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FINAL REPORT: USAF/EOARD Scientific Workshop on

PATTERN SINGULARITIES AND COLLAPSE: APPLICATIONS TO SEMICONDUCTOR LASERS AND CRITICAL FOCUSING OF ULTRASHORT OPTICAL PULSES, 21-26 August 1994

J G McInerney and J V Moloney

Report dated 11 July 1995

CONTENTS

Introduction, objectives and overview

This meeting was intended to be the first in a series of workshops to bridge the gap between the scientific communities in North America and Europe in critical areas of nonlinear optics and laser science. There was also a recognition that the differing viewpoints which exist in industry, government and academia should be reconciled. Finally, it was our intention that synergistic links should be forged between three distinct and almost entirely separate scientific communities, respectively concerned with (i) ultrashort pulse generation, (ii) fundamental semiconductor physics and (iii) semiconductor laser design engineering.

Attendance at the workshop was by invitation only, and we attempted to achieve a judicious balance between the different constituencies. The only significant improvement to be wished for in future workshops is a larger attendance from industry. Scientific communication between the various groups was free and uninhibited, assisted particularly by well attended and seeded discussion groups following the formal presentations. Cultural, social and personal interactions were also excellent.

Demographically, 21 of the 40 attendees came from North America (20 USA, 1 Canada) and 19 from Europe (Ireland 5, Germany 4, Italy 3, Russia 2, 1 each Denmark, France, Netherlands, Spain). Academic scientists numbered 26, while 11 came from government laboratories or organisations and just 3 from industry. Approximately half of the participants were under the age of 40.

The workshop succeeded remarkably well in achieveing the above objectives. This success will be discussed in greater depth in the final (Summary) section of this report.

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Monday 22 August

Keynote addresses and fundamental issues

0845 Opening remarks - J. G. McInerney and J. V. Moloney
0900 Towards a universal description of patterns - A. C. Newell (University of Arizona)
0945 Controlling chaos - C. Grebogi (Univ. of Maryland)
1030 Singularities and patterns in the dynamics of flame - M. Gorman (Univ. of Houston)
1430 Microscopic modeling of semiconductor lasers - S. W. Koch (Phillips Univ. Marburg)
1515 Self-focusing and spontaneous wiggling of light beams in nonlinear media with normal dispersion - V. E. Zakharov (Landau Institute Moscow and U.of Arizona)
1630 Group discussion

Tuesday 23 August

Generation and critical focusing ultrashort optical pulses: experiments

0900 Nonlinear propagation effects in ultra-short pulse generation - B. Bouma and J. G. Fujimoto (MIT)
1000 The link between short pulse self-focusing and continuum generation - D. Strickland (Princeton)
1100 Self-focusing of ultrashort pulses in gases - F.A. Ilkov, A.Brodeur, V. Francois and S.L. Chin (U. Laval)
1130 Retinal damage studies from ultrashort laser pulses - W. P. Roach (USAF Armstrong Laboratory)
1200 Nonlinear aspects of focusing of ultrashort laser pulses in the human eye - M.E. Rogers (USAF Armstrong Laboratory)

Critical self-focusing in nonlinear optics: theory

1400 The arrest of critical collapse: Applications in nonlinear optics - G. Luther (U. of New Mexico)
1430 Quasi-citical collapse: Theory and applications - S. K. Turitsyn (Novosibirsk)
1500 Pulse dynamics in nonlinear opical fiber arrays - A. Aceves (U. of New Mexico)
1600 Group discussion

Wednesday 24 August

Modes and patterns in large aspect ratio lasers

0900 Patterns in large aspect ratio lasers - J. Moloney (U. of Arizona and Univ. Coll. Cork)
0945 Pattern formation in lasers with curved mirrors - J. Lega (Nice)
1015 Transverse modes and patterns of electrically pumped vertical cavity surface-emitting semiconductor lasers - J. McInerney (Univ. College Cork and U. of Arizona)
1115 Polarisation dynamics and transverse effects in lasers - M. San Miguel (Mallorca and Arizona)
1145 Defects and space-like properties of delayed dynamical systems - G. Giacomelli and F.T. Arecchi (Inst Nazionale di Ottica, Florence)
1230 Group discussion

Thursday 25 August

Semiconductor lasers and amplifiers: high-power structures

0900 Spatial and spectral characteristics of high power, tapered amplifiers and oscillators - D. Mehuys (SDL Inc.)
0945 Controlling filamentation in broad area semiconductor lasers and amplifiers - D. Bossert (USAF Phillips Laboratory)
1015 Single-spatial-mode tapered amplifiers and oscillators - J.N. Walpole, E.S. Kintzer, S.R. Chinn, C.A. Wang and L.J. Missagia (MIT Lincoln Laboratory)

Femtosecond probes of semiconductor amplifiers

1400 Ultrafast carrier dynamics in semiconductor amplifiers - J. Moerk (Tele Danmark Research)
1430 Femtosecond pulse propagation and spectral hole burning in the gain region of inverted semiconductors, and applications to subpicosecond switching - N. Peyghambarian (Arizona)
1500 Frequency domain investigation of the ultrafast carrier dynamics in an InGaAsP bulk semiconductor amplifier - A. Mecozzi, A.D. Ottavi, E. Iannone, S. Scotti, P. Spano and R. Dall'Ara (Fondazione Ugo Bordoni)
1530 Discussion session on ultrafast semiconductor dynamics

Friday 26 August

Chaos and instabilities in semiconductor lasers

0900 Pulse pattern collapse in external-cavity diode laser with low-frequency fluctuations - G.H.M. Van Tartwijk, A.M. Levine and D. Lenstra (Amsterdam)
0930 Period-doubling route into and out of chaos in semiconductor lasers with optical injection. - V. Kovanis (USAF Phillips Laboratory)
1000 Picosecond pulse generation in semiconductor lasers - W. Elsaesser (Marburg)
1100 General discussion and workshop wrap-up

Publicity

The workshop audience and details of the technical contributions were solicited by direct contact with the organisers, *i.e.* each paper was invited. In addition, the workshop was publicised in the Irish public media: national and local (Cork) radio as well as two national newspapers (Irish Times and Cork Examiner). Financial support from USAF/EOARD was acknowledged in all such communications.

