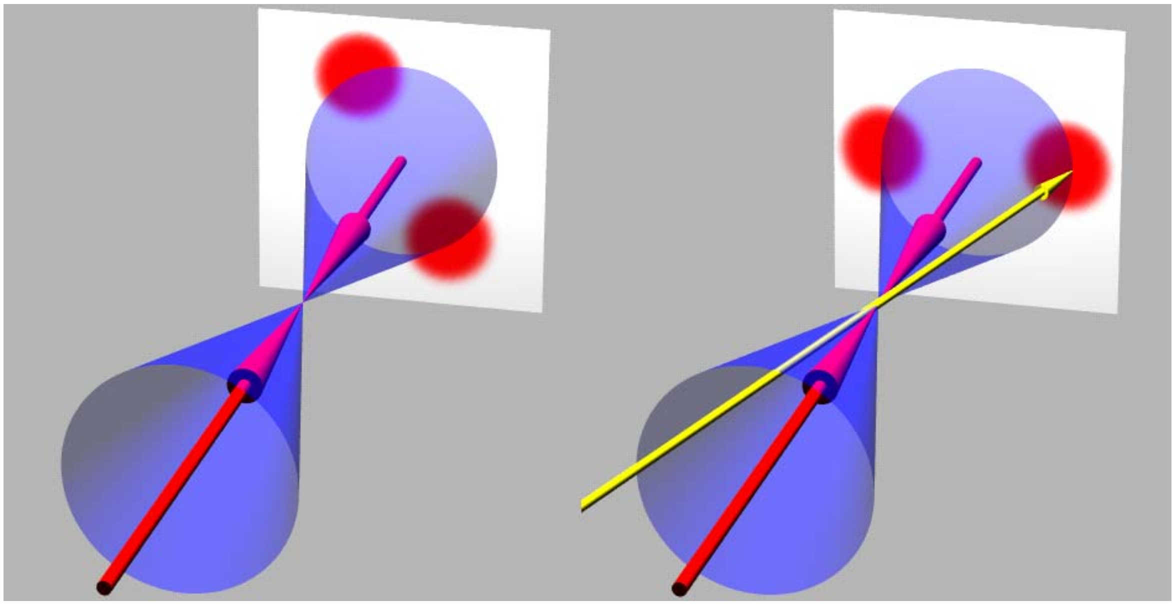

Figure 5.1: Ultra-low-light level optical switch. Left panel: Optical pattern formation occurring when laser beam propagate through a rubidium vapor. Right panel: A weak 'switching' beam causes the pattern to rotate.

switching at a level less than 10^{-2} photons per atomic cross section (a typical performance metric), which is a factor of 100 improvement over the best results reported to date.

There is currently a great need to develop all-optical switches that operate at ultra-low energies, where an incoming 'switching' beam redirects other beams via light-by-light scattering in a nonlinear optical material. Such switches are needed for future telecommunication networks where optical-electronic-optical conversion may not be possible. In addition, scaleable quantum information networks require optical switches that are actuated by a single photon.

A web site describing our research for the general public can be found at:
http://www.phy.duke.edu/research/photon/qelectron/proj/switch/intro.ptml

5.2. High-Speed Chaotic Electronic Oscillator

We have investigated a chaotic electronic chaos generator that consists an amplifier, nonlinear circuit containing clamping diodes and tunnel diodes, a Magic-T splitter, and a delay line as shown in Fig. 5.2. For low amplifier gain, the circuit displayed stable behavior at 0 V. At a critical value of the amplifier gain (the bifurcation parameter), the circuit displays periodic, essentially sinusoidal behavior whose frequency was correlated with the cable length and can be in the range from 100 MHz to 1 GHz. For increasing amplifier gain, the behavior displayed windows of intermittent periodic behavior, complex periodic patterns, quasi-periodicity, and chaos. The behavior was qualitatively similar for all cable lengths, although the window of chaotic behavior for short-length cable was small, if it exists at all.

