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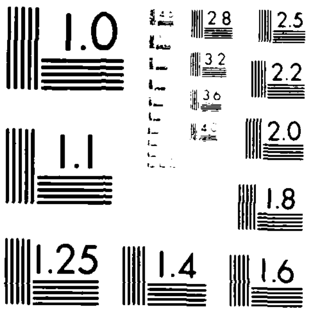
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The first tunable CW laser action in both mode-locked and unmode-locked (in both straight and ring cavity) configurations has been denonstrated. The gain media were platelets of CdS, CdSe, InGaAsP, and HgCdTe. Pulse as short as 2.8 Psec and continous tunability between .5 micrometers and 2.5 micrometers has been achieved. Picosecond spectroscopy of bound excitons, using a synchronously operating streak camera; and picosecond photoelectric emission from a Zirconium mental surface have been studied. The first experimental technique for compensating the pulse broading in single-mode optical fibers, using the "slow

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) anomalous pulse propagation in the exciton-polariton resonance in a Direct-gap semiconductor has been demonstrated.

AFOSR-TR- 83-0584

FINAL REPORT

Non-Linear Optical Interactions in Semiconductors

Air Force Office of Sponsored Research
Contract F49620-79-C-0071

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M. M. Salour

27 April 1983

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Research Laboratory of Electronics
Cambridge, Massachusetts 02139

This report was prepared by Professors H. A. Haus and E. P. Ippen pursuant to the resignation of Professor M. M. Salour.

Jonathan Allen

Jonathan Allen
Director

A

We have successfully demonstrated the first tunable cw radiation from a bulk semiconductor platelet in external cavities. Thus far we have demonstrated laser action in both mode-locked and unmode-locked configurations. The gain media were platelets of CdS,[1] CdSe,[3] InGaAsP,[4] and HgCdTe.[22] In addition we have demonstrated the first optically pumped semiconductor laser in a ring cavity[23-24] in both cw and mode-locked configuration. We have generated pulses as short as 2.8 psec and demonstrated potential for continuous tunability between 500 nm and 2.1 μm, a range which is not entirely available from dye lasers. Because of the lack of dye jet fluctuations, semiconductor lasers may provide narrower linewidths than dye lasers, and samples mounted adjacent to each other can be changed easily to provide tunability over a broad range. Furthermore, a very long shelf life and the lack of orientation and bleaching may make these lasers more practical than F-centers for many applications.

In another series of experiments, we have performed picosecond spectroscopy of bound excitons in CuCl using a synchronously operating streak camera. Single crystals of CuCl at 8°K were excited with the low-intensity frequency-doubled output of an actively mode-locked R6G dye laser. The time dependence of the bound exciton luminescence was measured directly by a synchronously operating electron-optical streak camera accumulating data at the dye laser repetition rate of 82 MHz. We have measured, for the first time, the bound exciton lifetime for the I line and also the formation time of the exciton and the delay between the excitation pulse and the exciton formation. This technique is important since it is one of the few methods available to directly measure the time-intensity variation of a picosecond optical event. Because of the inherent high sensitivity and dynamic range of the synchronous streak camera, we were able to obtain excellent signal-to-noise ratios even at extremely low excitation intensity, thereby eliminating contributions from unwanted high-density effects.

In collaboration with Professor N. Bloembergen's group we have studied[21] picosecond photoelectric emission and thermally enhanced photoelectric emission from a Zirconium metal surface. Our data show that the electron-phonon relaxation time in Zirconium is less than 10^{-12} sec and that the electron-phonon coupling constant is $\geqq 10^{11}$ W/cm^3 ^{o}K.

Finally, we have demonstrated the first experimental technique for compensating the pulse broadening in single-mode optical fibers, using the "slow" anomalous pulse propagation in the exciton-polariton resonance in a direct-gap semiconductor.[25]

An electron-optical streak camera is already being utilized with a temporal resolution of 10 picoseconds.[7] We have built this camera in our laboratory and have coupled it to an optical multichannel analyzer as a recording medium for the experiments currently in progress.

The U.S. Air Force has currently applied for six patents for the research performed under this contract. In addition, the construction of a high-power, tunable, picosecond oscillator amplifier chain was completed and the system was utilized to perform the experiment to observe thermally enhanced photoelectric emission from a Zirconium metal surface.

The picosecond and nonlinear optics laboratory was completed in June 1980. It contained two amplified Q-switched, Nd:YAG lasers, each pumping a dye laser oscillator-amplifier chain system for use in the study of nonlinear optical interactions. In addition, we operated a synchronously pumped, mode-locked, tunable dye laser system whose output consisted of transform-limited pulses of picosecond duration. Higher power picosecond pulses were produced by amplifying the selected pulses from the dye laser, in synchronism with the frequency-doubled output of an amplified Q-switched Nd:YAG laser. Four stages of amplification were used. In this way, powers of the order of five gigawatts at the repetition rate of 10 Hertz with pulses as short as .7 picosecond were obtained.[5] At present an experiment is in progress in collaboration with Professor W. Paul of Harvard University and another experiment, in collaboration with Dr. R. Aggarwal and Professor P.A. Wolff of F.B. National Magnet Laboratory of M.I.T., in which pulsed optical pumping of semiconductors proposed in this contract is being investigated.