Summary

Comments from the participants on informal "exit interviews" were extremely positive about the technical, administrative and social/personal aspects of the workshop. The organisers and the participants believe that a good start has been made in achieving the initial objectives of (a) bridging the gap between the scientific communities in North America and Europe in critical areas of nonlinear optics and laser science, (b) reconciling the diverse viewpoints in industry, government and academia, and (c) building connections between the distinct scientific communities concerned with (i) ultrashort pulse generation, (ii) fundamental semiconductor physics and (iii) semiconductor laser design engineering. The efficient logistical arrangements and friendly staff were uniformly praised. Even the notoriously unpredictable Irish weather was not criticised too adversely.

The prospect of a series of similar workshops held in Cork also won wide support in broad terms. Based on the success of this first effort and the comments of the participants, we believe we should continue to exploit Ireland's strategic location as a gateway between North America and Europe, organising workshops in this general area of research every 2-3 years with external sponsorship. We tentatively plan on holding the next in the second half of July 1996.

Acknowledgements

We thank the authorities of University College Cork for allowing use of the College facilities. We are immensely grateful to the USAF European Office of Aerospace Research and Development in London for financial sponsorship, and we are particularly grateful to Lt Col Don Erbschloe DPhil, Chief of International Programs at EOARD, for his unstinting support and helpful suggestions. We wish to join with the workshop participants in thanking and congratulating the Workshop Secretary, Ms Irene Horne BA, on a job well done. Irene's hard-working student assistants, Finbarr Livesey and Maire McCarthy, as well as the general administrative and technical staffs of the Physics Department at UCC, also deserve our thanks.

Signed in Cork, 11 July 1995:

John McInerney, Professor of Physics (UCC) and Adjunct Professor of Optical Sciences (U of Arizona)
Jerry Moloney, Professor of Mathematics & Optical Sciences (Arizona) and Visiting Professor of Physics (UCC)

Joint workshop co-chairmen:

Appendices

Appendix 1 : technical abstracts
Appendix 2 : list of participants

APPENDIX ~~2~~ 1 : ABSTRACTS (alphabetical, by first author)

PULSE DYNAMICS IN NONLINEAR OPTICAL FIBER ARRAYS

Alejandro Aceves
Department of Mathematics, Univ. of New Mexico, Albuquerque, NM 87131, USA

The dynamics of pulses in an array of equally spaced identical fibers is well described by the coupled mode theory. It is then shown that strong localization, reminiscent of the collapse phenomenon of the 2dim. Nonlinear Schroedinger Equation, arises for different forms of the initial input. This includes as an important case, modulationally unstable cw and soliton pulse inputs.
The characteristics of the localized output, including its stability, suggest using this array as a device for generating short pulses.

CONTROLLING FILAMENTATION IN BROAD AREA SEMICONDUCTOR LASERS

David J. Bossert
USAF Phillips Laboratory, Kirtland AFB, NM 87117, USA

Experimental and numerical studies investigating the operating characteristics and filamentation tendencies of broad area semiconductor lasers and amplifiers are described. Data from an array of diagnostics including spatial coherence, spectrally resolved farfield and gain/index measurements are highlighted. These results are shown to be accurately predicted by a steadystate numerical beam propagation analysis. Optical feedback is also shown to have a dramatic effect upon the spatial coherence of broad area lasers. Time averaged and dynamic behavior of virtual source lasers under weak optical feedback are described.

NONLINEAR PROPAGATION EFFECTS IN ULTRASHORT PULSE GENERATION

B. Bouma and J. G. Fujimoto
Department of Electrical Engineering and Computer Science
Massachusetts Institute of Technology, Cambridge, MA 02139, USA

In recent years, novel applications of nonlinear propagation effects in solid-state lasers have made possible the development of a wide range of modelocked laser sources. This technique, called Kerr lens modelocking, has revolutionized the field of ultrashort pulse generation. In this talk, we will present a simple theoretical description of intracavity nonlinear effects and optimization criteria that allow the development of new compact femtosecond lasers.

ULTRASHORT TIME RESOLVED INVESTIGATIONS OF THE GAIN DYNAMICS OF MODE LOCKED SEMICONDUCTOR LASERS

Wolfgang Elsaßer
Philipps-Universitat Marburg Fachbereich Physik - AG Halbleiterphysik, Marburg, Germany

We study the temporal and spectral gain dynamics of an actively modelocked diode laser by applying a newly developed electrical pump - optical probe technique. The gain is determined by measuring the transmission of a modelocked Ti:sapphire laser synchronized to the semiconductor laser. Our results show that the gain transients exhibit a strong temporal asymmetry which is attributed to be one of the major reasons leading to incomplete modelocking.