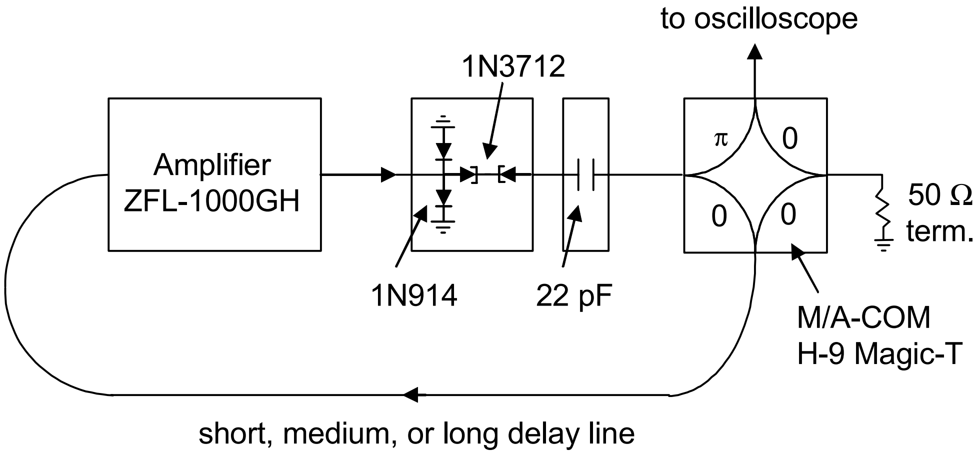

Figure 5.2: High-speed time-delay band-limited chaotic electronic oscillator.

5.3. Bifurcation Analysis of a Time-Delay System with Band-Limited Feedback

We have studied both the global and local stability of the steady-state solution for delay systems with band-limited feedback. We have derived explicitly equations for the Hopf bifurcation curves and use center-manifold techniques to provide a simple criteria that determines whether the Hopf bifurcation is supercritical or subcritical. We also have found that the presence of double-Hopf bifurcations of the steady state solution, which indicates possible quasiperiodic and chaotic dynamics in such systems. The work demonstrates that band-limited feedback dramatically modifies the bifurcation sequence in comparison to a situation where there is only low-pass filtering.

5.4. High-speed chaos in an optical feedback system with flexible timescales

In this phase of research program, we have focused our attention on a class of nonlinear devices known as time-delay dynamical systems. The specific nonlinear system is an opto-electronic device with time-delayed feedback that uses a Mach-Zehnder interferometer as passive nonlinearity and a semiconductor laser as a current-to-optical-frequency converter. Bandlimited feedback allows tuning of the characteristic time scales of both the periodic and high dimensional chaotic oscillations that can be generated with the device. Our implementation of the device produces oscillations in the frequency range of tens to hundreds of MHz. As an example of our results, Fig. 5.3 shows the measure time series of the chaotic fluctuations for three different values of the bifurcation parameter and the associated power spectrum. Figure 5.3f demonstrates that the bandwidth of the chaos extends beyond 100 MHz.

We have developed a fairly complete mathematical model of the device and used it to explore the experimentally observed Andronov-Hopf bifurcation of the steady state and to estimate the dimension of the chaotic attractor. Using this model, we can accurately predict the dominant frequency of oscillation of the system just beyond the threshold from steady