In another series of experiments we have examined the use of semiconductors as a medium for saturable absorbers. This experiment is currently under progress and will be completed at a later date.

Picosecond optics has a large number of potential uses in the infrared, including the probing of optical fibers.[13] Dye lasers, however, are not convenient at wavelengths much beyond 1.0 μm due to dye instability problems.[14] F-center lasers[15] or frequency-conversion techniques[16] are available, but they are relatively difficult to use in practice. III-V semiconductors can be grown with bandgaps in the infrared, and they have the bandwidth necessary for ultrashort pulse generation. For example, mode-locked InGaAsP injection lasers[17] have been demonstrated. Optically pumped lasers developed under this contract do not require complicated heterostructures and thus can be easily tuned by varying the sample composition. InGaAsP layers epoxied between two mirrors to form an ultrashort cavity have been pumped by subpicosecond pulses to produce pulses as short as 6 ps.[7] These lasers, however, lack the beam quality and direct tunability provided by an external cavity. Further, these lasers require a subpicosecond passively mode-locked pump source to temporarily obtain a gain level sufficiently above threshold to build up amplified spontaneous emission into laser action, resulting in uncontrolled broad spectral characteristics. By comparison, the synchronously pumped mode-locked laser can achieve a steady state via synchronous self-injection and can approach the minimum possible time-bandwidth product.

We recently reported[4] the first optically pumped, mode-locked semiconductor laser operating at wavelengths longer than 1.0 μm. Laser operation was achieved in two separate compositions of $In_{1-x}Ga_xAs_yP_{-1y}$ at 1.1 and 1.2 μm with x = .20, y = .4 and x = .24, y = .55, respectively. CW operation was obtained with more heating problems than were observed in Cds and CdSSe due to the relatively poor thermal conductivity in the quaternary layer. To reduce this effect during pulse-width and spectral measurements the pump beam was mechanically chopped.

The samples used were fabricated from wafers prepared by Liquid Phase Epitaxial (LPE) growth on InP substrates of (100) orientation. No intentional impurity doping was used and the nominal impurity level of the layers was $N_D-N_A \simeq 1x10^{16} cm^{-3}$, where N_D and N_A are the donor and acceptor densities, respectively. The sample with the best thermal conductivity had a 2 μm thick grown InGaAsP layer, followed by a 5 μm thick grown layer of InP. The sample was fabricated by masking and etching using HCl as a selective etch[18] to remove the substrate, leaving a two-layer InGaAsP/InP heterostructure. This configuration had the advantage that the high-thermal-conductivity InP can be used for cooling, while the quaternary composition can be varied to select the laser wavelength. Lasing had also been achieved with single layers of InGaAsP without the InP cladding layer, but in this case heating problems were more severe.

In collaboration with Dr. T.C. Harman of Lincoln Laboratory we have also completed the first optically pumped HgCdTe laser in an external cavity. The laser operates in the range of 1.2μ-2.μ utilizing samples prepared by Dr. Harman using Liquid Phase Epitaxy on CdTeSe substrates. We have achieved a peak output power of 50 watts when mode-locked with an average output power of as much as 5.6 MW. Output pulses as short as 5.3 psec were measured with a time-band width product of 0.55. Unmode-locked operation, and operation at temperatures above 10°K were also demonstrated. A paper describing the HgCdTe laser in an external cavity is currently under preparation.

While these powers are lower than those obtainable from F-center lasers, they are much higher than those which can be obtained from mode-locked diode lasers[19] or other optical pumping schemes.[20] Also a single, easily available laser can be used to pump different compositions. We have demonstrated that these techniques should work for quaternary compounds with bandgaps at 77°K out to 1.6 μm and provide a convenient, tunable picosecond source further in the infrared.

Theses completed under AFOSR support supervised by Michael M. Salour:

S.B. Theses

Miller, David Erwin, "Microprocessor Controlled Passive Area Navigation System for Light Aircraft," June 1978.

Messinger, Barbara J., "Angular Distribution of Electrically Scattered Light from Cylindrical Glass Fiber," June 1980.

Abrams, Michael, "Detector Electronics for an Improved Laser Interferometer Wavemeter," June 1982.

Deuser, Mark, "Data Storage of Spectroscopy Experiments at 10 Hz," June 1982.

Fried, Jeff, "Extended Animation Capability for Laser Graphics," June 1982.

Hawes, David, "Software User Interface of a Laser Image Projecting System," June 1982.

Miller, Daniel P., "A Microprocessor Based Laser-Scanner Imaging System," June 1982.

O'Neil, Sean D., "Stochastic Approximation of Prior Probabilities in a Gaussian Mixture," June 1982.

Poonpol, Chanchai, "Electronic Sweeping Devices for Streak Camera," June 1982.

Ralston, John, "Dye Laser Amplifier with Synchronously Operating Electron-Optical Streak Camera," June 1982.

S.M. Theses

Rotman, Stanley R., "Active Feedback Stabilization of Ultrashort Pulses in a Synchronously Mode-Locked Dye Laser," June 1980.