Systematic investigations of the gain transients at different probe wavelengths provide the spectrum of the differential gain dg/dN. We find a pronounced increase of dg/dN towards shorter wavelengths with the dg/dN maximum blue-shifted by about 20nm from the gain maximum. From the differential gain spectrum we obtain the spectrum of the linewidth enhancement facotr α via a Kramers-Kronig transformation. We find that α decreases towards shorter wavelengths and nearly vanishes in the region of maximum differential gain. These experimental observations are confirmed by microscopic calculations based on a quasiequilibrium many-body theory.

Finally remarkable improvements of the mode locking performance are discussed based on these findings.

DEFECTS AND SPACE-LIKE PROPERTIES OF DELAYED DYNAMICAL SYSTEMS

G. Giacomelli and F. T. Arecchi
Instituto Nazionale di Ottica, Largo Enrico Fermi 6, 50125 Firenze ITALY

In a laser with delayed feedback operation in an oscillatory regime, phase defects appear for delays longer than the oscillation period. These defects are visualized by rearranging the data in a two-dimensional representation. Two distinct disordered phases are observed, one of weak turbulence characterized by phase fluctuations, and one of highly-developed turbulence characterized by a constant density of defects. The transition between the two regimes is analyzed by studying the dependence of the defect life-time on the delay. The experimental findings are modeled via a generalized Landau equation which includes a delayed coupling.

SINGULARITIES AND PATTERNS IN THE DYNAMICS OF FLAMES

Michael Gorman
University of Houston, Texas, USA

At low pressure on a flat flame burner premixed flames can form ordered patterns of concentric rings of cells. The darker boundaries of the brighter cells correspond to cooler regions which extend away from the burner. Because there is no surface tension the ordered cells form an array of cusps and folds. Periodic states, in which the cells move coherently in the ring structure by rotating and hopping, bifurcate from these ordered states. These periodic states can also be described by the motion of the cusps and folds which behave like (pseudo) singularities as they move. Videotape of all these phenomena will be shown. A particularly unusual feature of the ordered states is that the ordered patterns are not steady, they are chaotic; the cells subtly change their size and shape. Concentric ring patterns have also been observed in laser systems and it may be possible that some of these characteristics may be present in these systems.

CONTROLLING CHAOS

Celso Grebogi
Department of Mathematics, University of Maryland, College Park, MD 20742, USA

It is common for systems to evolve with time in a chaotic way. In practice, however, it is often desired that chaos be avoided and/or that the system be optimized with respect to some performance criterion. Given a system which behaves chaotically, one approach might be to make some large (and possibly costly) alteration in the system which completely changes its dynamics in such a way as to achieve the desired objectives. Here we assume that this avenue is not available. Thus we address the following question" Given a chaotic system, how can we obtain improved performance and achieve a desired attracting time-periodic motion by making only *small* controlling temporal perturbations in an acessible system parameter. The key observation is that a chaotic attractor typically has embedded densely within it an infinite number of unstable periodic orbits. In addition, chaotic attractors can also sometimes contain unstable steady states. Since we wish to make only small controlling perturbations to the system, we do not envision creating new orbits with very different properties from the already existing unstable periodic orbits and unstable steady states. Our approach is as follows: We first determine some of the unstable low-period periodic orbits and unstable steady states that are embedded in the chaotic attractor. We then examine these orbits and choose one which yields improved system performance. Finally, we apply small controls so as to stabilize this already existing orbit.

Controlled chaotic systems offer an advantage in flexibility in that any one of a number of different orbits can be stabilized by the small control, and the choice can be switched from one to another depending on the current desired system performance. I will give many relevant applications to the sciences and engineering including applications to biological systems.

SPATIO-TEMPORAL DYNAMICS OF BROAD-AREA LASERS: FILAMENTATION AND BEAM-PROPAGATION

Ortwin Hess
Fachbereich Physik, Philipps-Universitat Marburg, Renthof 5, D-35032 Marburg, Germany

The spatio-temporal dynamics of semiconductor laser is numerically modelled on the basis of free-carrier Maxwell-Bloch equations in relaxation-time approximation. The explicit consideration of the spatio-temporal dynamics of the polarization variable together with the carrier density and the counterpropagation optical fields has the advantage of naturally including in the theory and the numerical modelling

(1) nonlinear gain-enhancement and -saturation effects
(2) frequency dependence and spectral properties
(3) nonlinear dispersion and absorption.

Moreover, the unphysical "high-k instability" is avoided. In the numerical modelling of typical broad-area semiconductor lasers the formation and longitudinal propagation of unstable transverse optical filaments is observed as well as simultaneous spectral and spatial holeburning in the carrier distributions.

SELF-FOCUSING OF ULTRASHORT PULSES IN GAS MEDIA AND ACCOMPANYING PHENOMENA

F. A. Ilkov, A. Brodeur, V. Francois and S. L. Chin
Centre d'Optique, Photonique et Laser, Département de Physique, Université Laval
Québec G1K 7P4 Canada

J. Squier, S. Dutta, G. A. Mourou
Center for Ultrafast Optical Science, Univesity of Michigan, Ann Arbor, MI 48109-2099, USA

Threshold power for self-focusing, optical breakdown and supercontinuum gereration in high pressure gas media have been measured under different external focusing conditions. The relationship between these phenomena is discussed. Experiments on propagation of ultrashort intense laser pulses in high pressure (1-40 atm) gas media are described. Self-focusing (SF) was observed under various conditions of gas pressure and laser power, accompanied by such phenomena as supercontinuum (SC) generation, conical emmision (CE) and optical breakdown (OB).