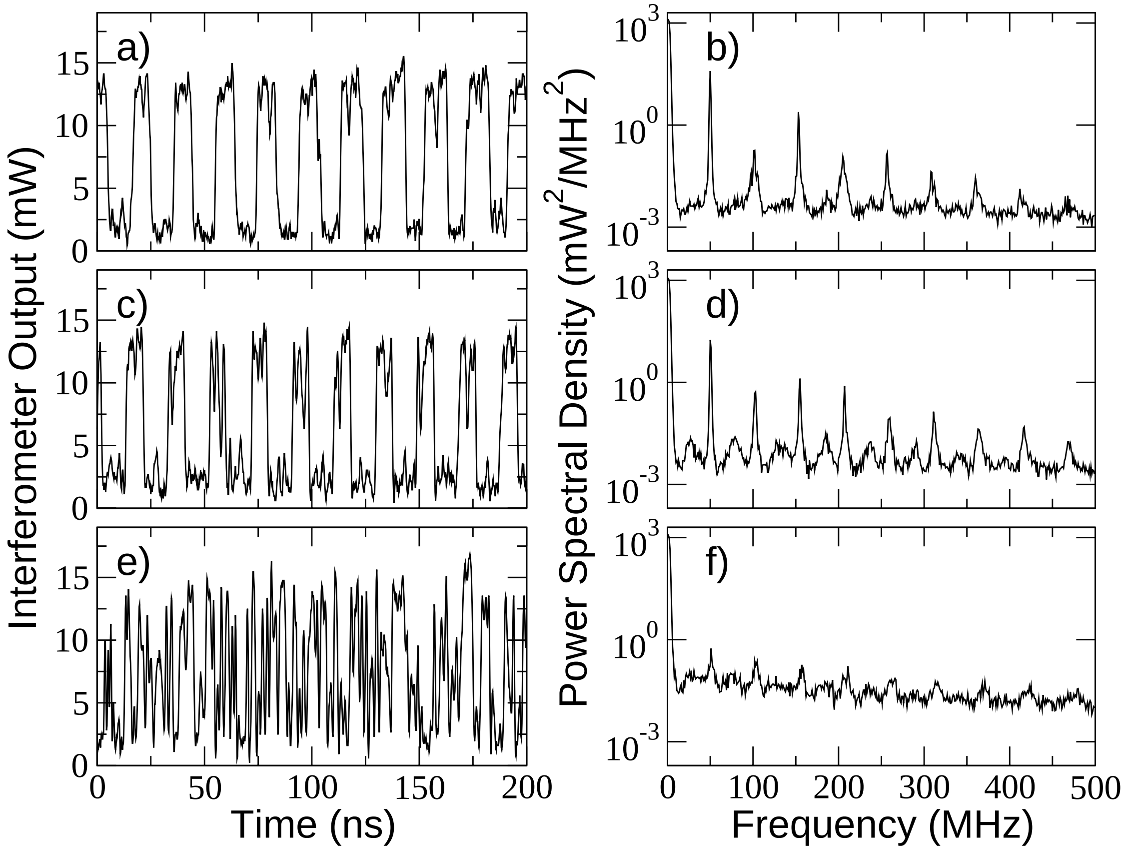

Figure 5.3: Experimentally measured time series (panels a,c, and e) produced by the chaotic electro-optic device and the corresponding power spectrum (panels b, d, and f) as a function of increasing bifrucation parameter which increases the complexity of the chaos.

to periodic behavior. Also, we can obtain reasonable agreement between the predictions of the model (Fig. 5.4) and the experimental observations shown in Fig. 5.3.

Based on this work, we are investigating a general approach to designing high-speed chaotic systems. Currently, we are looking into the development of high-speed electronic oscillators (RF frequency band) for use in communication systems and for radar applications (see the Technology Transfer section below).

5.5. Controlling Fast Chaos

Related to our goal of controlling the dynamics of the fast electro-optic device, we have demonstrated that we can control chaos using closed-loop feedback. We have demonstrated the deleterious effects of control loop latency can be reduced or removed entirely our time-delay dynamical system. Control with reduced control-loop latency is achieved by measuring the state of the system at one location in the delay loop, processing the information to generate the control signal, and injecting the control perturbations at a later point in the