Fujimoto, James G., "Direct Determination of Excitonic Lifetime in CuCl Using Picosecond Synchroscan Streak Camera," June 1981.

Ph.D. Theses

Roxlo, Charles B., "Optically Pumped Synchronously Mode-Locked Semiconductor Laser," September 1981.

Putnam, Roger S., "Optically Pumped Semiconductor Lasers in the Infrared," April 1983.

Dr. T.K. Yee who completed his postdoctoral fellowship under this AFOSR contract is currently a permanent staff member at Lincoln Laboratory.

Dr. G.W. Fehrenbach who was a visiting scientist under this AFOSR contract returned to the University of Dortmund in West Germany.

Dr. Pierre Kayoun has completed his 16 months at MIT as was arranged with the Government of France.

Mr. Roland Welte and Mr. Adrian Fuchs have both finished their projects at MIT and have returned to Switzerland.

Publications under AFOSR contract - Michael M. Salour:

1. "Pulsewidth Stabilization of a Synchronously Pumped Mode-Locked Dye Laser," S.R. Rotman, C.B. Roxlo, D. Bebelaar, and M.M. Salour, Appl. Phys. Lett. 36, 886 (1980).
2. "Tunable CW Bulk Semiconductor Platelet Laser," C.B. Roxlo, D. Bebelaar, and M.M. Salour, Appl. Phys. Lett. 38, 507 (1981).
3. "Synchronously Pumped Mode-Locked CdS Platelet Laser," C.B. Roxlo and M.M. Salour, Appl. Phys. Lett. 38, 738 (1981).
4. "Picosecond Spectroscopy of Bound Excitons in CuCl Using a Synchronously Operating Streak Camera," J.G. Fujumoto, T.K. Yee, and M.M. Salour, Appl. Phys. Lett. 39, 12 (1981).
5. "Picosecond Laser Interaction with Metallic Zirconium," R. Yen, J.M. Liu, N. Bloembergen, T.K. Yee, J.G. Fujimoto, and M.M. Salour, Appl. Phys. Lett. 40, 185 (1982).
6. "Optically Pumped Semiconductor Platelet Lasers," C.B. Roxlo, R.S. Putnam, and M.M. Salour, IEEE J. Quantum Electron. QE-18, 338 (1982).
7. "Dewar Design for Optically Pumped Semiconductor Lasers," C.B. Roxlo and M.M. Salour, Rev. Sci. Instrum. 53, 458 (1982).
8. "Optically Pumped Bulk Semiconductor Laser" (Invited paper), M.M. Salour, in Laser Spectroscopy (Springer Verlag, Volume 30, 1981), p. 469.

9. "Optically Pumped Mode-Locked InGaAsP Lasers," R.S. Putnam, C.B. Roxlo, M.M. Salour, S.H. Groves, and M.C. Plonko, Appl. Phys. Lett. 40, 660 (1982).

10. "Polariton-Induced Compensation of Pulse Broadening in Optical Fibers," G.W. Fehrenbach and M.M. Salour, Appl. Phys. Lett. 41, 4 (1982).

11. "Ultrafast Picosecond Chronography," J.G. Fujimoto and M.M. Salour, in Picosecond Lasers and Applications, SPIE Vol. 322, 137-165 (1982).

12. "Optically Pumped Semiconductor Platelet Lasers," C.B. Roxlo, R.S. Putnam, M.M. Salour, in Picosecond Lasers and Applications, SPIE vol. 322, 31-36 (1982).

13. "Active Generation, Stabilization, and Amplification of Subpicosecond Optical Pulses," S.R. Rotman, C.B. Roxlo, D. Bebelaar, T.K. Yee, and M.M. Salour, Appl. Phys., B28, 319-326 (1982).

14. "Optically Pumped CW Semiconductor Ring Laser," A. Fuchs, D. Bebelaar, and M.M. Salour, submitted to Appl. Phys. Letters.

15. "Dewar Design for Optically Pumped Ring Semiconductor Laser," A. Fuchs, and M.M. Salour, submitted to the Reviews of Scientific Instruments.

16. "Synchronously Mode-Locked, Optically Pumped $Hg_{1-x}Cd_xTe$ Laser in External Cavity," R.S. Putnam, M.M. Salour and T. Harman (in preparation).

Patents filed under AFOSR contract:

1. "Synchronously Pumped Mode-Locked Semiconductor Platelet Laser," Serial #361019, filed March 23, 1982, Air Force Invention #14693.

2. "Dewar Cooling Chamber for Semiconductor Platelet," Serial #361020, filed March 23, 1982, Air Force Invention #15095.

3. "Tunable CW Semiconductor Platelet Laser," Serial #361021, filed March 23, 1982, Air Force Invention #14692.

4. "Distortion Free Fiber Optic System," Air Force Invention #15096.

5. "Optically Pumped CW Semiconductor Ring Laser," MIT Case #3788, Air Force Invention # will be received shortly.

6. "Dewar Design for Optically Pumped Semiconductor Ring Laser," MIT Case #3789, Air Force Invention # will be received shortly.

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