行政院國家科學委員會專題研究計畫　期中進度報告

子計畫一:兆位元時代光電科技之基礎研究(2/4)

計畫類別：整合型計畫
計畫編號：NSC94-2752-E-009-007-PAE
執行期間：94 年 04 月 01 日至 95 年 03 月 31 日
執行單位：國立交通大學光電工程學系(所)

計畫主持人：潘犀靈
共同主持人：許根玉，王興宗
計畫參與人員：潘犀靈 ，許根玉 ，王興宗 ，林恭如 ，林烜輝 ，李柏璁 ，郭浩中 ，許晉瑋 ，

報告類型：完整報告

處理方式：本計畫可公開查詢

中　華　民　國 95 年 3 月 29 日

COVER

Program for Promoting Academic Excellence of Universities（Phase II）

Midterm Report

建構兆位元紀元的光電科技-子計畫一：兆位元時代光電科技之基礎研究
Photonic Sciences and Technologies for the Tera Era:
Subproject 1: Fundamental Studies on Photonic Science and Technology for the Tera Era

NSC 94-2752-E-009-007-PAE

Overall Duration: Month 4 Year 2004 - Month 3 Year 2008
Midterm Duration: Month 4 Year 2004 - Month 3 Year 2006

National Chiao Tung University
2006.02.26

I. BASIC INFORMATION OF THIS SUB-PROJECT (FORM 1)

Project Title: Photonic Sciences and Technologies for the Tera Era--Subproject 2: Next Generation Optical Communication and Optical Storage Technologies 建構兆位元紀元的光電科技-子計畫一：下世代光通訊與儲存技術					
Serial No.: NSC 94-2752-E-009-007-PAE			Affiliation		National Chiao Tung University 國立交通大學
Principal Investigator	Name	Ci-Ling Pan 潘犀靈	Project Coordinator	Name	Gong-Ru Lin 林恭如
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	Expenditures[1] (in NT$1,000)		Manpower[2]:Full time/Part time(Person-Months)	
	Projected	Actual	Projected	Actual
FY2004				
FY2005	12,947,000	7,504,215	165	165
FY2006		-		-
FY2007		-		-
Overall				

Notes: [1,2] Please explain large differences between projected and actual figures.

Principal Investigator's Signature:

II. EXECUTIVE SUMMARY ON RESEARCH OUTCOMES OF THIS PROJECT (FORM 2) (PLEASE STATE THE FOLLOWING CONCISELY AND CLEARLY)

1. GENERAL DESCRIPTION OF THE PROJECT: INCLUDING OBJECTIVES OF THE PROJECT (MAXIMUM 3 PAGES)

The main goals of this project are to design, construct and characterize new optical and optoelectronic functional devices and modules to meet the challenge of the tera-bit information era. To achieve these goals, we focus our research on the following fundamental research topics:

(I) Coherent and THz Photonics;
(II) Quantum (Photonic Crystal) structures and Enabling devices;
(III) Volume Holographic Materials, Technology and Enabling devices

(I) Coherent and THz Photonics

One of the current trends in photonics is the development of a technology based with better control of the light-matter interaction. Employing advanced laser-based techniques, novel design concept, and fabrication technologies of novel photonic structures from potential photonic materials, we shall be able to steer photon energies into specific degrees of freedom of complex systems or materials, to create new materials, to generate new functionality from a device. One of the goals of the present project is thus the development and employment of advanced laser technology, in particular, ultrafast-laser-based techniques such as coherent control, spatially, temporally, and spectrally resolved real-time imaging, and laser-assisted fabrication and properties modification for fundamental studies of photonic properties of various novel photonic materials, structures and devices.

In view of the emerging applications of electromagnetic waves at millimeter-wave or THz frequencies in remote sensing, imaging, and communication, we will conduct studies on various aspects of THz photonics and applications, employing the coherent photonic tools developed in our laboratories over the years.

Our main objectives are studies of photonics-based ultra-wideband (THz) wireless communication and frequency measuring technologies for the next generation. Two emerging technologies will be explored: (1) coherent THz communication; The frequency of the carrier wave for this technology is in the sub-millimeter wave (0.1 to 10 THz, 1 THz = 1×1012 Hz) band; and (2) optical-impulse THz radio communication, which is carrier free. In both approaches, photonics-based technologies will be used for the generation and detection of THz radiation. Sub-millimeter wave or THz communication combines the merits of optical and wireless communication technologies. It is particularly suitable for short-distance, point-to-point, high information-data-rate (multi-Mb/s to Gb/s), and secure communication channels. A related but critical technology is precision measurement of the frequency of the THz band of the electromagnetic wave. Possible THz frequency standards might emerge from this research. This technology would be based on the femtosecond optical frequency comb generator spanning hundreds of THz of bandwidth (1200 – 1600 nm) and traceable to known frequency standards. I note that the femtosecond frequency comb is one the subject cited for the 2005 Nobel laureates in physics, Prof. Ted Hansch and Dr. John Hall. Our work would also allow precision measurement of present and future communication channels (the International Telecommunication Union or ITU grid) for (ultra) dense wavelength division multiplexed (DWDM) optical communication.

The advances in THz applications would also require concurrent progress in THz photonic elements, such as generators, detectors, polarizers, attenuators, modulators and phase shifters. Novel materials and structures need be explored to address this need. We have made good progress in broad-band THz receivers and liquid crystal THz optics in the past. In this work, we would like to investigate (1) highly efficient THz emitters and detectors, (2) explore the possibility of combining liquid crystals with photonic crystals and meta-materials for tunable THz optics. With the structured material or meta-material and highly birefringent materials such as liquid crystals for added functionality, new possibilities arise for novel optical elements because of the strong coupling of these novel materials with the electromagnetic wave. Starting from the theoretical analysis, we will work on design and fabrication of various THz optical components. Our long-range goal would be highly directional and intense THz sources, taking advantage of the unique properties of photonic crystals or meta-materials. The technologies developed in this project would also make possible advances in other important applications of THz science and technology, e.g., biomedical sensing and imaging.

(II) Quantum (Photonic Crystal) structures and Enabling devices

The main objectives of this research project will be focus on 3 parts. First, Development and study of novel blue and UV-LED and surface emitting laser, the specific objectives of this proposal include (1) to development nitride-based blue and UV material and optoeletronic device; (2) to development novel process for obtaining high performance of blue and UV LED and LD. Second, to investigate nanotechnology and nano-photonics. This part of the object will focus on investigating the optical properties of mesoscopic GaN-based quantum confined structures and to achieve controlled photon emission from the GaN-based quantum confined structures. The specific objectives of this proposal include (1) establishment of the fabrication technology of GaN quantum confined structures such as quantum dots and nanostructures; (2) simulation and modeling of the op;tical properties of microcavity quantum confined structures and development of device design guidelines for fabrication of microcavity quantum confined structures; (3) fabrication of devices that incorporate the quantum confined structures into a microcavity such as vertical cavity surface emitting laser (VCSEL) structures; (4) investigation of the optical properties of the fabricated quantum confined structures and microcavity structures; and (5) investigation and demonstration of the controlled photon emission from the microcavity quantum confined structures or devices. Third, for the fabrication of long wavelength VCSEL (LW-VCSEL) and high speed VCSEL for communication, the specific objectives of this proposal include (1) fabrication single mode high speed GaAs or InP -based VCSEL; fabrication of InP based 1300 nm or 1500nm Long Wavelength VCSEL; (2) VCSEL Arrays Chip and Multiple-Wavelength or tunable Source.

- The GaN-based UV LD have applicatics to the high density storge in the storge project..
- The Long Wavelength VCSEL will be useful to the optical communication project.

(IV) **(III)** Volume Holographic Materials, Technology and Enabling devices

Volume holographic technology and applications have been explored for past 50 years but still have not yet achieved significant breakthrough. The development of the proper recording material is a fundamental key to the success for the holographic systems. Therefore, in this sub-project, we plan to develop novel volume holographic materials and explore its applications on novel information processing with ultrahigh density (1 Tbits/in2) and ultrafast fast (Tbps). Through the innovative researches and international collaborative efforts, we anticipate becoming a world class leader in the field of parallel information photonic system.

2. BREAKTHROUGHS AND MAJOR ACHIEVEMENTS

(I) Coherent and THz Photonics

1. Freezing phase scheme for fast adaptive coherent control:

The operational principle is based on a concept that the highest peak intensity will correspond to a frozen phase state of all spectral components involved in a coherent optical pulse. It is fast and immune to the noise and laser power fluctuation, and useful for a variety of applications that require complete-field characterization and adaptive coherent control on the same setup [JOSA B 22:1134 (2005), selected by the Virtual Journal of Ultrafast Sciences, Vol. 4, No. 6, June 2005].

2. Ultrafast Photoconductive Switch and THz Spiral Antenna Fabricated on Multi-Energy Arsenic-Ion-Implanted GaAs:

With multi-energy implantation and post annealing, the dark current of a GaAs:As+ PCS antenna is reduced to 24 A/cm2. The device exhibits a nearly identical rising and falling response and exhibits 2.7-ps switching response with operational bandwidth exceeding 150 GHz. This multi-energy implantation results in a shorter THz emission pulse with central frequency and spectrum linewidth extending to 0.2 THz and 0.18 THz, respectively [JAP 98:013711 (2005), selected by the Virtual Journal of Ultrafast Sciences, Vol. 4, No. 8, August 2005].

3. Directly modulated THz Communication link:

We have demonstrated for the first time transmission of audio and burst signals through a prototype THz analog communication link, employing dipole antenna as THz emitter and receiver. The transmission distance is about 100 cm. By using a direct voltage modulation format, we observed a clearly demodulated burst signal with a rising time of 32 μs. The highest audio modulating bandwidth achieved was 30 kHz in this first experiment. The transmission of a six-channel analog and burst audio signal with least distortion is also demonstrated [Opt. Exp., 13:10416, 2005].

4. A powerful THz emitter in the 800nm wavelength regime:

In this project, a GaAs/AlGaAs based Unitraveling Carrier Photodiode (UTC-PD) at a wavelength of around 830nm is demonstrated. Compared with the performance of control GaAs based p-i-n photodiode, UTC-PD can attain resembling external efficiency with much better electrical bandwidth performance under higher output photocurrent. Significant bandwidth enhancement can occur in a much lower photocurrent density (0.3mA/μm2 vs. 0.017 mA/μm2) than that of the reported InP-InGaAs based UTC-PD with a similar degree of enhanced optical-to-electrical (O-E) bandwidth (~10GHz) by optimizing the p-type doping profile in the absorption region. The results indicate that the demonstrated device structure has the potential to increase the linear operation regime of UTC-PD and serve as a powerful THz emitter in the 800nm wavelength regime.

The conceptual band diagram and cross-sectional view of demonstrated UTC-PD device is shown in Figure 1 (a) and (b), respectively. The inset of Figure 1 (a) shows the top-view of a fabricated device. In order to accelerate the photo-generated electron, in Figure 1 (b), we adopted a graded p-type doping profile in the GaAs based photo-absorption layer with 160nm total thickness.

To characterize the dynamic performance of our devices under continuous-wave (CW) operation, a heterodyne-beating system and a lightwave-component-analyzer (LCA) system have been established to measure the frequency responses of microwave and optical-to-electrical (O-E) scattering (S) parameters of devices. Figure 2 (a) and (b) represents the measured frequency responses of demonstrated UTC-PD and the control p-i-n under a fixed 50_ load (RF spectrum analyzer), the same optical pumping power (15mW), and different reverse bias voltages (-1V, -3V, and -5V). It is clear that UTC-PD has much better high-speed performance than the control p-i-n PD especially under high reverse bias voltages (-5V) and high output photocurrent (~1mA), and both devices exhibit nearly similar responsivity performance (~0.07A/W). Such measured result indicates that, compared with control p-i-n, the efficiency performance of our UTC-PD will not be sacrificed for its better high-power and high-speed performance.

The measured f3dB bandwidths of similar two devices under different operation conditions are shown in Figure 3. Under the high reverse bias voltage (-5V), significant bandwidth enhancement of UTC-PD has appeared under ~1mA output photocurrent.

A GaAs/AlGaAs based UTC-PD at an 830nm wavelength has been demonstrated. Compared with the control p-i-n PD, our device can have superior speed and power performance without sacrificing its responsivity performance. According to the O-E measurement result, the self-induced field and optimized p-type doping profile in the absorption layer causes significant bandwidth enhancement .The demonstrated device has the potential to serve as a powerful THz emitter under 800nm wavelength.