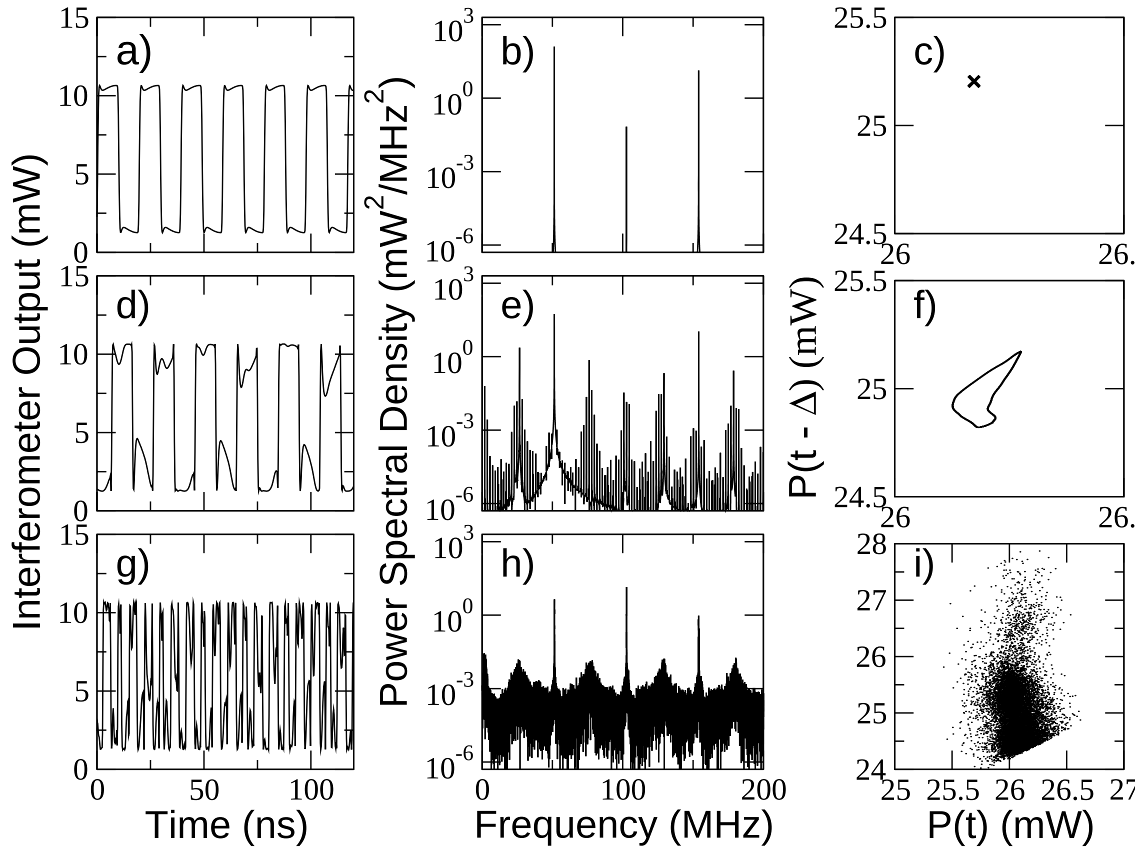

Figure 5.4: Numerically predicted time series (panels a,d, and g), power spectra (panels b, e, and h), and Poincare sections (panels c, f, and i) corresponding to the experimental data shown in Fig. 5.3.

delay loop. The timing of the perturbations is adjusted so that they arrive at the same time as the fluctuating signal propagating through the time-delay transmission line.

The effects of control-loop latency can be removed entirely if the generation and propagation of the control signal is equal to the time delay of signal propagating in the time-delay loop. The fact that the control-loop latency can be removed implies that extremely high-frequency chaotic fluctuations can be controlled in theory, which is important for potential applications of this device for high-speed communication of information. Figure 5.5 show the uncontrolled chaotic time series, which is compared to the controlled periodic orbit. Note that the frequency if the controlled orbit is of the order of 100 MHz, one of the fasted controlled orbits to date.

5.6. Semiconductor laser with controlled current inputs

We have conducted theoretical research demonstrating that significant performance enhancements for high bit rate communication is achieved by judiciously controlling the current

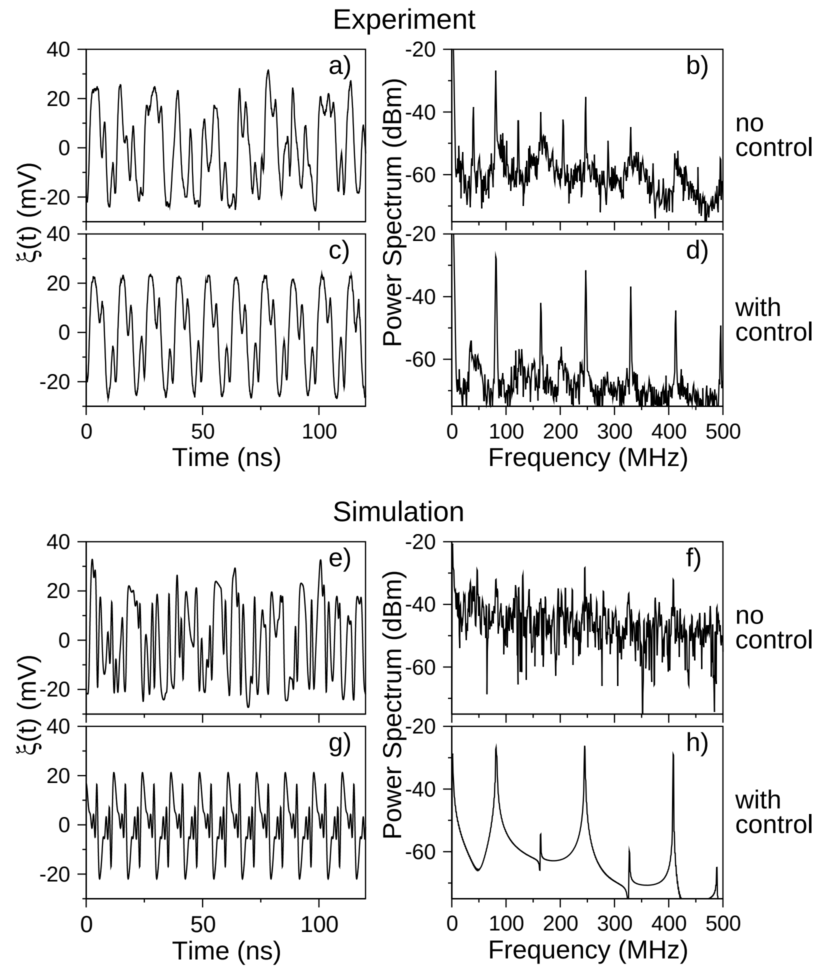

Figure 5.5: Experimental (a-d) and theoretically predicted (e-h) data showing control of fast chaos.