Experimental comparison of the power thresholds of optical breakdown (P_{OB}) and supercontinuum (P_{SC}) in a gas medium for different gas pressures and external conditions was performed. The results show that by varying the focal length, f, of the focusing lens it is possible to observe either (i) optical breakdown preceding supercontinuum, (ii) optical breakdown accompanied by supercontinuum or (iii) supercontinuum generation without optical breakdown. Therefore, optical breakdown is not an initiator of supercontinuum generation. Analyses of P_{OB} vs f and P_{SC} vs f show that in the case of OB, self-focusing acts only to increase the local intensity whereas in the case of SC generation the role of self-focusing is more pronounced and complex. We also measured the spectral evolution of the supercontinuum radiation as a function of incident laser power and gas pressure. Attention was paid to the behaviour of spectral broadening at the thresholds of self-focusing and optical breakdown. Their influence on the supercontinuum spectral width evolution is experimentally demonstrated.

Since in an extended non-linear medium self-focusing becomes unavoidable at laser powers which are required for supercontinuum generation, the interpretation of experimental results is greatly complicated. Indeed, after self-focusing such very important parameters as actual laser intensity, interaction length and interaction time become a subject of speculation. The measurement of optical breakdown power thresholds under diverse external focusing conditions allowed us to evaluate the critical power P_{Cr} for self-focusing and optical breakdown intensity without measuring the actual focal spot. As a result we were able to extimate the working range of the laser intensities and the value of the nonlinear refractive index n_2. Thus the number of free parameters in the analysis of the experimental data were reduced.

MICROSCOPIC MODELLING OF SEMICONDUCTOR LASERS AND AMPLIFIERS

S. Koch
Fachbereich Physik, Phillips-Universitat Marburg, Renthof 5, D-35032 Marburg, Germany

Any modelling of realistic semiconductor laser structures need a microscopic description of the gain medium in order to incorporate the fundamental tradeoffs between gain, refractive index, carrier relaxation, optical dephasing, and coupling between laser field and medium. This talk reviews a semiconductor laser theory, which is evaluated in detail for the example of microcavity surface emitting structures. Based on the general theory, a hierarchy of models will be outlined, which can be used in certain parameter ranges to obtain numerically less involved laser models.

PERIOD-DOUBLING ROUTE INTO AND OUT OF CHAOS IN SEMICONDUCTOR LASERS WITH OPTICAL INJECTION

Vassilios Kovanis
Nonlinear Optics Center, Phillips Laboratory, Kirtland AFB, NM 87117, USA

Experimental measurements and a theoretical analysis of a quantum-well laser diode subject to strong optical injection are combined to demonstrate the existence of a bounded regime of chaotic dynamics. As the chaotic regime is approached from both lower and higher injection levels, the laser diode follows a period-doubling route to chaos. All relevant laser parameters used in the calculations, including the influence of spontaneous emission noise, were experimentally determined based on the four-wave mixing technique. The transition to chaos can be used to reduce the uncertainty in the value of the linewidth enhancement factor.

PATTERN FORMATION IN LASERS WITH CURVED MIRRORS

Joceline Lega
Institut Non Linéaire de Nice UMR CNRS 129 1361 Route des Lucioles 06560 Valbonne, France

When transverse effects are taken into account, the Maxwell-Bloch equations for the 2-level laser have solutions above threshold which, depending on the sign of the detuning between the cavity and atomic frequencies, correspond either to transverse spatially homogeneous oscillations, or to transverse travelling waves. These solutions, however, are formally valid for a laser with flat end reflectors, and infinite transverse section. Whereas finite size effects can easily be seen to disappear if one increases the transverse section of the lasing system, the nature of the laser transition itself may be changed by the presence of curved mirrors. Indeed, the latter can be shown to add a rotationally invariant term to the equation for the electric field, which breaks the initial translation invariance of the system in the transverse directions. Using a model equation which phenomenologically captures the features of the laser transition, we will describe the patterns to be expected at threshold in terms of a phenomenological parameter which measures the mirrors curvature. It will be shown that whereas travelling waves are selected for flat reflectors, patterns resulting from a combination of many Gauss-Laguerre modes are favored by curved mirrors. Nevertheless, in the case of slightly curved mirrors, travelling waves are recovered further from threshold.

THE ARREST OF CRITICAL COLLAPSE: APPLICATIONS IN NONLINEAR OPTICS

Gregory G. Luther
Department of Mathematics and Statistics, University of New Mexico, Albuquerque, NM 87131, USA

It was pointed out in the 1960's that the peak intensity of a beam of light increases rapidly reaching very high values in a finite distance for initial powers exceeding some threshold value. This process is modeled by the 2D nonlinear Schroedinger equation and is associated with singular solutions which are often called critical collapse events. In this talk corrections to the NLS model that arise in describing the nonlinear propagation of very short light pulses will be described, and the influence of some of these corrections on the critical collapse process will be illustrated. Applications in nonlinear optics where collapse plays an important role will also be discussed.

TRANSVERSE MODES AND PATTERNS OF ELECTRICALLY PUMPED VERTICAL CAVITY SURFACE EMITTING SEMICONDUCTOR LASERS

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Vertical cavity surface emitting semiconductor diode lasers (VCSELs), in which lasing and light emission occur normal to the junction plane, have become practical only during the past five years. during this time, they have attracted much interest for several applications involving a high degree of parallelism: high-speed spatial light modulation, high-brightness displays, light source arrays for parallel optical communication or computing systems, optical free-space data interconnects between wafers. Individual VCSELs can be made to lase in circular, low-divergence, single longitudinal and transverse modes for improved coupling to optical fibers, and two dimensional phase-coupled grid contact VCSEL arrays have been developed as high-intensity light sources.