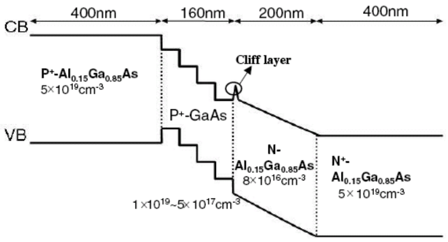


Fig. 1a

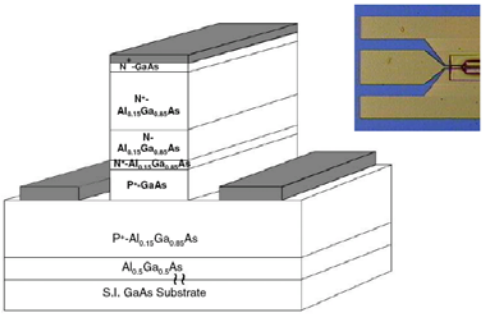


Fig. 1b

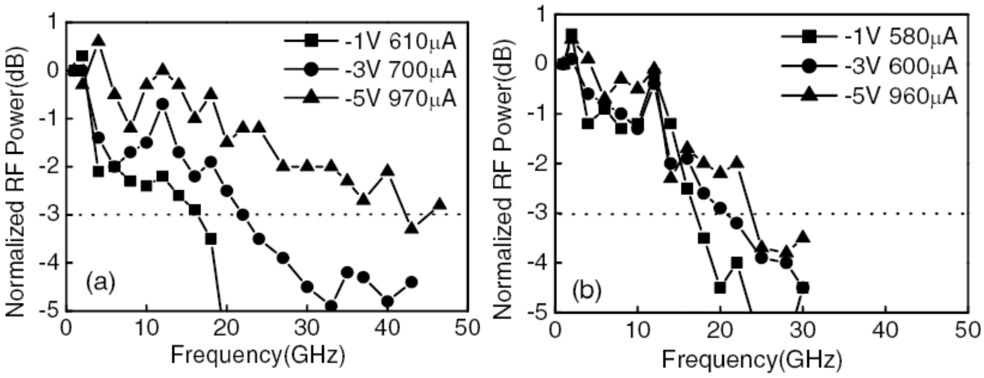


Fig. 2

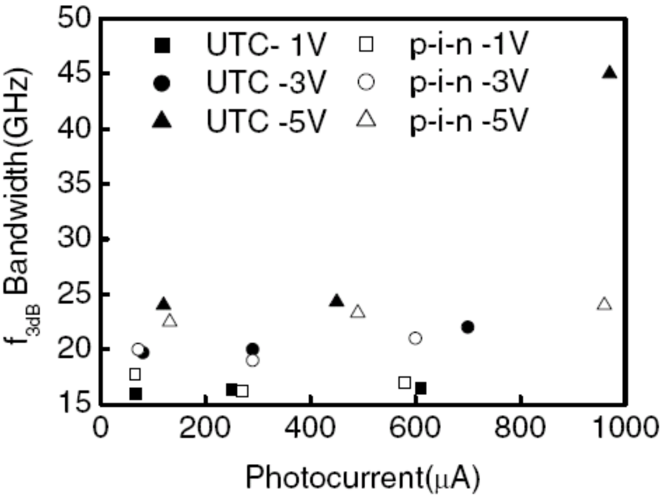


Fig.3

(II) Quantum (Photonic Crystal) structures and Enabling devices

<u>1. Development and study of novel blue and UV-LED and surface emitting laser</u>

(a) We successfully improved the performance of LEDs using two methods: (1)micro-hole array LED (2) undercut LED

(b) The process of p-side down GaN LEDs on Cu substrate using Laser lift-off was established.

(c) The LLO LEDs on Cu substrate showed linearly increased light output-power as the driving current was increased up to 1A with large emitting area of 1mm×1mm.

(d) Demonstration of laser action in GaN vertical micro-cavity under optical pumping at room temperature

(f) Demonstration of high reflectivity and crack-free AlN/GaN DBR

<u>2. Development and study of nanotechnology and nano-photonics</u>

(a) Fabrication InGaN/GaN MQW nanorods of 100 nm in diameter by ICP etching for the first time

(b) We present a novel method to fabricate High density (3.0×1010 cm-2) GaN-based nanorod -LED with controllable dimension and density using Ni mask.

(c) About 5 times enhancement of intensity from the InGaN/GaN nanorod was also observed

(d) Fabrication first GaN nanorod with MQW structures and showed light emission enhancement in GaN light emitting devices

(e) Fabrication of nano structures and demonstration of high Q micro-cavity

<u>3. Development and study of long-wavelength VCSEL</u>

(a) We fabricated the PC-VCSEL by proton implant and ICP etching

(b) single mode output with SMSR > 50 dB was obtained by proton implanted PC-VCSEL.

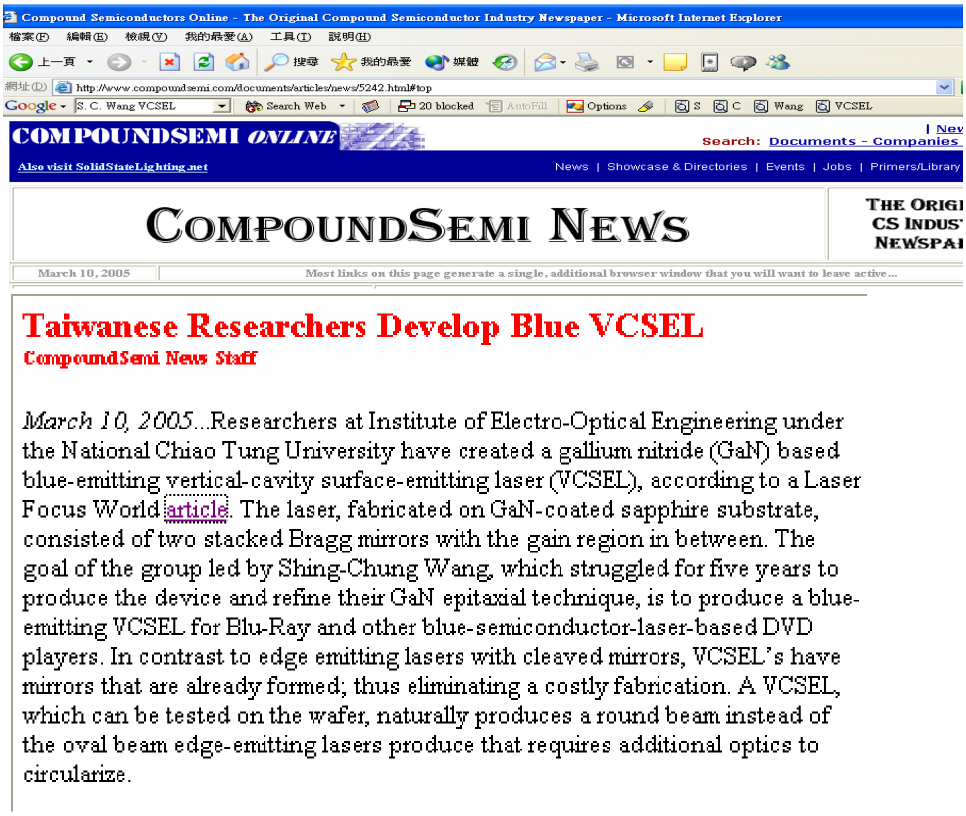
(c) Demonstration of singlemode Quantum-Dot VCSEL in 1.3 um with Side-mode Suppression Ratio over 30dB

(d) Demonstration of 1.3 μm Quantum Dot Vertical Cavity Surface Emitting Laser with

External Light Injection

(e) Demonstration of singlemode InAs quantum dot photonic crystal VCSELs

World Class results
GaN VCSEL



Taiwanese Researchers Develop Blue VCSEL

CompoundSemi News Staff

March 10, 2005...Researchers at Institute of Electro-Optical Engineering under the National Chiao Tung University have created a gallium nitride (GaN) based blue-emitting vertical-cavity surface-emitting laser (VCSEL), according to a Laser Focus World article. The laser, fabricated on GaN-coated sapphire substrate, consisted of two stacked Bragg mirrors with the gain region in between. The goal of the group led by Shing-Chung Wang, which struggled for five years to produce the device and refine their GaN epitaxial technique, is to produce a blue-emitting VCSEL for Blu-Ray and other blue-semiconductor-laser-based DVD players. In contrast to edge emitting lasers with cleaved mirrors, VCSEL's have mirrors that are already formed; thus eliminating a costly fabrication. A VCSEL, which can be tested on the wafer, naturally produces a round beam instead of the oval beam edge-emitting lasers produce that requires additional optics to circularize.

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An Enlightening Breakthrough

Taiwan's First Blue Light VCSEL is Developed at National Chiao Tung University

A research team led by Prof. Wang Shing-chung of the Department of Photonics, National Chiao Tung University successfully developed a gallium nitride (GaN) blue vertical cavity surface emitting laser (blue VCSEL) on February 24, 2005. The first blue VCSEL developed in Taiwan, this pioneering breakthrough is comparable to or even surpasses the work of leading research laboratories in the US and Japan, and raises Taiwan's blue VCSEL research to a world-class level.

According to Prof. Wang, the blue VCSEL developed by his team consists of a vertical cavity and a multiple quantum well light emitting structure. Due to the lack of GaN substrate material, the epitaxial growth of GaN material and device structures is technically a very difficult process. Ordinary GaN light emitting devices can only achieve incoherent light emitting diode (LED) stage, and it is a great challenge just to fabricate conventional blue edge emitting lasers. Further, the realization of GaN blue VCSELs requires a pair of very high reflectivity multiple-layer structure to form the vertical cavity in order to achieve laser operation. Therefore, the technical difficulties involved here are much greater than that of edge emitting lasers.

Prof. Wang's team has conducted research on GaN blue VCSEL for nearly five years under the support of the NSC, the National Science and Technology Program for Nanoscience and Nanotechnology, the Ministry of Education's Program for Promoting Academic Excellence of Universities, and National Chiao Tung University. The team has been developing the epitaxial growth process and multiple-layer vertical cavity fabrication technique, and has established device-processing steps. This breakthrough was finally achieved after countless iterations and constant improvements over many years. One of the key advantages of this blue VCSEL design is the ease with which the fabrication process can be transferred to mass production.

Blue VCSELs are expected to have a wide range of applications in high-density optical storage (HD-DVDs), large area laser displays, and lighting devices. Furthermore, the micro-cavity structure of GaN VCSEL gives them unique electronic and optical characteristics that can be used to control photon generation. Future applications may include quantum information and nanotechnology. Prof. Wang's research team is now working closely with the Quantum Information Laboratory headed by Prof. Yoshihisa Yamamoto of Stanford University. The team is also conducting research collaboration with the US Air Force Research Laboratory (AFRL).

Prof. Wang observing GaN blue laser operation.

GaN blue VCSEL in operation.

4. Develop high-quality 1.55μm InGaAsP/InP MQW epitaxial structures as the active region of the 2D photonic crystal defect laser cavities.

5. Develop wafer bonding technique to integrate InGaAsP/InP MQW wafer with Sapphire substrate that has higher thermal conductivity than air. Achieve the air bubble-free and stress-free bonding quality by using a pre-made channel structure on wafer.

6. Evelop fabrication technology of 2D photonic crystal defect cavity structures which is based on electron beam lithography, RIE SiNx etch, and HDP InGaAsP/InP etch

7. Establish the measurement setup for defect cavities based on an infrared micro-PL system to characterize and analyze the basic characteristics of 2D photonic crystal lasers including PL spectra near and above threshold and L-L curve. We also study the thermal effects including the red shifts of lasing wavelength and the threshold dependences under different substrate temperatures and different pumping conditions. An ultra-low threshold pump power of 3.4μW is obtained under 1% duty cycle pumping condition.

(III) Volume Holographic Materials, Technology and Enabling devices

Our comprehensive studies on doped photopolymer can provide researchers invaluable guidance for the design, fabrication and characterization of novel holographic materials. The methodology of our investigation can also be excellent reference for developing new recording materials. Those thick holographic materials can open new widows for innovative applications in optical information processing.

3. CATEGORIZED SUMMARY OF RESEARCH OUTCOMES. IN EACH RESEARCH AREA, PLEASE GIVE A BRIEF SUMMARY OF THE RESEARCH OUTCOMES ASSOCIATED WITH THE AREA. NOTE THAT THE SUMMARIES SHOULD BE CONSISTENT WITH THE STATISTICS GIVEN IN FORM 3. PLEASE LIST AND NUMBER OF EACH RESEARCH OUTCOMES IN ORDER IN APPENDIX II, AND LIST ALL THE PUBLICATIONS IN TOP CONFERENCES AND JOURNALS IN APPENDIX III.