inputs of semiconductor lasers. This work was started by one of us, Dr. Lucas Illing, as part of his dissertation research at the University of California, San Diego. The paper describing this research was written while he was a post-docotoral research associate at Duke University and while he was supported by this grant. The paper appeared in the *IEEE Journal of Quantum Electronics*.

Changing the input current of semiconductor lasers in order to produce time-dependent output intensities (direct modulation) is a convenient and inexpensive way to impart digital information on optical carrier signals. Direct modulation is therefore widely used for low bit rate optical communication. However, an attempt to communicate at high bit rates will result in nontrivial laser dynamics, including chaos, thereby limiting the use of the direct modulation scheme.

Nontrivial internal laser dynamics are excited when the modulation frequency of the input current is comparable to the relaxation frequency of the laser. For typical semiconductor laser the relaxation oscillation frequency is on the order of a few GHz, but special lasers have been developed that allow 40 GB/s communication rates. Our technique of controlling the inputcurrents allows a given laser to be operated without performance degradation at bit-rates that are at least equal to the laser's relaxation oscillation frequency; a regime that would lead to communication breakdown without input-current control.

The technique that we developed determines the shape of the current inputs that will result in an optical output free of relaxation oscillations. As a result, dynamical memory in the physical laser device is avoided. That is, the output will not be influenced by previously communicated information.

We quantified the performance enhancement by calculating the bit-error rate as a function of the signal-to-noise ratio for a communication channel with white Gaussian noise. The result is shown in Fig. 5.6, where it is seen that for high bit rates only shaped currents allow communication with reasonable bit-error rates. On the other hand, current control does not lead to a significant performance enhancement for low bit rates (inset of Fig. 5.6).

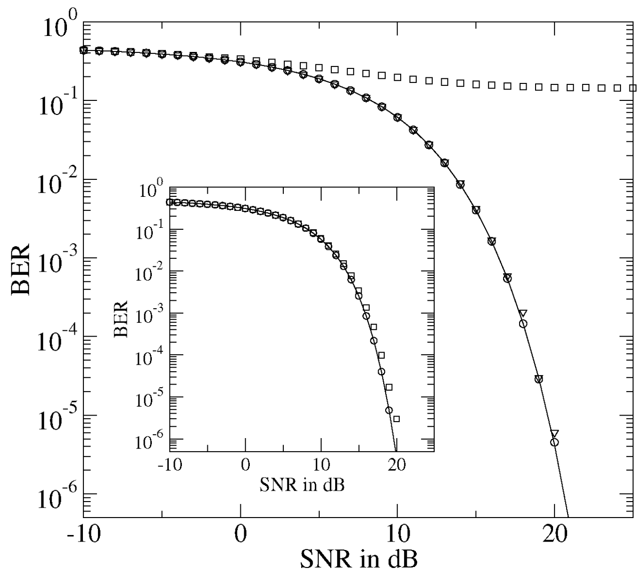

Figure 5.6: The signal-to-noise ratio (SNR) versus the bit-error-rate (BER) is presented for the laser being driven by both shaped currents (circles and lines) and square-like currents (squares). The main panel shows high bit rate (T_{bit} = 2) and the inset lower bit rate (T_{bit} = 8) communication. The symbols represent results obtained by numerical integration and the lines are theoretical curves. We display as triangles results where stimulated emission noise is simulated.

6. List of Publications

6.1. Papers published in peer-reviewed journals

A.M.C. Dawes, L. Illing, S.M. Clark, and D.J. Gauthier, 'Optical switching in rubidium vapor,' Science **308**, 672 (2005).

J.N. Blakely, L. Illing, and D.J. Gauthier, 'Controlling fast chaos in delay dynamical systems,' Phys. Rev. Lett. **92**, 193901 (2004). Selected to appear in the Virstual Journal of Ultrafast Science, Volume 3, Issue 6, June 1, 2004.