From the point of view of fundamental laser physics, VCSELs have many interesting aspects because of their very short cavity lengths and the possibility of large Fresnel numbers (>100). A rich variety of spatio-temporal dynamics can therefore be expected in these systems. One important question relates to the symmetry of the modes relative to that of the laser structure, and to the nature of any symmetry breaking mechanisms involved.

In this paper we will discuss some fundamental characteristics of VCSELs and present the results of measurements of optical polarization characteristics, transverse mode spectra well above lasing threshold, and how these mode spectra can be controlled by external light injection from another semiconductor laser source.

FREQUENCY DOMAIN INVESTIGATION OF THE ULTRAFAST CARRIER DYNAMICS IN A InGaAsP BULK SEMICONDUCTOR AMPLIFIER

A. Mecozzi, A. D'Ottavi, E. Iannone, S. Scotte, P. Spano and R. Dall'Ara*
Fondazione Ugo Bordoni,,Via B. Castiglione 59, 00142 Roma, Italy.
*Inst. of Quantum Electron., ETH Hönggerberg HPT, 8093 Zurich, Switzerland.

The ultrafast carrier dynamics in a InGaAsP bulk semiconductor amplifier is investigated by a highly-nondegenerate four-wave mixing experiment. The maximum pump-probe detuning is 4.3 THz. This detuning is larger than about the factor of two than the maximum values reported to date. The equivalent temporal resolution, 40 fs, is the highest reported for both pulsed time-domain and pump-probe experiments in semiconductor amplifiers at 1.5μ m. Four-wave mixing is intrinsically a small signal technique, pulsed pump-probe is not. Hence, four-wave mixing permits to gain informations on the ultrafst carrier dynamics in a cleaner way than time-domain pump-probe experiments.

In the experiment, carrier-beating shows up at low frequency detuning, The cooling time of carrier distribution is about 800 fs. The high temporal resolution of the experiment permits to distinguish for the first time between the contribution of spectral-hole burning, those time constant is about 100 fs, and the instantaneous, within our resolution, gain and index dynamics attributed to two-photon absorbtion and Kerr effect. The simultaneous presence of spectral-hole burning and the instantaneous component is required to explain the four-wave mixing response at frequency detunings larger than 2 THz.

The experimental data have been fitted by an analytical theory that includes both propagation effects and gain saturation of the amplifier. The inclusion of traveling-wave effects is required because in non-resonant amplifiers pump, probe and conjugate beams are amplified of more than 15 dB during propagation. The inclusion of saturation is also required because the highest conjugate output is produced under high gain saturation conditions for the amplifier, and these are the conditions of the experiment. The analytical theory has been checked against numerical solutions of the traveling-wave equations, and they have been found to be indistinguishable for frequency detuning larger than few tens of GHz, the interesting case for experiments.

SPATIAL AND SPECTRAL CHARACTERISTICS OF HIGH-POWER, TAPERED AMPLIFIERS AND OSCILLATORS

David Mehuys
SDL Inc., 80 Rose Orchard Way, San Jose CA 95134 USA

Tapered amplifier technology has enabled both research demonstration and commercialization of Watt-range semiconductor lasers and amplifiers. Among the newly-developed diffraction-limited sources are monolithically-integrated master oscillator power amplifiers, flared unstable resonators, and wavelength-tunable external-cavity oscillators. All of these sources share common technical challenges such as filament suppression, astigmatism correction, and feedback sensitivity. In this talk, the spatial and spectral characteristics of these high-power, flared-contact sources will be discussed. Both the master oscillator power amplifier (MOPA) and unstable resonator configurations have demonstrated near-diffraction-limited emission of ~3 Watts cw, and 5-10 Watts under pulsed operation in InGaAs/AlGaAs quantum well structures. The advantage of the MOPA configuration is that its distributed Bragg reflector master oscillator provides single-mode operation and narrow linewidth approaching 1 MHz. The unstable resonator, on the other hand, is easily configured into an external-cavity laser to provide wavelength tunability over tens of nanometers. For both MOPAs and unstable resonators, bulk optics and spatial filters have been used successfully to achieved collimated, circularized, and diffraction-limited beams emitted from compact packages with near-TEM_{OO} beam quality of M^2-1.3.

In addition to high-power cw operation, these novel tapered devices have also been characterized under mode-locked operation, where discrete tapered amplifiers and external-cavity unstable resonators have demonstrated pulse energies exceeding 100 pJ in pulses as short as 4 ps. Finally, tapered amplifier technology is easily extended to other semiconductor laser material systems, witnessed by recent flared amplifier and unstable resonator demonstrations in the visible spectrum, at 680 nm, and in the mid-infrared spectrum, at 1.8 μm wavelength.

ULTRAFAST CARRIER DYNAMICS IN SEMICONDUCTOR LASER AMPLIFIERS

Jesper Moerk
Tele Danmark Research, Lyngsoe alle 2, DK-2970 Hoersholm, Denmark

High-speed applications of semiconductor laser devices are governed by carrier dynamic processes occuring on picosecond and even sub-picosecond time-scales. The talk will address recent progress in understanding these ultrafast processes obtained through time-domain pump-and-probe measurements and numerical modelling. The frequency domain characteristics of the carrier dynamic processes, as studied in four-wave mixing experiments, will also be discussed.