A. Prof. Ci-Ling Pan

I. THz Photonics

A detection bandwidth exceeding 30 THz was reported for THz dipole antenna fabricated on InP:H+ [Opt. Exp. 12(13):2954, 2004, selected by the Virtual Journal of Ultrafast Science, August 2004]. This is an extension of our previous work on Arsenic-ion-implanted GaAs [APL 83(7)1322, 2003, selected by the Virtual Journal of Ultrafast Science, September, 2003]. Both types of devices exhibit the broadest bandwidth reported for THz antennas based on ion-implanted photoconductors and comparable to that of LT-GaAs, the current state-of-art material for such applications. Our most recent work in this area was the report of multi-Energy Arsenic-Ion-Implanted GaAs Photoconductive THz Spiral Antenna [JAP 98:013711, 2005. Selected by the Virtual Journal of Ultrafast Science, Vol. 4, No. 8, August 2005]. In order to generate higher THz power, we experimented on coherent array of antennas [Opt2005]. Enhancement of THz amplitude by 2.2 times by a 2-element array was achieved. Using photoconductive antenna technology, we also report the first directly modulated THz communication link. The transmission distance is about 100 cm. By using a direct voltage modulation format, we observed a clearly demodulated burst signal with a rising time of 32 μs. The highest audio modulating bandwidth achieved was 30 kHz in this first experiment. The transmission of a six-channel analog and burst audio signal with least distortion is also demonstrated [Opt. Exp., 13:10416, 2005]. We also report exploratory work on biomedical applications of THz technology at a local conference [OPT2005]. On another front, we have successfully generated and detected CW THz radiation by photomixing of two laser diodes. Using an external cavity (ECL) configuration, the two laser diodes can be phase locked to a femtosecond laser frequency comb. The beat note of the 2 ECLs locked at 0.7131000 THz and 0.4571000 THz were demonstrated. This is important for our goal of establishment of THz frequency standard using the femtosecond frequency comb.

1. S. L. Wu (吳勝隆) and T. A. Liu (劉子安) and C. L. Pan (潘犀靈), “Spectroscopy of flour, lactose and starch in the THz range,” paper PE64, presented at Annual Meeting of the Physical Society, Feb. 9-11, 2004, Kaoshiung, Taiwan, in Conference Proceedings, 物理雙月刊, Vol. 27, No. 1, February 2005, p. 217.
2. Tze-An Liu, Gong-Ru Lin, Yen-Chi Lee, Shing-Chung Wang, M. Tani, Hsiao-Hua Wu, and Ci-Ling Pan, “Multi-Energy Arsenic-Ion-Implanted GaAs Photoconductive THz Spiral Antenna with Suppressed Dark Current and Trailing Edge,” J. Appl. Phys., Vol. 98, 013711-1 to -4, July 15, 2005, selected by the Virtual Journal of Ultrafast Science, Vol. 4, No. 8, August 2005.

3. Tze-An Liu, Gong-Ru Lin, Yung-Cheng Chang, Ci-Ling Pan, “A wireless audio and burst communication link with directly modulated THz photoconductive antenna,” Optics Express, Vol. 13, No. 25, pp. 10416-10423, 12 December, 2005.
4. Tze-An Liu(劉子安) , Chao-Jen Huang, Teh-Ho Tao, Ci-Ling Pan, “Thz Radaition From An Array Of Three Photoconductive Dipole Antennas,” C-SA-V4-1, presented at OPT2005 (Optics and Photonics Taiwan), Dec. 9-10, 2005, Tainan, Taiwan.
5. Tze-An Liu(劉子安) , Sheng-Lung Wu, Ci-Ling Pan, “Birefringence Measurement In Burned And Unburned Porcine Skin By THz Time Domain Spectroscopy,” C-SA-V5-4, presented at OPT2005 (Optics and Photonics Taiwan), Dec. 9-10, 2005, Tainan, Taiwan.
6. Tze-An Liu(劉子安) , Sheng-Lung Wu, Ci-Ling Pan, “Burn-Depth Detection Of Pork With T-Ray Technology,” PF-FR2-30, presented at OPT2005 (Optics and Photonics Taiwan), Dec. 9-10, 2005, Tainan, Taiwan.
7. Cheng-Yao Kao(高禎佑),Chih-Yu Wang, Yu-Ping Lan, Chao-kuei Lee, Jin-Long Peng, Ci-Ling Pan, “Towards Thz Frequency Metrology III: Frequency Locking Of Two Laser Diodes To The Femtosecond Frequency Comb,” C-SA-V6-7, presented at OPT2005 (Optics and Photonics Taiwan), Dec. 9-10, 2005, Tainan, Taiwan.

II. Liquid crystal THz photonics:

We have pioneered this field. Previously, we reported for the first time optical constants of several important liquid crystals in the THz regime [Appl. Opt., 42(13): 2372, 2003 and J. Biological Phys. 29(2-3):335, 2003]. Unexpected large birefringence was observed for the liquid crystals 5CB and E7 in the nematic phase. These properties were utilized to demonstrate both magnetically and electrically controlled THz phase shifters [APL 83(22): 4497, 2003; IEEE MWCL 14(2):77, 2004], culminating in the first room-temperature, 0-2π tunable THz phase shifter [Opt. Exp. 12(12): 2625, 2004, Selected by the Virtual Journal of Ultrafast Science, September 2004, Taiwan Patent 200186, US patent filed]. The device operates at room temperature, as opposed to previous devices needing liquid N2 for cooling and achieving phase shift of a few degrees at best. Important applications such as THz phased arrayed radar would be possible. Due the impact of our work, Prof. Pan was asked to present several invited talks, including a keynote speech on the subject. Recently, we have made several advances in THz Liquid crystal photonics.

(a) Control of enhanced THz transmission through 2-D metallic hole arrays using magnetically controlled birefringence in a nematic liquid crystal cell. [Opt. Exp. 13(11):3921, 2005].

(b) A liquid-crystal-based electrically tunable THz phase shifter and quarter-wave plate [presented at LEOS’05, Opt. Lett., to be published].

(c) A tunable liquid crystal Lyot filter. This is the first reported birefringent THz filter, to our knowledge [presented at LEOS’05, invited talk at the annual meeting of the Liquid Crystal Society, Appl. Phys. Letter, to be published].

In related work, we demonstrated a THz plasmonic filter [J. Phys. D, and studied the effect of hole materials in THz photonic crystals [presented at LEOS’05, submitted to Opt. Lett.].

1. Bor-Yuan Shew, Han-Chieh Li, Ci-Ling Pan and Cheng-Hao Ko, “ X-ray micromachining SU-8 resist for a terahertz photonic filter,” Journal Of Physics D-Applied Physics Vol. 38, No. 7, pp. 1097-1103, 7

April 2005.

2. Ci-Ling Pan, “Progress in Liquid Crystal THz Optics,” keynote speech, presented at Workshop On Global Perspectives In Frontiers Of Photonics: Computational Imaging, Biophotonics And Nanophotonics,” Durham, North Carolina, USA, May 18-19, 2005.
3. Ci-Ling Pan, Cho-Fan Hsieh, and Ru-Pin Pan, Masaki Tanaka, Fumiaki Miyamaru, Masahiko Tani, and Masanori Hangyo, “Control of enhanced THz transmission through metallic hole arrays using nematic liquid crystal,” Optics Express, Vol. 13, No. 11, pp. 3921 - 3930, May 30, 2005.
4. Ci-Ling Pan, “Recent Progress in Liquid Crystal THz Optics,” invited paper, presented at "Frontiers of Laser and Optical Sciences", October 1 - 2, 2005, Faculty of Science, Building No. 4, Room 1220 (2nd Floor), Hongo Campus, The University of Tokyo, Tokyo, Japan.
5. Ru-Pin Pan, Chao-Yuan Chen, Cho-Fan Hsieh, and Ci-Ling Pan, “A Liquid-Crystal-Based Terahertz Tunable Lyot Filter,” paper #ThCC3, presented at the 18th annual meeting of IEEE/LEOS, LEOS 2005, Sydney, Australia, October 23-27, 2005.
6. Cho-Fan Hsieh, Hung-Lung Chen, Chao-Yuan Chen, Ru-Pin Pan, and Ci-Ling Pan, “Voltage Controlled Liquid Crystal Terahertz Quarter Wave Plate,” paper # ThCC5, ibid..
7. Cheng Lo, Cho-Fan Hsieh, Ru-Pin Pan and Ci-Ling Pan, “Effects of Hole Material on Enhanced Terahertz Transmission through Metallic Hole Arrays,” paper # ThCC4, ibid..
8. Ci-Ling Pan, “A Liquid-Crystal-Based Terahertz Tunable Lyot Filter,” invited talk, presented at the annual meeting of the Liquid Crystal Society, Taiwan, Republic of China, December 30, 2005, Hsinchu, Taiwan.
9. Ci-Lin Pan and Ru-Pin Pan, “Recent progress in liquid crystal THz optics,” invited talk, presented at Photonics West 2006, San Jose, California, USA, Jan. 21-26, 2006, invited paper to be published in Proceedings of SPIE Vol. #6135, Liquid Crystal Materials, Devices, And Applications XI, Liang-Chy Chien, ed..
10. Ci-Ling Pan, “兆赫液晶光學,” invited talk, presented at 光學工程研討會 Optical Engineering Forum -- Meet SPIE Fellows, 14 February 2006, Chun-Li, Taiwan.
11. Chao-Yuan Chen, Cho-Fan Hsieh, Yea-Feng Lin, Ci-Ling Pan and Ru-Pin Pan, “A Liquid-Crystal-Based Terahertz Tunable Lyot Filter,” submitted to Appl. Phys. Lett., July 26, 2005 (accepted for publication, February 8, 2006).
12. Cho-Fan Hsieh and Ru-Pin Pan, Tsung-Ta Tang, Hung-Lung Chen, and Ci-Ling Pan, “Voltage-controlled liquid crystal terahertz phase shifter and quarter wave plate,” submitted to Optics Letters, November 5, 2005 (accepted for publication, 9 January, 2006).

B. Prof. Shiuan-Huei Lin

The main target of this project is to explore novel materials for volume and/or dynamic holographic recording and its applications on ultrahigh density storage (1 Tbits/in2). During the second year of project, we have investigated on the optimization of our doped PMMA photopolymers. Experimentally, we have developed novel photopolymer materials, such as doubly doped PMMA, quonone-based molecule doped PMMA, and doped copolymer…etc. We have also performed holographic recording in these photopolymer materials. In addition, the sample have been shaped as a 5-inch diameter disk with 2-mm thickness. It was put into a shift-multiplexed holographic data storage system (shown in Fig. 1.) and used to stored binary data as a computer data bank. The picture of disk sample is shown in Figure 2. We have written ~57 holograms, at a storage density of ~ 45 bits/m2, corresponding to ~ 50Gbytes of the storage capacity in this 5-inch disk. Raw bit error rate has been estimated to be ~0.0015. This result demonstrates that our material can support for the high-quality volume holographic storage applications.