L. Illing and M.B. Kennel, 'Shaping current waveforms for direct modulation of semiconductor lasers,' IEEE J. Quantum Electron. **40**, 445 (2004).

J.N. Blakely, L. Illing, and D.J. Gauthier, 'High speed chaos in an optical feedback system with flexible timescales,' IEEE J. Quantum Electron. **40**, 299 (2004).

D.J. Gauthier, 'Resource Letter: CC-1: Controlling Chaos,' an Invited paper in Am. J. Phys. **71**, 750 (2003).

6.2. Papers published in non-peer reviewed journals or in conference proceedings

None to report.

6.3. Papers presented at meetings, but not published in conference proceedings

* denotes invited presentation

L. Illing, D. Gauthier, * 'Hopf Bifurcations in Time-Delay Systems with Band-Limited Feedback,' SIAM Conference on Applications of Dynamical Systems, Snowbird, UT, May 22-26, 2005.

L. Illing, A. Dawes, S. M. Clark, and D. J. Gauthier, * 'Ultra-low-level all-optical switching using a collective instability,' CNCS Seminar Series, Durham, NC, February 15, 2005.

D. J. Gauthier, A. M Dawes, L. Illing, and S. M. Clark * 'Ultra-low-light-level all-optical switching using dissipative optical patterns,' NC Photonics Seminar Series, Durham, NC, January 28, 2005.

A. Dawes, S. M. Clark, L. Illing, D. J. Gauthier, * 'Observation of ultra-low-light-level all optical switching,' Photonics West, San Jose, CA, January 22-27, 2005.

L. Illing, S. M. Clark, A. Dawes, D. J. Gauthier, 'Ultra-low-level light-by-light switching using a collective instability,' Long Beach, CA, Dynamics Days 2005, January 7-10, 2005.

D. J. Gauthier, A. M Dawes, L. Illing, and S. M. Clark * 'New techniques for ultra-low light-level nonlinear optics,' XXXV Winter Colloquium on the Physics of Quantum Electronics, Snowbird, UT, January 3, 2005.

L. Illing, 'Controlling fast chaos in a time delay systems', Understanding Complex Systems Symposium, University of Illinois at Urbana-Champaign, May 17-20, 2004.

L. Illing, * 'Control of fast chaos in a time delay system', Third Physical Institute, University of Göttingen, Germany, Seminar, Mar. 1, 2004.

D. Gauthier, (Invited Presentation) 'Controlling chaos in fast dynamical systems,' Laser Science Conference XIX, Tuscon, AZ, Oct. 8, 2003.

L.Illing, J. N. Blakely, and Daniel J. Gauthier, 'Control of fast Chaos in a Time-Delay System', Gordon Research Conference on Nonlinear Science,' Tilton, NH, August 3-8, 2003.

D. Gauthier, 'A new electro-optic device for generating high-speed chaos,' 2003 Annual Meeting of DAMOP, Boulder, CO, May 21-24, 2003.

6.4. Manuscripts submitted, but not published

L. Illing and D.J. Gauthier, 'Hopf bifurcations in time-delay systems with band-limited feedback,' accepted for publication in Physica D (2005).

6.5. Related Materials, Abstracts, Theses submitted to ARO

J.N. Blakely, 'Experimental control of a fast chaotic time-delay opto-electronic device,' Ph.D. dissertation, Duke University (2003), unpublished.

6.6. Technical reports submitted to ARO

None to report.

7. Scientific Personnel

Dr. Lucas Illing (Research Associate), Mr. Jonathan Blakely (Graduate Research Assistant), and the PI have been partially supported by this project.

Dr. Illling is a Senior Research Scientist at Duke University.

Dr. Blakely received the Ph.D. degree during the period of the grant (September 2003). Upon graduation, he accepted an NRC post-doctoral research associateship to work on controlling and synchronizing chaos at the Weapons Sciences Directorate, AMSAM-RD-WS-ST Missile Research, Development and Engineering Center, U. S. Army Aviation and Missile Command, Redstone Arsenal, AL.

8. Inventions

We have filed on July 20, 2005 a patent disclosure to the Duke University Office of Science and Technology, entitled 'Generation of chaotic RF-signals using band-limited time-delayed feedback.' Some of the work described in this disclosure was conducted during the period of this grant. The reason that the disclosure was filed after the end date of this grant is because some work was conducted under our new grant with the U.S. ARO (W911NF-05-1-0228).