PATTERNS IN LARGE ASPECT RATIO LASERS

J.V. Moloney
Arizona Center for Mathematical Sciences, University of Arizona, Tucson, AZ 85721, USA

The natural transverse modes of wide aperture lasers with flat end-reflectors are not the conventional TEM modes imposed by spherical mirror geometries but rather, are dictated by the nonlinear interactions occurring in the laser gain medium. The natural lasing state is an off-axis emission when the laser is detuned to the positive side of the gain peak or a uniform illumination permeated by topological defects (optical vortices) when the detuning is negative. In either case the output may be stable or weakly turbulent depending on the mode of initiation of lasing and the relevant operating parameters of the system. The lack of polarization discrimination in such systems suggests that novel lasing modes (patterns) involving polarization domains can appear.

Analytical insight into the physics of the relevant nonlinear interactions can be obtained by exploiting the analogy with critical phenomena in spatially extended physical systems. Physics not evident in the original mathematical formulation of the Maxwell-Bloch laser equations begins to emerge. Moreover, spurious nonphysical transverse instabilities arising from an ad hoc truncation of the laser equations for a Class B laser, are avoided.

The relevance of these results towards achieving nonlinear control and stabilization of technologically important high power lasers sources will be discussed.

TOWARDS A UNIVERSAL DESCRIPTION OF PATTERNS

Alan Newell
Department of Mathematics, University of Arizona, Tucson AZ 85721 USA

Patterns of almost periodic or quasiperiodic natures are seen all over the place. They arise in spatially extended, dissipative systems which are driven far from equilibrium by some external stress and their presence represents the fact that, when the uniform background state destabilizes, certain shapes and configurations are preferentially amplified. In this talk, I will survey theoretical approaches which attempt to describe patterns from a macroscopic viewpoint that both unifies and simplifies the behaviors of patterns and their defects in a wide variety of seemingly unrelated contexts, from convection in fluids to fat lasers.

FEMTOSECOND PULSE PROPAGATION AND SPECTRAL HOLE BURNING IN THE GAIN REGION OF INVERTED SEMICONDUCTORS AND APPLICATIONS TO SUBPICOSECOND SWITCHING

N. Peyghambarian
Optical Sciences Center, Unviersity of Arizona, Tucson, AZ 85721 USA

Propagation of femtosecond pulses in the gain region of a GaAs-based waveguide is studied. We observe that for pulses above a certain intensity, the medium actually behaves like an absorber rather than an amplifier. This observation will be compared with recent theoretical results that predict similar phenomenon and explains it in terms of the interplay between the gain and absorbing regions of the inverted semiconductor. Our recent spectral hole burning measurements in the gain region and measurements of the T_2 times for frequencies in the vicinity of the chemical potential will also be discussed. Furthermore, our demonstration of a subpicosecond current-injected directional coupler switch with ≈6-pJ switching energy will be summarized.

RETINAL DAMAGE STUDIES FROM ULTRASHORT LASER PULSES IN THE VISIBLE AND NEAR INFRARED SPECTRAL REGIONS

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Relatively little experimental and theoretical data exist on the retinal hazards of ultrashort laser pulses operating in the visible and near infrared spectral regions. Because of potential nonlinear effects that can occur as high peak irradiance, ultrashort laser pulses propagate from the cornea to the retina, we have undertaken two separate in-vivo experiments. This was done to address the lack of National and U.S. Air Force Laser Safety Standards and to investigate the issue that hemorrhagic retinal lesions produced by subnanosecond laser pulses, specifically at 100 femtosecond (fs) or below, are believed impossible to produce. This latter idea is suggestive of some energy limiting mechanism for retinal damage, where for picosecond pulses at relatively low energies a catastrophic retinal hemorrhage would have occurred. We discuss 50% probability for damage (ED_{50}) threshold values for nanosecond (ns), picosecond (ps), and femtosecond (fs) single pulses for invivo ocular exposures in Dutch Belted rabbits and Rhesus monkeys using pulses in the visible spectral region and present our preliminary evaluation of hemorrhagic and non-hemorrhagic 100 fs single pulses in rabbits and primates.

The ultrashort pulse laser system used in our laboratory produces a large number of pulsewidths, wavelengths and energy levels. It produces single pulses with an adjustable pulse repetition rate between single pulses and 10 pulses per second (pps). All pulses generated can have energies greater than 100 μJ. The system consists of a dye laser pumped by a modelocked (82 MHz) pulse compressed, frequency doubled Nd:YAG laser. The dye laser output is amplified by a three stage pulse dye amplifier (PDA) which is pumped by a seeded, frequency doubled Nd:YAG regenerative amplifier. Pulse widths are measured by an INRAD Slow Scan Autocorrelator. The pulses from the PDA can also be compressed to achieve below 100 fs pulses by chirping the pulses before amplifying and rephasing afterwards. Pulses at a wavelength of 580 nm are obtained for pulsewidths of 90 fs to 3 ps. Pulses of 50 ps and 5 ns at a wavelength of 532 nm are obtained from the seeded Nd:YAG regenerative amplifier or the Nd:YAG Q-switched laser with pulse energies in the millijoule range.

Threshold measurements for Minimum Visible Lesions (MVL) at the retina for laser pulses in Rhesus monkey and Dutch Belted rabbit eyes are calculated using the ED_{50} dosages for 1 hour and 24 hour post-exposures at the 95% confidence level. The ED_{50} values were found to decrease with pulsewidth down to 600 fs. At 90 fs the ED_{50} dosages were noted to increase slightly when compared with the 3 ps and 600 fs values. Our evaluation of hemorrhagic and non-hemorrhagic 100 fs single pulses in rabbits and primates showed two different hemorrhagic events occurring at the retina with delivery of 100 fs pulses. First, in the Dutch Belted rabbit, we found large amounts of energy per pulse (from 20 to 60 times ED_{50}) were required for formation of subretinal hemorrhages. Second, in the Rhesus monkey, significant numbers of small intraretinal hemorrhages from relatively low energy 100 fs pulses were observed. In both the Dutch Belted rabbit and the Rhesus monkey, no consistent subretinal hemorrhagic lesions from very high pulse energies was seen. Such findings suggest more energy absorption at the level of the retinal circulation than the choroidal circulation with our laser system. One precaution with this finding, however, is the distinct differences between primate and non-primate ocular focusing efficiency.