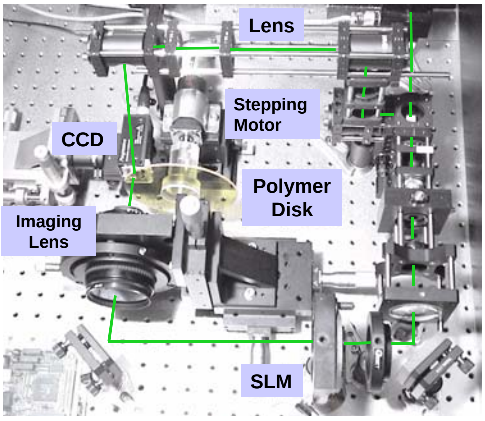


Figure 1. The picture of holographic data storage system

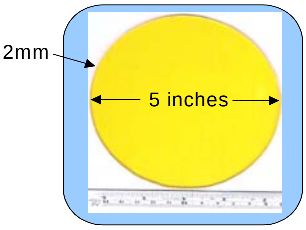


Figure 2. The holographic disk

C. Prof. Hao-Chung Kuo

I. Development and study of novel blue and UV-LED and surface emitting laser

InGaN-based quantum-well (QW) light-emitting diodes (LEDs) are affecting the development of full-color displays, illumination, and exterior automotive lighting over a spectral range from near ultraviolet to green and amber. However, the internal quantum efficiency for GaN-based LEDs is far smaller than 100% at room temperature due to the activation of non-radiative defects. In addition, the external quantum efficiency of the nitride-based LEDs is often low due to the large refractive index difference between the nitride epitaxial layer and the air. In order to achieve high efficient light emitting diodes, we developed some methods as following:

II. Micro-hole array light emitting diode

The processing of the InGaN-based micro-hole array LEDs began with electron-beam evaporated Ni (5 nm)/Au (8 nm) to form a high-transparency p-type Ohmic contact. The holes and the rectangular mesa (360 µm × 250 µm) were fabricated simultaneously by photolithographic patterning, the wet etching of Ni/Au layers and inductively coupled plasma (ICP) self-aligned dry etching (SAMCO ICP-RIE 101iPH). The diameters of the holes were 3, 7, 11, and 15 µm, as determined using a scanning electronic microscope (SEM) measurement. Spacing between two holes was fixed at 25 µm. Thermal annealing was applied to the p-type contact alloy at 500oC in air for 5 minutes. Finally, the trilayers of Ti/Pt/Au (50 nm/20 nm/200 nm) for p-type pad were deposited. Fig. 1 shows an optical microphotograph of the top of a micro-hole array LED chip and d = 7 µm, a bright luminescence ring is observed at the periphery of the hole. Figure 2 plots the light output-current density (L-J) curves. The micro-hole array LED with d = 7 µm has a light output power of ~ 3.0 mW at 22.2 A/cm2 (corresponding to a driving current of 20 mA for the conventional BA LED), which is 36% greater than ~ 2.2 mW for the conventional BA LED. Moreover, the light output power of the micro-hole array LEDs decreases as the d increases above 11 μm and the light output power of the micro-hole array LED with d = 15 μm is less than that of the conventional BA LED. These facts are attributable to combination of the enhancement in extraction efficiency by increasing the area of the sidewall surfaces and the reduction of the active areas of the micro-hole array LEDs. Optimally designed InGaN-based micro-hole array LEDs exhibit improved light output efficiently and are candidate for white-light LEDs or high-power/ high-efficiency large-area LEDs.

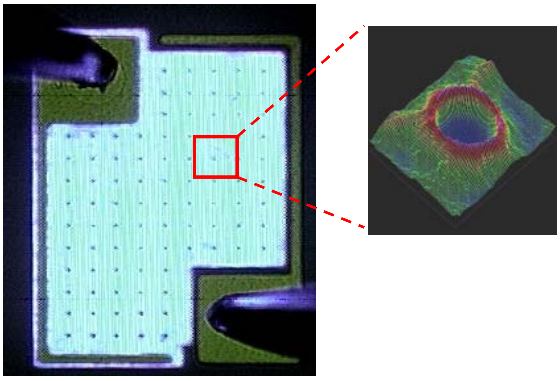


Fig. 1 The optical microphotograph of the top of a micro-hole array LED chip and *d* = 7 μm

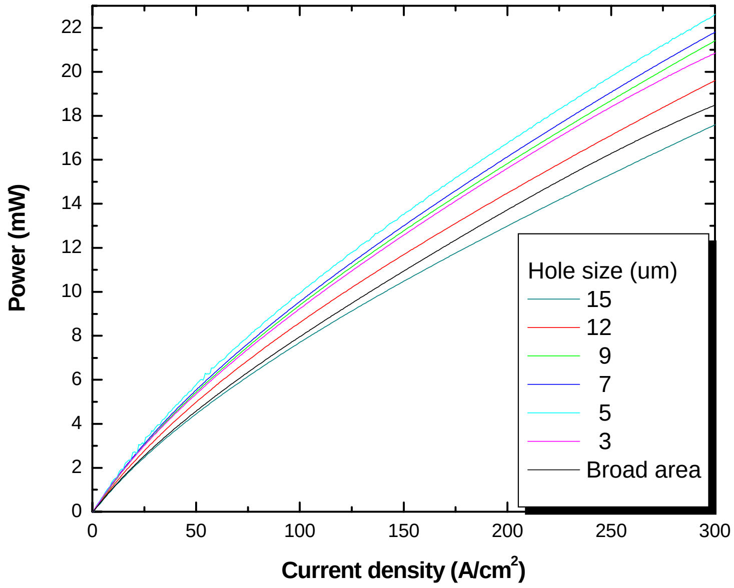


Fig. 2 The light output-current density (*L*-*J*) curves

III. Undercut LED

The process for conventional LED (LED I) and undercut LED (LED II) began with the deposition of 0.6-μm-thick SiNx onto the sample surface using plasma enhanced chemical vapor deposition (PE-CVD). Fig. 1 shows the schematic diagram of the undercut LED. The mesa etching was then performed with Cl2/Ar as the etching gas in an ICP-RIE system. An additional etching for LED II to form undercut side walls ~ 22o was carried out after mesa etching with zero bias power. Finally, the metal contact layers, included transparent contact and pad layers, were deposited onto samples using electron beam evaporation. Fig. 2 shows the SEM picture of side walls profile on LED II. Fig. 3 shows the intensity–current (L–I) characteristics of LED I and LED II. It can be seen that EL intensity of the LED II is larger than that observed from the normal LED. With 20 mA injection current, the light output power of LED I and LED II was about 3 mW and 5.1 mW, respectively. In other words, we could achieve a factor of 1.7 times output power enhancement from the InGaN–GaN MQW LEDs by the introduction of the undercut side walls. This simple and controllable method is beneficial to fabricate brighter LEDs.

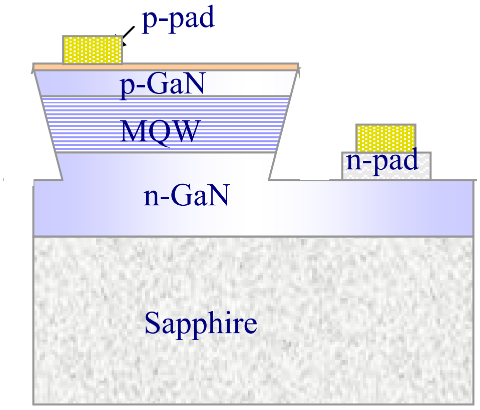


Fig1. The schematic diagram of the undercut LED.

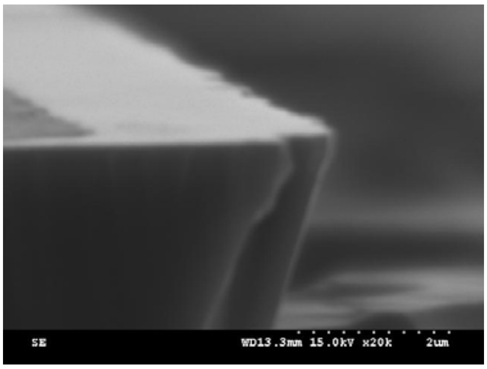


Fig. 2 The SEM picture of side walls profile on LED II.

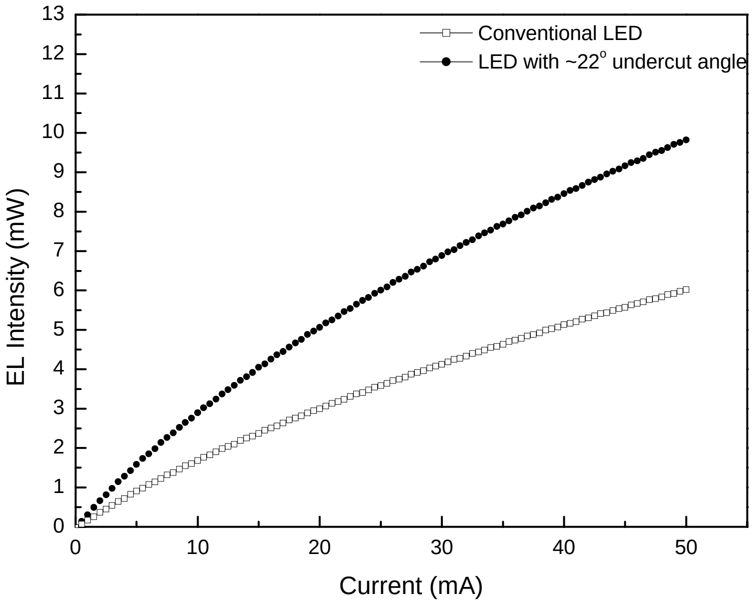


Fig. 3 The intensity–current (*L–I*) characteristics of LED I and LED II.

IV. Fabrication and performance of blue GaN-based vertical-cavity surface emitting laser

Our research group have recently successfully fabricated GaN-based micro-cavity VCSEL and achieved laser operation under optical pumping conditions. These results were shown in the following Figures and published in Applied Physics Letters. Fig.1 shows the laser emission intensity versus pumping energy with clear threshold condition. The inset shows the emission spectrum below and above threshold. Fig. 2 shows the laser emission image and beam intensity profile. we have investigated the performance of the GaN-based VCSEL with emission wavelength at 448 nm under the optical pumping at room temperature. The laser beam has a nearly linear polarization property with a degree of polarization of about 84% as shown in Fig. 3. The laser has a high β value of about 5×10-2 indicating the coupling coefficient enhancement due to the laser microcavity, and a high characteristic temperature of 244 K as shown in Fig. 4 suggesting potential for high temperature applications.

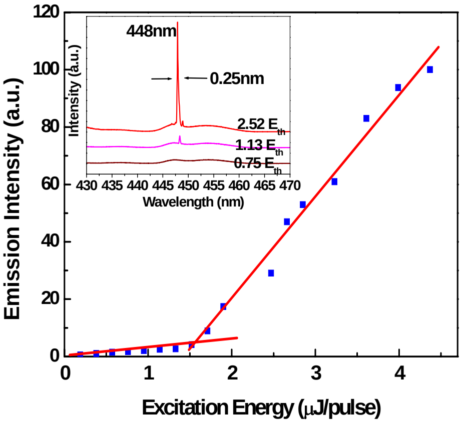


Fig 1. The lasing characteristics of the GaN-based micro-cavity VCSEL.

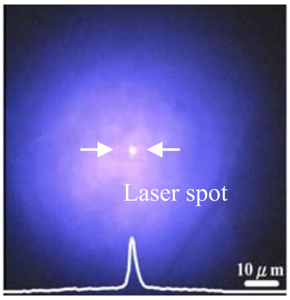


Fig 2. The laser emission images of the GaN-based micro-cavity VCSEL.

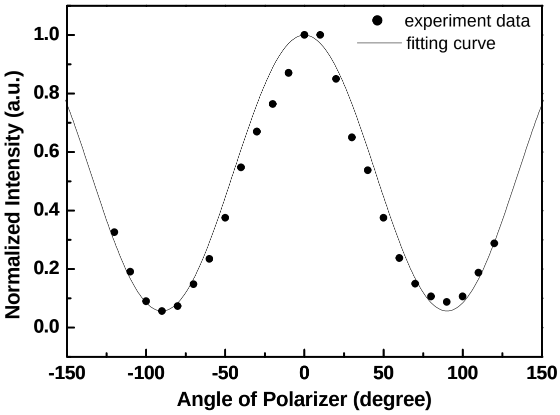


Fig 3. The polarization characteristic of the laser emission at the pumping energy of 1.71E$_{th}$. The solid dot shows the experiment data and the solid line is the fitting curve.

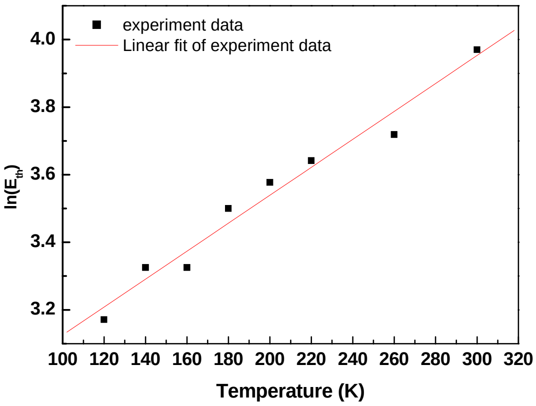
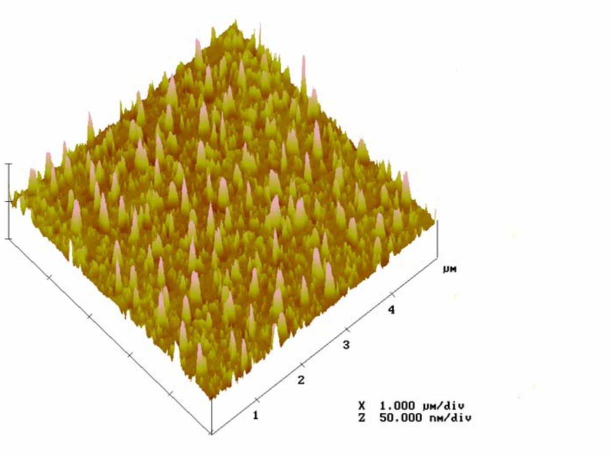


Fig 4. The semi natural-logarithm threshold energy as a function of the operation temperature. The solid dot shows the experiment data and the solid line is the linear fit of the experiment data.

V. Enhanced light output of InGaN/GaN light emitting diode

The external quantum efficiency of GaN-based LEDs is low because the refractive index of the nitride epitaxial layer differ greatly from that of the air, which limits the external quantum efficiency of conventional GaN-based LEDs to only a few percent. The light from LEDs can be enhanced either through the sample surface or through the side walls of the chip. This investigation describes the improvement of an InGaN/GaN MQW light emitting diode by nano-roughening the p-GaN surface using Ni nano-mask and laser etching as shown in Fig. 1. The nano-roughened surface improved the escape probability of light output inside the LED structure, increasing by 55% the light output of InGaN/GaN LED at 20 mA. As shown in Fig. 2, the operating voltage of the InGaN/GaN LED was reduced from 3.54 to 3.27V at 20 mA and the series resistance was reduced by 32% by the increase in the contact area of the nano-roughened surface. The wall-plug efficiency of the InGaN/GaN LED was increased by 68% by nano-roughening the top p-GaN surface using the Ni nano-mask and laser etching.



RMS roughness=5.8 nm

Fig. 1 AFM images of the top surface morphology of a LED sample with nano-roughened LED top p-GaN surface image.

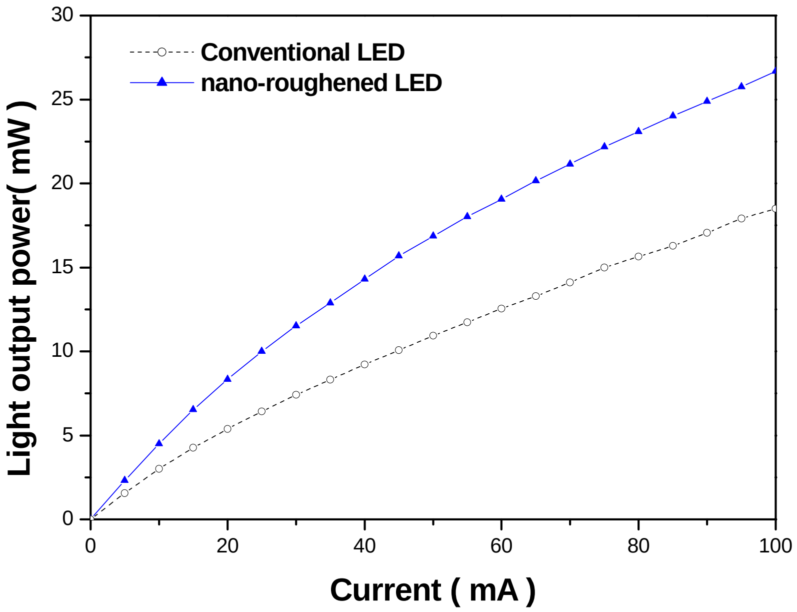


Fig.2 Light output power-current (L-I) characteristics of conventional and nano-roughened LEDs

VI. Development and study of nanotechnology and nano-photonics

Recently, due to the fast development of the quantum electronics and nano-science, fabrications and studies of quantum-confined structures have attracted a great deal of interests for potential applications on optoelectronic devices such as quantum cryptography, quantum information, single photon emitter and nano-light-emitting device. For GaN-based materials, the low dimensional nanostructures have attracted many interests for fundamental physical researches and potential applications. However, these GaN-based nanostructures are mostly pure or single crystalline, and exhibit different electronic and optical properties depending on their size and geometry. Many GaN-based devices must take advantages of the multi-quantum-wells (MQWs) structure such as InGaN/GaN MQWs. For this reason, it is necessary to fabricate the MQWs nanostructures and many of their novel optical properties still remain a great challenge to be resolved. We have successfully fabricated the nanorod composed of InGaN/GaN MQW structure using two methods:

VII. Directly etching by ICP-RIE

The sample of grown wafer structure was subjected to dry etching technique for nanorods formation using ICP system (SAMCO RIE-101iPH). The etching process of nanorods was performed under an inductively coupled plasma produced by a gaseous mixture of Cl2/Ar (10/25 sccm) at a chamber pressure of 20 mTorr. The ICP has a power of 200 W and a bias power of 200 W. For PL measurement, a doubled Ti: Sapphire laser operating at 390 nm with a spot diameter of 40 μm and a liquid helium flow cryostat for low temperature were employed. Figure 1 displays a typical SEM image of In0.3Ga0.7N/GaN MQWs nanorods. The nanorods fabricated by ICP dry etching were almost vertical and straight shape. The nanorods have lengths up to 500 nm and diameters ranging from 60 to 100 nm. Nanorods with diameters less than 55 nm were also observed. Structural characterization using TEM confirmed that the MQWs structure in nanorods was intact in structure, as shown in figure 2. A typical PL spectrum of InGaN/GaN nanorods under an excitation density of 0.9 W/cm2 was measured at 4 K as shown in figure 3. It consists of several discrete emission peaks whose positions are at 449, 453 and 457 nm respectively. The strong narrow emission peak at 457 nm has a full width at half maximum (FWHM) of about 1.5 nm. The position difference between each peak is estimated to be 4 nm (24 meV). The insert in figure 3 is the spectrum from the as-grown bulk wafer before ICP etching, which was measured at the same condition for the nanorods. It shows a typical InGaN/GaN MQWs spectrum with a FWHM of about 26.5 nm and an undulation behavior which is probably due to the Fabry-Perot interferences within the epitaxial layers. Indeed, fabrication of nanorods structure from the In0.3Ga0.7N/GaN MQWs bulk wafer does exactly show the different behavior than the typical PL emission spectra of bulk MQWs. This could be due to the decrease of in-homogeneous broadening in wells of nanorods. Figure 4 shows a series of spectra record at different excitation densities between 0.9 and 10.1 W/cm2 for In0.3Ga0.7N/GaN MQWs nanorods at 4K. Under low excitation densities, the e1-h1 peak at 457 nm is dominant. However, with increasing excitation density, the intensity of peak on the high-energy side of the e1-h1 peak increases. Finally, this peak at 453 nm becomes dominant over the e1-h1 emission. It have been demonstrated that the existence of three-dimensionally localized, QDs-like states/structure from the appearance of individual spectrally narrow emission lines. These experimental results suggest that excitons are strongly localized or confined in QDs-like structure. Such a circumstance presents interesting challenges to present efforts to develop blue nitride-based nano-optoelectronics devices.

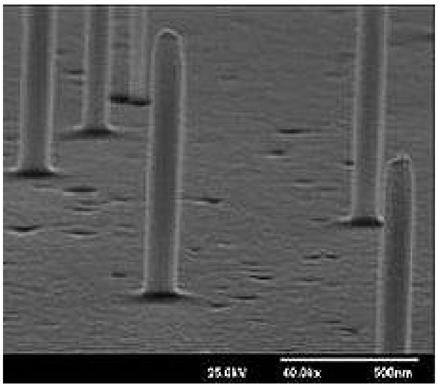


Fig. 1 Scanning electron microscopy image of $In_{0.3}Ga_{0.7}N/GaN$ MQWs nanorods.

Fig. 2 Transmission electron micrograph of a single $In_{0.3}Ga_{0.7}N/GaN$ MQWs nanorod.

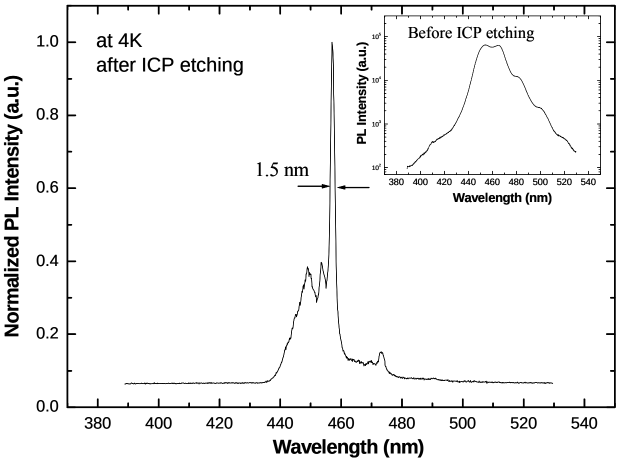


Fig. 3 Photoluminescence spectrum of $In_{0.3}Ga_{0.7}N/GaN$ MQWs nanorods excited under 0.9 W/cm^2. The insert is a photoluminescence spectrum of the as-grown bulk sample.

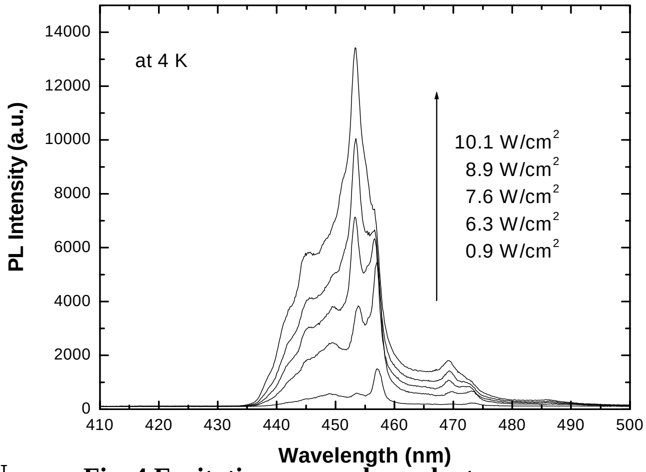


Fig. 4 Excitation power dependent photoluminescence spectra of $In_{0.3}Ga_{0.7}N/GaN$ MQWs nanorods.

VIII. Etching with Ni mask

Fig. 1 shows the fabrication flowchart of the InGaN MQWs nanorods. First, a 3000 Å-thick Si3N4 thin film was deposited on the samples using the method of photo enhanced chemical vapor deposition (PECVD), and then followed by the deposition of 50, 100, and 150 Å-thick Ni film respectively by electron-beam evaporation system. Then the samples were treated with rapid thermal annealing (RTA) of 850 degree under nitrogen ambiance for one minute to form self-assembled Ni nano-sized masks or clusters. In order to transfer the nano-sized masks down to Si3N4 layer, a reactive ion etching (RIE) was conducted to etch Si3N4 film using mixture gases of CF4/O2. Then the samples were etched down to the n-type GaN layer by ICP-RIE (SAMCO ICP-RIE 101iPH) with the nano-sized masks. Finally, the remain of nano-masks were removed in buffer oxide etchant to expose the InGaN/GaN MQW nanorods. Fig. 2 shows the mean dimension and density of InGaN MQWs nanorods as a function of Ni-mask film thickness of 50 to 150 Å. The InGaN/GaN MQW nanorods densities increase form 2.2x109 to 3x1010 cm-2 and the dimension decrease from 150 to 60 nm as the Ni film thickness decrease from 150 to 50 Å. The scanning electron microscope (SEM) image of the finished InGaN/GaN MQW nanorods fabricated by the ICP-RIE dry etching using self-assembled Ni nano-masks is shown in Fig. 3. The transmission electron microscopy (TEM) (JEOL, JEM-200CX) image of a single InGaN/GaN MQW nanorod is illustrated in Fig. 4. It shows clearly that the diameter and height of a single nanorod are approximately 80 nm and 1 μm. The active region of five-period MQW is also observed evidently from the TEM image. The width of the quantum well and barrier are estimated to be about 5 and 25 nm. Fig 5 shows the emission peaks of room temperature photoluminescence of the bulk and nanorods GaN LEDs at 451 and 446 nm. The blue-shift could be attributed to the partial strain relief in the well and quantum confinement effect. In addition, the PL intensity in the nanorods is enhanced by a factor of about 5 times than the bulk emission. The enhancement could be due to the better overlap of the electron and hole wave functions with a reduced piezoelectric field, and increasing of the radiative recombination rate. The light scattering off the etched sidewalls of the nanorods could also increase the PL intensity. These results with MQW structure should be applicable for fabrication of GaN-based light-emitting device.