These studies give reasonable estimates of the damage thresholds and insight into the biophysics of how ultrashort pulses interact with ocular media. Further, they are suggestive of nonlinear propagation effects such as self focusing or optical breakdown (LIB) from high peak powers produced by the subnanosecond single pulses. Our efforts to date have involved the development of experiments to characterize the onset of nonlinear phenomena as a response to high intensity fields (gigawatt or greater peak powers per pulse) generated by our laser system. Along with the in-vivo experiments we have also examined the phenomena of nonlinear absorption, self-focusing, and LIB. If nonlinear absorption is significant as the laser pulse propagates from the cornea to the retina, then the retinal irradiance would be reduced below the value we would estimate based on linear propagation theory. Self-focusing, resulting from a positive nonlinear index of refraction, could cause the laser beam to collapse to a filament, greatly increasing the irradiance and LIB would become important because it would potentially mediate the resulting retinal damage observed. Continued study experimental study is suggested, coupled with ongoing theoretical work.

Notes

The work presented here is the result of a dedicated scientific team, Dr. Mark Rogers, Dr. Ben Rockwell, Dr. Paul Kennedy, Dr. Clarence Cain, Dr. Randy Thompson,
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NONLINEAR ASPECTS OF THE FOCUSING OF ULTRASHORT LASER PULSES IN THE HUMAN EYE

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The human eye represents a unique focusing system for optical energy in the visible and near infrared region of 400 to 1400 nanometers. The fluence of a laser pulse incident at the cornea increases roughly 100,000 times as the beam if focused on the retina. Of current concern to the laser safety community, as well as the laser medicine community, is how ultrashort laser pulses propagate from the cornea to the retina and how they interact at the retina to cause damage. Such pulses typically have high peak powers even at modest energy. We discuss three possible nonlinear processes that may have a key role in the effects of ultrashort laser pulses on ocular tissue: nonlinear absorption, self-focusing, and laser-induced breakdown.

Past animal studies indicated atypical behavior in retinal damage from sub-picosecond pulses when the pulse energy was increased substantially above the damage threshold. In one study, no increase in damage was seen. Similar studies in our laboratory indicated unexpected trends in the damage, such as differing onset times and inverted sensitivity in fluorescein-angiographic and ophthalomoscopic damage assessment. These experimenatal studies suggest the retinal fluence differs from what would be predicted by linear optics and that a different damage mechanism may be dominating the process.

Two relevant nonlinear processes can occur in propagating the laser pulse from the cornea to the retina. The first is two photon absorption (TPA) in the ocular tissues. The TPA would decrease the retinal fluence from that expected by linear methods. The energy would likely be dposited throughout the vitreous humor, a jelly-like substance that appears water-like in its absorption spectrum, as this is the ocular fluid that is traversed when the peak power of the pulse is highest. A simple model of TPA for collimated beams predicts that the nonlinear absorption would be significant at peak powers of about 100 MW/cm^2 using values for the two photon absorption coefficient obtained from our experiments and literature. At these powers, other nonlinear processes might be occuring as well. We are continuing our studies to asess the role of TPA in ultrashort laser pulse effects.

The second propagation effect is self-focusing. The values of the nonlinear index of refraction have been measured by our group for various ocular tissues and related substances. It is likely that the laser pulses are below the critical power for beam collapse for the powers in the biological experiments. Thus, we are studying the case of weak self-focusing and how it alters the retinal fluence. Our model uses the nonlinear diffraction scaling method of Huang et al. to account for thevarious nonlinear media in the propagation path. The results indicate a decrease in the spot size at the retina with no discernable focal plane shift, consistent with the aberrationless model of Yariv and Yeh. This trend would indicate a decreased corneal fluence for threshold retinal damage, consistent with biological experiments, except at shortest pulses of 90 to 100 femtoseconds. This analysis indicates the self-focusing effects below the beam colllapse threshold are important.

When the peak power reaches a sufficiently large value, laser-induced breakdown (LIB) of the medium can occur. This process is commonly used by ophthalmologists for posterior capsulotomy where a opacified membrane is repeatedly ruptured by a short pulses of laser radiation to restore vision. The LIB generates a small region of plasma followed by bubble formation and shock wave generation, all of which can damage tissue. We have studied LIB in ocular and related tissues (e.g. ultrapure water, normal saline tap water, vitreous humor) to determine the threshhold, size, location, and energy that passes through the plasma in order to assess the role of LIB in retinal damage. It is clear from these studies that beam collapse can precipitate LIB as the pulse propagates through the tissue. It is also evident that ithe LIB event can be very damaging to the retina if it occurs at the retina, and protective of the retina if it occurs some distance in front of the retina. We will review the trends we have observed in LIB as well as the first order models that we have developed to describe the LIB process.

Ultrashort pulses of modest energies (i.e., microjoules) have sufficiently high peak powers that nonlinear optical processes can occur during the propagation in and interaction with ocular tissue. Understanding these processes are critical to developing correct safe exposure standards for these rapidly developing lasers.