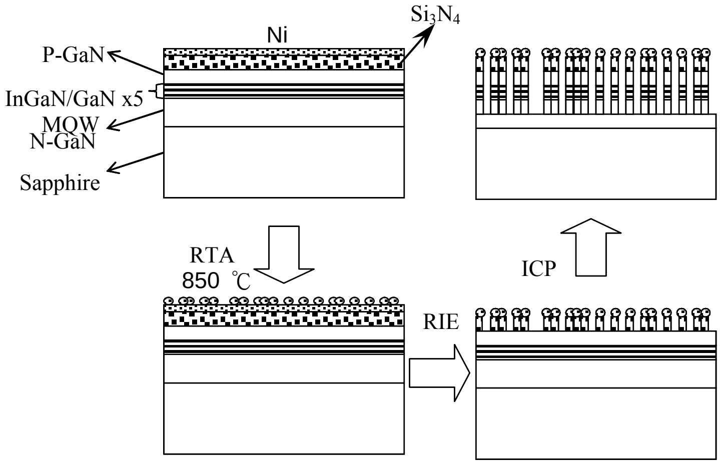


Fig. 1 The fabrication flowchart of the InGaN MQWs nanorods.

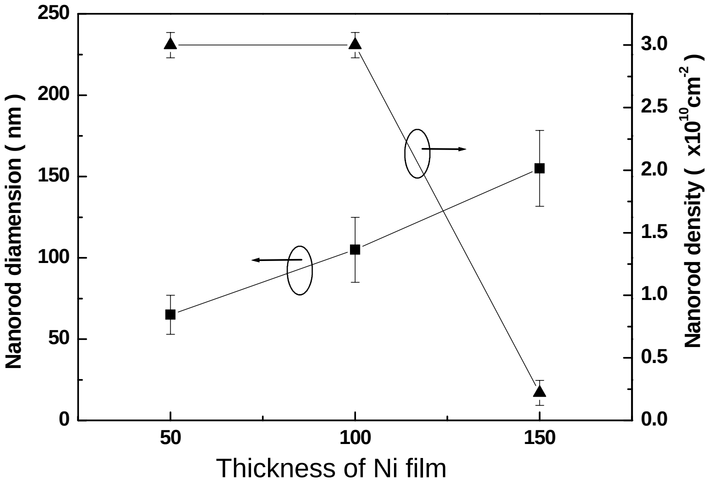
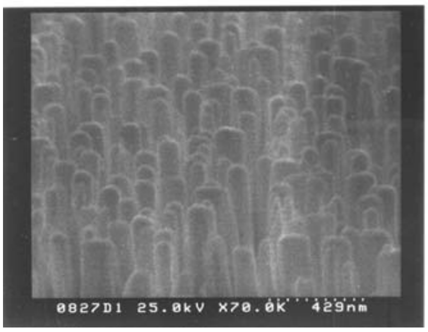


Fig. 2 The mean dimension and density of InGaN MQWs nanorods as a function of Ni-mask film thickness of 50 to 150 Å.



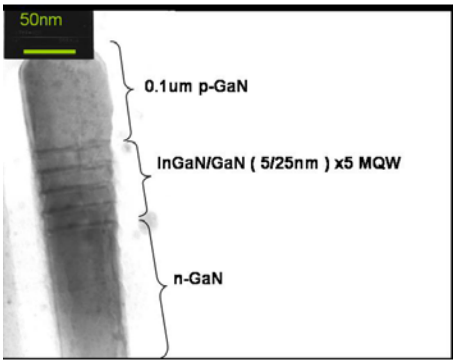


Fig. 3 The mean dimension and density of InGaN MQWs nanorods as a function of Ni-mask film thickness of 50 to 150 Å.

Fig. 4 The scanning electron microscope (SEM) image of the finished InGaN/GaN MQW nanorods.

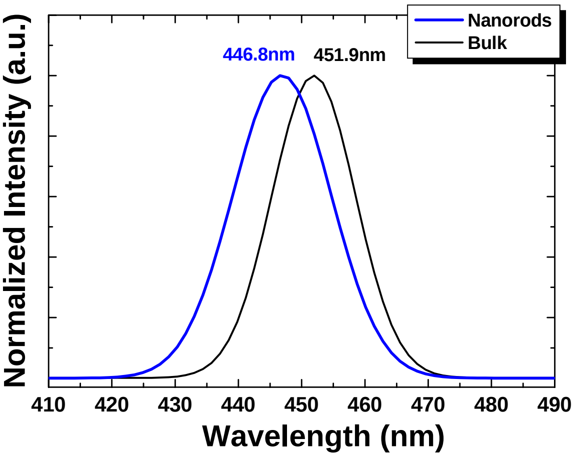


Fig. 4 The emission peaks of room temperature photoluminescence of the bulk and nanorods GaN LEDs

IX. InGaN self-assembled quantum dots grown by metalorganic chemical-vapor deposition

We have successfully grown self-assembled InGaN QDs structures by MOCVD system as shown in Fig. 1. The thermal budget control in the growth device, such as QDs LED or LD, is an important issue due to the instability of InGaN under high process temperature. In order to realize the effect of thermal annealing on QDs optical properties, the theoretical and experimental study of QDs postgrowth annealing were carried out. Self-assembled InGaN QDs structures were grown on sapphire substrates by MOCVD with growth interruption. The flat GaN layer on the sapphire substrate with an average deviation Ra = 0.14 nm of roughness over an area of 1 μm square was used as the template to grow InGaN QDs under a low V/III ratio (~8300), the low growth temperature (660oC) conditions and various interruption time. Grown InGaN QDs at tint = 60s have a density of about 4.5 × 1010 cm-2 with an average lateral size of 11.5 nm and an average height of 1.6 nm was obtained. The interruption time on the morphological and optical properties of the InGaN QDs suggest that the desorption effect during the growth interruption could decrease the dimensions of the InGaN QDs structure, the surface diffusion effect during the growth interruption could increase the QDs coverage occupied on the surface above the wetting layer, and extend the emission wavelength to the short wavelength region as the increase of the interruption time. By properly adjusting the interruption time, the uniformly distributed InGaN QDs with small dimensions can be obtained and should applicable for the applications of GaN-based light emitting device

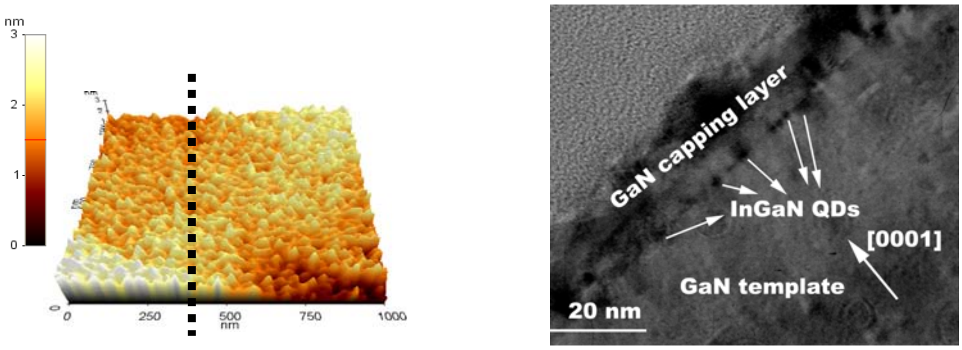


Fig 1. InGaN QDs grown on GaN by MOCVD investigated by AFM and TEM.

X. Development and study of long-wavelength VCSEL

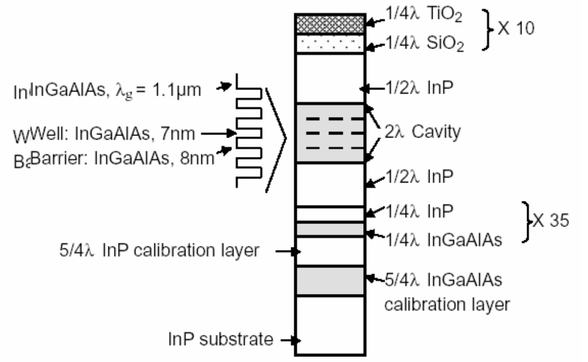
Long-wavelength (1.3–1.5mm) vertical cavity surface emitting lasers (VCSELs) are considered the best candidate for the future light sources in fiber communications. The advantages of VCSELs include single longitudinal mode output, small divergence circular emission beam profile, low power consumption and low-cost reliable productions. The absence of high refractive index contrast in InP-lattice-matched materials impeded the progress of the development of 1.3–1.5 mm VCSELs in comparison to the short-wavelength (0.78–0.98 mm) VCSELs. Recently, long-wavelength VCSELs have been successfully demonstrated with several different approaches, including wafer fusion technique; the InGaNAs 1.3 mm VCSELs grown on GaAs substrates, but to extend the

InGaNAs gain peak to beyond 1.5 mm is rather difficult. Recently, the DBRs based on relatively large refractive index contrast (Δ=0.34) material combination of InP/InGaAlAs have also been demonstrated. This material combination not only has a larger refractive index contrast than the conventional InP/InGaAsP and InAlAs/In-GaAlAs material systems, but it also has other benefits including the smaller conduction band discontinuity, which is good for n-type DBRs, and the better thermal conductivity due to the binary alloy of InP. So, we developed novel resonance cavity and distributed Bragg reflector.

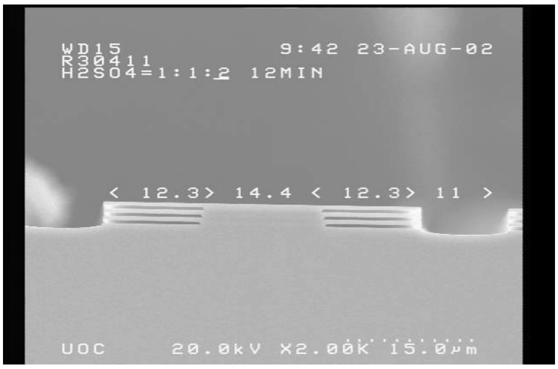
XI. Developing novel resonance cavity and distributed Bragg reflector

The InP and InGaAlAs belong to different group-V-based materials. Problems like the As carry over, the transitional interface, and lateral uniformity will affect the quality of the epitaxial layers and the reflectivity of the DBRs. As a result, the challenge of growing this combination relies on perfect switching between InP and InGaAlAs. The growth interruptions have been frequently used in the metal organic chemical vapor deposition (MOCVD) growth of the InGaAs/InP or InGaAs/InGaAsP quantum wells in order to obtain abrupt interface, but the growth of the InP/InGaAlAs DBRs using growth interruptions has not been investigated. We report the effect of the growth interruptions on fabrication of the InP/InGaAlAs DBRs. The lateral uniformity and the reflectivity of the DBRs are very sensitive to the stabilization time of each terminated interface. We incorporated an in situ laser reflectometry while growing DBRs with thickness more than 8 mm to insure minimum fluctuation in the center wavelength of the stopband. The optically pumped 1.56 mm VCSELs with 35 pairs InP/InGaAlAs DBRs achieved stimulated emission at room temperature with the threshold pumping power of 30mW.

In investigation of InP-based VCSEL, We have developed high quality active layer of InGaAlAs and developed high reflective InP/InGaAlAs DBR, and this result was published in Journal of Crystal Growth. We also developed InP/air-gap DBR and this result was published in Solid-State Electronics.



Laser structure of TiO_2/SiO_2 and InGaAlAs/InP DBR



Air gap distributed Bragg reflector

XII. Singlemode Monolithic Quantum-Dot VCSEL in 1.3 um

We demonstrate monolithic quantum-dot vertical-cavity surface-emitting laser (QD VCSELs) operating in the 1.3 μm optical communication wavelength. The QD VCSELs have adapted fully doped structure on GaAs substrate. The output power is ~ 330 μW with slope efficiency of 0.18 W/A at room temperature. Single mode operation was obtained with side-mode suppression ratio of > 30 dB. The schematic diagram of the QD VCSEL is shown in Fig. 1. The structure is grown on a GaAs (100) substrate using molecular beam epitaxy (MBE) by NL Nanosemiconductor GmbH (Germany). The epitaxial structure was as follows (from bottom to top) - n+-GaAs buffer, 33.5-pair n+-Al0.9Ga0.1As/n+-GaAs (Si-doped) distributed Bragg reflector (DBR), undoped active region, p-Al0.98Ga0.02As oxidation layer, 22-pair p+-Al0.9Ga0.1As/p+-GaAs DBR (carbon-doped) and p+-GaAs (carbon-doped) contact layer. The graded-index separate confinement heterostructure (GRINSCH) active region consisted mainly of five groups of QDs active region embedded between two linear-graded AlxGa1-xAs (x = 0 to 0.9 and x = 0.9 to 0) confinement layers. Fig. 2 plots curves of light output and voltage versus current (LIV). The threshold current is ~ 1.8 mA and the threshold current density is 7.6 kA/cm2. The output power rollover occurs as the current increases above 4mA with maximum optical output of 0.33mW at 20°C. Fig. 3 shows the typical emission spectra of the quantum-dot VCSELs, which indicate single transverse mode operation in the whole operation range with a lasing wavelength of ~1.278 μm and side mode suppression ratio (SMSR) > 30dB. To investigate the temperature dependence of the QD VCSEL, LI curves were measured from room temperature to 55oC with current step of 0.01 mA, as shown in Fig. 4. The threshold current varies only 0.15 mA (< 10% of Ith) with temperatures from 10°C to 45°C and the slope efficiency drops from 0.18 to 0.1 W/A.

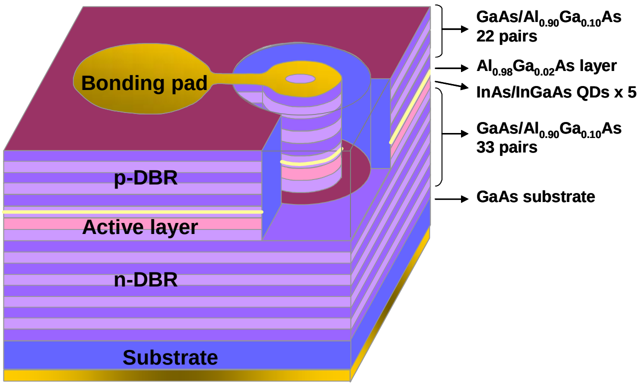


Fig. 1 QD VCSELs device structure.

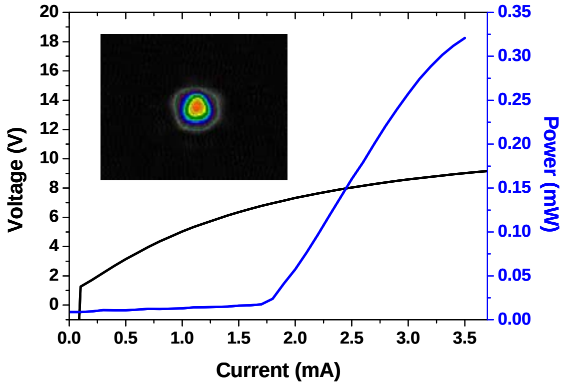


Fig. 2 L-I-V relationship of QD VCSEL. Inset is the near-filed pattern of the VCSELs at 3mA.

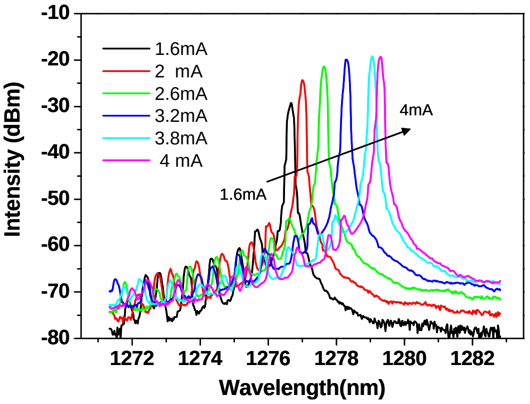


Fig. 3 Emission spectra of QD VCSEL at room temperature.

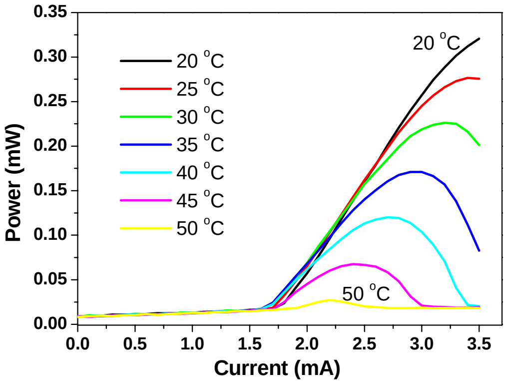


Fig. 4 Temperature dependent L-I relationship of QD VCSEL.

XIII. 1.3 μm Quantum Dot Vertical Cavity Surface Emitting Laser with External Light Injection

This investigation presents and experimentally demonstrates an 1.3μm quantum dot vertical-cavity surface-emitting laser (QD VCSEL) with external light injection. The 3 dB frequency response of QD VCSEL based on TO-Can package is enhanced from the free-running 1.75 GHz to 7.44 GHz with the light injection technique. Fig.1. shows the experimental setup for the injection locking of QD VCSEL. The QD VCSEL is hermetically sealed by a standard TO-Can laser package (TO-46) with a built-in lens. The QD VCSEL TO-Can package and the single-mode fiber are assembled by laser welding technique. Fig. 2 shows the frequency response of QD VCSEL. The 3 dB frequency response is 1.75 GHz at operating bias of 4 mA. The inset of Fig. 2 shows the output spectra of the QD VCSEL, which indicate single transverse mode operation and the side mode suppression ratio over 30 dB. The QD VCSEL is used as the slave laser while a DFB laser is used as the master laser. The QD VCSEL is biased at 4 mA. The injection power is varied by a variable optical attenuator at the output of the DFB laser. The polarization of the DFB laser is adjusted using a polarization controller before injecting into the QD VCSEL. In the experiment, the polarization and the center wavelength of DFB laser are adjusted that the QD VCSEL has the most significant enhancement in the frequency response. Fig. 3 shows the frequency response of the QD VCSEL at different injection powers. This figure clearly shows that external injection can achieve a significant enhancement in frequency response. Moreover, when the QD VCSEL is injection locked, as show in the inset of Fig. 3, its optical spectrum shifts a slightly longer wavelength. We observe that the 3 dB frequency is over 7.1 GHz when injection power is more than 2 dBm.

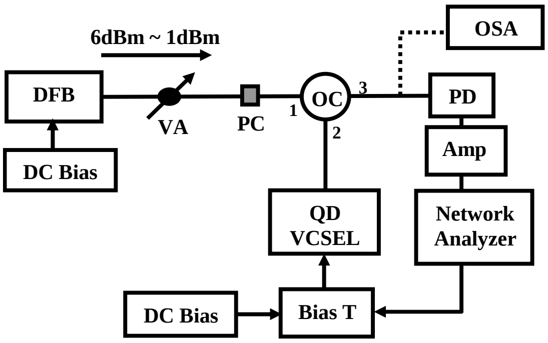


Fig.1. Experimental setup for the injection locking of QD VCSEL (DFB: DFB laser, VA: variable optical attenuator, OC: optical circulator, OSA: optical spectrum analyzer, PC: polarization controller, PD: photodetector, Amp: electrical amplifier)

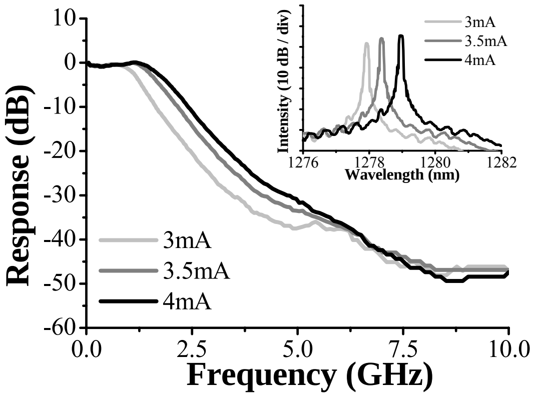


Fig.2. Small-signal frequency response of QD VCSEL at different bias currents.

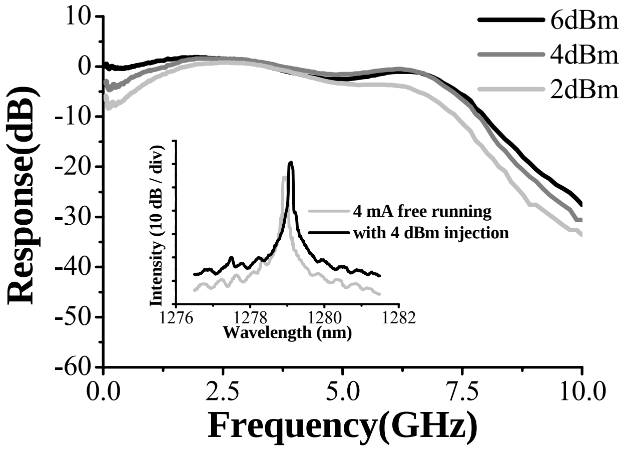


Fig.3. Small-signal frequency response of QD VCSEL at different injection powers.

XIV. Singlemode InAs quantum dot photonic crystal VCSELs

An InAs quantum dot photonic crystal vertical-cavity surface-emitting laser (QD PhC-VCSEL) for fibre-optic applications is first demonstrated. Single fundamental mode CW output power of 0.2 mW has been achieved in the 1300 nm range, with a threshold current of 4.75 mA. Side-mode suppression ratio larger than 40 dB has been observed over the entire thermally limited operation range. The device structure is shown in Fig. 1. By using two types of apertures in this device, we decouple the effects of the current confinement from the optical confinement. To clarify the effect of the photonic crystal index-guiding layer, a VCSEL with H+ implant aperture was also fabricated for comparison. Fig. 2 shows the CW light-current-voltage (L–I–V) output and near-field image operated at 6 mA (inset) of the PhC-VCSEL. The VCSEL emits 0.2 mW peak power and exhibits single modes throughout the current range of operation. The threshold current (Ith) of the PhC-VCSEL is 4.75mA. The I–V characteristics exhibit higher series resistance for the PhC-VCSEL, which should be mainly due to proton implantation through the p-ohmic contact of the device and blocking of the current flow in the region by photonic crystal holes. The output power could be improved by reducing the series resistance of the PhC-VCSEL. Lasing spectra of the PhC-VCSEL is shown in Fig. 3a, confirming singlemode operation within the overall operation current. The peak lasing wavelengths are 1268 and 1272 nm at 6 and 22 mA, respectively. The PhC-VCSEL exhibits an SMSR > 40 dB throughout the current range. For comparison, a lasing spectra of a QD VCSEL without photonic crystal holes shows multiple mode operation as the driving current increased above 5 mA (Fig. 3b). The QD VCSEL showed multiple transverse mode characteristics over a broader wavelength span.

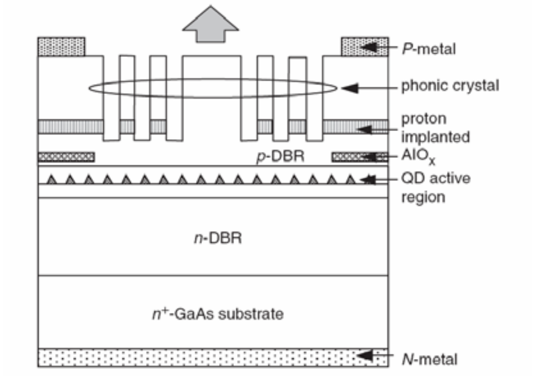


Fig. 1 Schematic of QD PhC-VCSEL

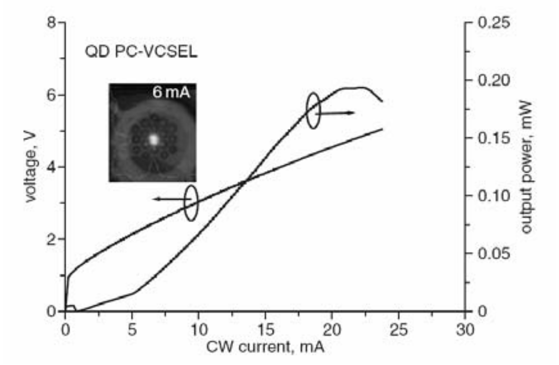


Fig. 2 CW L-I-V characteristics and near-field image (inset) PhC-VCSEL

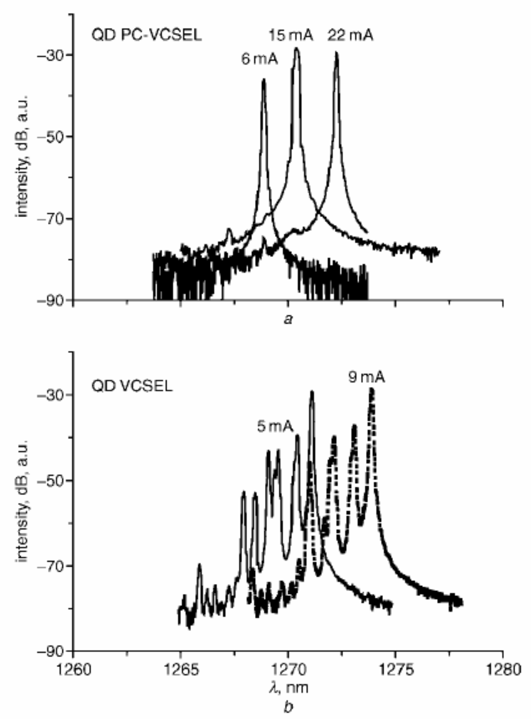


Fig. 3 Spectra of QD
a PhC-VCSEL
b VCSEL without PhC holes

D. Prof. Gong-Ru Lin

I. Erbium-doped fiber laser

Suppression of Phase and Supermode Noises in a Harmonic Mode-Locked Erbium-Doped Fiber Laser with a Semiconductor Optical Amplifier Based High-Pass Filter

By operating an intra-cavity semiconductor optical amplifier (SOA) based high-pass filter at nearly transparent current condition, the supermode noise, the relaxation oscillation, and the single-sided-band (SSB) phase noise can be simultaneously suppressed in an actively mode-locked erbium-doped fiber laser (EDFL). The SOA at nearly transparent condition enhances the SMN suppression ratio of the EDFL from 32 dB to 76 dB at a cost of phase noise degrading from -114 dBc/Hz to -104.2 dBc/Hz and a broadening pulsewidth from 36 ps to 61 ps. With an optical bandpass filter (OBPF), the SSB phase noise and the SMN suppression ratio can further be improved to -110 dBc/Hz and 81 dB, respectively. The EDFL pulse can further be shortened to 3.1 ps with a time-bandwidth product of 0.63 after compressing.