POLARIZATION DYNAMICS AND TRANSVERSE EFFECTS IN LASERS

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The interplay between transverse effects and polarization dynamics is considered. An appropriate modelling of the laser properties associated with the vector character of the electric field requires taking into account the spin degrees of freedom. A prototype model for a $J=1 \rightarrow J=0$ transition, including transverse effects, will be discussed.

An amplitude equation description leads to a Vector Complex Ginzburg Landau Equation. The preferred polarization state (elliptic, circular or linear) is determined by the ratios of different damping rates of spin sub-levels. Phase instabilities of polarized transverse patterns are characterized. Stable standing waves with a spatially periodic angle of linear polarization are found.

THE LINK BETWEEN SHORT PULSE SELF-FOCUSING AND CONTINUUM GENERATION

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An ultra-short pulse with power exceeding the critical power for self-focusing does not spatially collapse. Rather the spectral bandwidth of the pulse expands catastrophically generating what is known as continuum. The spectral and spatial modulation of continuum generation was studied experimentally to demonstrate that the moving focus model of pulsed self-focusing can explain this phenomenon.

QUASI-CRITICAL COLLAPSE. THEORY AND APPLICATIONS

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Overview of the recent results concentrated near the so-called critical collapse phenomenon will be done. A wide array of physical problems may be modelled by different modifications of two-dimensional nonlinear Schroedinger equation (NLSE).

We discuss a new physical mechanism of optical pulse compression based on the blow-up principle and a possibility to utilize nonlinear fiber array as a collapse-effect compressor. Quasi-collapse in discrete systems will be discussed on the example of the discrete NLSE. It will be shown that a quasi-collapse may play a role of energy localization mechanism it lattices.

We demonstrate how discreteness reduces (in comparison with the continuum limit) the critical nonlinearity parameter that separates stable and unstable regimes. We present evidence of blow-up in the three-dimensional negatively dispersive media. Such a system models the evolution of ion Bernstein waves and Whistler waves in plasma, dynamics of deep-water gravity waves, propagation of a short optical pulse in the normal dispersion region etc. We demonstrate that a specially chirped single-peak pulse collapses even propagating in the normal dispersion region.

PULSE PATTERN COLLAPSE IN EXTERNAL-CAVITY DIODE LASER LOW-FREQUENCY FLUCTUATIONS

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A diode laser subjected to delayed optical feedback exhibits various types of unstable dynamical behavior. Several modes of operation have now been classified as strange attractors, the corresponding dynamics being quite well understood. A notable exception is the so-called Low-frequency fluctuations (LFF) phenomenon, which usually is observed when the laser, operating near its solitary threshold, is subject to moderate amounts of delayed optical feedback. In the LFF state, the average optical field power passes through cycles which consist of a sudden drop-out followed by a gradual build-up to approximately the original average power level. We have made a detailed numerical study of the (Lang-Kobayashi) delay-differential equations describing the complex optical field and the inversion of the diode laser exposed to optical feedback. The steady-state solutions of the system are characterized by a constant field amplitude, constant inversion, and a constant *phase-difference* $\varphi(t) = \varphi(t - r)$ (where r is the feedback delay time). The constant phase-difference causes the associated frequencies of these solutions to be shifted from the solitary laser frequency. The solutions are alternating stable and unstable (saddle-node instability) fixed points, and in a typical LFF situation there may be a few thousand of these fixed points. One of the stable fixed points is the so-called minimum threshold mode and designates where the system's power profits most from the feedback.

We observe that in LFF, the optical field power consists of strong irregular pulses, indicating a continuing frustration of mode locking on the fixed points. In fact, only the atractor ruins (scars) of these fixed points remain and the system visits thousands of these ruins on its way to the minimum threshold state. On this route the pulse pattern becomes more and more erratic and eventually the system will reside too long on an attractor ruin of an unstable fixed point, so that a saddle-node instability will set in, causing a drop-out of power and collapse of the pulse pattern. Thus LFF is an example of chaotic itinerancy in an infinite dimensional nonlinear system. It can also be described as a true Sisyphus effect, where the system is constantly trying to reach the minimum threshold mode, only to fall down each time it comes too close to an unstable fixed point.

SINGLE-SPATIAL-MODE TAPERED AMPLIFIERS AND OSCILLATORS

J. N. Walpole, E.S. Kintzer, S. R. Chinn, C. A. Wang and L. J. Missaggia
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Over 2 W cw optical power at 980 nm has been obtained in a nearly diffraction-limited spatial lobe from semiconductor diode amplifiers and oscillators fabricated in GAInAs-AlGaAs-GaAs strained single-quantum-well, graded-index separate-confinement heterostructures grown by organometallic vapor phase epitaxy. The devices were made with a laterally tapered electrical contact, etched grooves designed to spoil Fabry-Perot cavity modes, and cleaved facets. To fabricate amplifiers, both facets were coated with SiO to obtain a reflectivity of ~1%. To fabricate oscillators, only the facet at the wide end of the taper was coated. Device fabrication, experimental characterisation, and theoretical analysis will be presented.

SELF-FOCUSING AND SPONTANEOUS WIGGLING OF LIGHT BEAMS IN THE NONLINEAR MEDIA WITH NORMAL DISPERSION

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The stationary self-focused wave guide is unstable in a nonlinear medium with any dispersion. In media with normal dispersion (w") the instability is the spontaneous bending (wiggling) of a beam. A nonlinear theory of such instability is developed in the presented talk. It is described by a system of PDE for the position of the beam and its local thickness. The system has a wide family of self-similar solutions describing simultaneous self-focusing and curving of the beam.

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