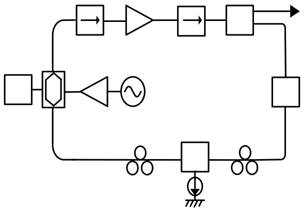
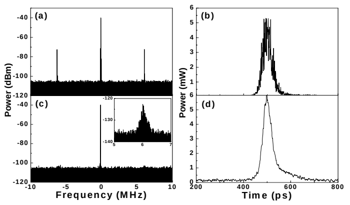
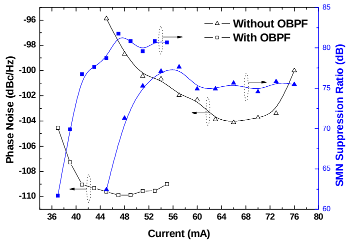
		

Fig. 1 The experimental setup of SOA filtered EDFL. MZM: Mach-Zehnder intensity modulator; PC: polarization controller; OC: optical coupler; OBPF: optical band-pass filter; EDFA: erbium-doped fiber amplifier; SOA: semiconductor optical amplifier.	Fig. 2 Upper: (a) SMN spectrum (measured at VBW and RBW of 300 kHz) and (b) pulse shape of mode-locked EDFL without intra-cavity SOA filter. Lower: (a) SMN spectrum and (b) pulse shape of mode-locked EDFL with intra-cavity SOA and OBPF. Inset: the SMN spectrum measured at VBW and RBW of 1 Hz.	Fig. 3 The SMN suppression ratios and the SSB phase noises of the mode-locked EDFL with SOA filter (hollow and solid triangles) or with SOA and OBPF filters (hollow and solid squares) at different SOA currents.

The experimental setup is shown in Fig. 1. The small-signal power gain of the erbium doped fiber amplifier (EDFA) can be as high as 31 dB, and the total cavity loss of the EDFL is about 23 dB. A commercial fiber-pigtailed SOA with small-signal gain and saturation output power of 25 dB and 8 dBm, respectively, is used as an SMN filter in the EDFL. A LiNbO3 Mach-Zehnder intensity modulator (MZM) biased at half-wave voltage (V . ≅ 8 V) is driven by a microwave synthesizer at 22 dBm and 977.64 MHz. A pair of polarization controllers (PCs) and Faraday optical isolators are employed to optimize the polarization orientation of the circulating pulses and ensure the unidirectional propagation. The output coupling ratio of the EDFL is 10%. The length of the EDFL ring cavity is 32.1 m (corresponding to a longitudinal mode spacing of 6.24 MHz). The OBPF (JDS, TB1500B) inserted between the EDFA and SOA exhibits a 3-dB bandwidth of 1.38 nm, which enhances the gain profile of the SOA at 1532 nm and reduces the ASE components over a wide wavelength range. The SSB phase noise spectral power density of the mode-locked EDFL pulse-train are measured by a high-speed photodetector (New Focus Model 1014) and an RF spectrum analyzer (HP8565E). For a mode-locked EDFL without intra-cavity SOA, the pulsewidth and timing jitter are 36 ps and 0.6 ps, respectively. The SMN suppression ratio of such a general EDFL is only 32 dB, as illustrated in Fig. 2(a). The insertion of an SOA and the OBPF greatly enhances the SMN suppression ratio and reduces the intensity fluctuations, as shown in Figs. 2(c) and 2(d). When operating at nearly transparent condition, the SOA exhibits a small-signal gain of only 14 dB and a saturation output power of about 0.7 mW. Typically, the extremely long upper-level lifetime of excited erbium ions in EDFL (~10 ms) may lead to a large power fluctuation (see Fig. 2(b)) and a strong supermode beating effect of the output pulse. In experiment, the SSB phase noise is changed from -96 to -100 dBc/Hz (measured at 100 kHz offset frequency from carrier) and the SMN suppression ratio is enhanced from 62.4

to 76 dB by increasing the driving current of the SOA from 45 to 76 mA. The minimum SSB phase noise of -104.2 dBc/Hz is observed by driving the nearly transparent current (~66 mA), as shown in Fig. 3. It is evident that the SMN suppression ratio slightly improves as the SOA gain increases, especially when the SOA switches from absorption to gain regimes.

Ultrahigh supermode noise suppressing ratio of a semiconductor optical amplifier filtered harmonically mode-locked Erbium-doped fiber laser

The supermode noise suppressing ratio (SMSR) and the phase noise of a harmonically mode-locked Erbium-doped fiber laser (HML-EDFL) with an intra-cavity semiconductor optical amplifier (SOA) and an optical band-pass filter (OBPF) are improved and compared with a state-of-the-art Fabry-Perot laser diode (FPLD) injection-mode-locked EDFL. By driving the intra-cavity SOA based high-pass filter at unitary gain condition, the SMSR of the HML-EDFL is enhanced to 82 dB at the cost of degrading phase noise, increasing jitter, and broadened pulsewidth. The adding of OBPF further improves the SMSR, pulsewidth, phase noise, and jitter of the SOA-filtered HML-EDFL to 90 dB, 42 ps, -112 dBc/Hz, and 0.7 ps, respectively. The ultrahigh SMSR of the SOA-filtered HML-EDFL can compete with that of the FPLD injection-mode-locked EDFL without sacrificing its pulsewidth and jitter performances.

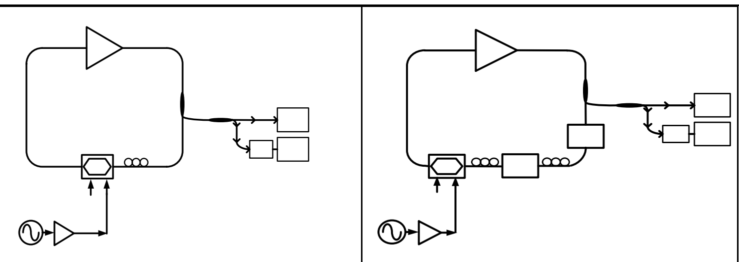
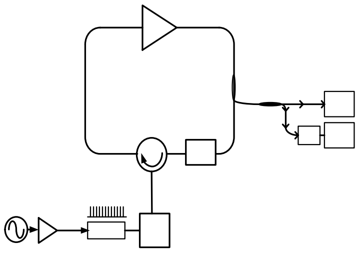
	

Fig. 1 The schematic diagrams of the (a) HML-EDFL and (b) SOA-and-OBPF-filtered HML-EDFL. PC: polarization controller; OC: optical coupler; EDFA: Erbium-doped fiber amplifier; MZM: Mach-Zehnder intensity modulator; SOA: semiconductor optical amplifier; OBPF: optical bandpass filter.	Fig. 2 The schematic diagram of the EDFL mutually injection-mode-locked with a gain-switched FPLD. Comb: Electrical pulse generator; FPLD: Fabry-Perot laser diode.

Figure 1(a) illustrates a typical HML-EDFL with an intra-cavity EOM based mode-locker, which consists of an Erbium-doped fiber amplifier (EDFA), a pair of Faraday optical isolators, a polarization controller (PC), a LiNbO3 Mach-Zehnder interferometer based EOM, and an optical coupler (OC) with 10 % output coupling ratio. The EOM DC-biased at its half-wave voltage (V . ≅ 8 V) is driven by a microwave synthesizer (Rhode & Schwartz, SML01) with the output power and the SSB phase noise of 22 dBm and -130 dBc/Hz (measured at offset frequency of 100 kHz from carrier), respectively, at frequency of 1 GHz. The PC is properly adjusted to optimize the polarization of the circulating pulses for the EOM, and two Faraday optical isolators ensure the unidirectional propagation of light in the EDFL cavity. As a result, the stable HML-EDFL pulse-train can be obtained when the modulating frequency is detuned to coincide with one harmonic of longitudinal modes in the EDFL cavity. The length of the EDFL ring cavity is 32 m, providing a longitudinal mode spacing of 6.25 MHz. On the other hand, the schematic diagram of an SOA-filtered HML-EDFL is shown in Fig. 1(b). The commercial fiber-pigtailed SOA exhibits a small-signal gain of 25 dB and a saturated output power of -1.5 dBm when operating at unitary gain (or nearly transparent) condition. In this case, the bias current, operating temperature, 3-dB linewidth and central wavelength of the SOA are set as 57 mA, 24 oC, 30.4 nm, and 1530 nm, respectively. A PC is used to adjust the polarization of light for the SOA. To suppress the supermode noise and SSB phase noise, an OBPF (JDS Uniphase, TB1500B) with 3dB bandwidth 1.38 nm is inserted into the HML-EDFL. On the other hand, the FPLD-IML-EDFL is performed by seeding the EDFL with a gain-switched FPLD, as shown in Fig. 2. It consists of a close-loop EDFA with 10 % output coupling ratio, a comb-generator-driven FPLD, an OBPF, and an optical circulator. The wavelength, threshold current, and longitudinal mode spacing of the free-running FPLD operated at 25 oC are about 1550 nm, 8 mA, and 1.2 nm, respectively. A comb generator driven by 27-dBm microwave signal at 1 GHz is employed to provide an electrical pulse-train for gain-switching the FPLD DC-biased at 3.4 mA. The central wavelength of the OBPF is adjusted to match that of the FPLD, which avoids the feedback injection of the amplified spontaneous emission (ASE) of the EDFL into the FPLD. In particular, the gain-switched FPLD pulse amplified by the EDFL is fedback into the FPLD itself, achieving a mutual IML between the FPLD and EDFL link. Such a configuration effectively suppresses the ASE as well as the SSB phase noise of the EDFL. The feedback injection from EDFL is also used to facilitate single longitudinal mode lasing of the FPLD with improved SMSR. Note that the feedback wavelength of the amplified FPLD pulses must coincide with the central longitudinal mode of the FPLD at 1550 nm in order to obtain the lowest SSB phase noise (timing jitter) and the highest SMSR. The parametric comparisons on different EDFL systems are summarized in Table 1.

Table 1. Comparisons on performances of versatile EDFL systems

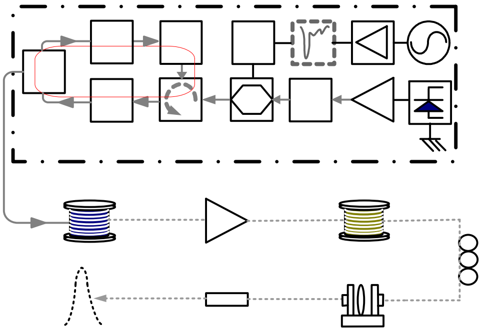
Configurations	HML-EDFL	HML-EDFL with SOA	HML-EDFL with SOA and OBPF	FPLD-IML-EDFL
Pulsewidth (ps)	36	61	42	22
Peak Power (mW)	12.3	14	11.1	40.7
SSB Phase Noise (dBc/Hz)	-114	-104.2	-112	-121.2
Timing Jitter (ps)	0.6	1.4	0.7	0.25
SMSR (dB)	45	86	90	91

II. Semiconductor optical amplifier based fiber laser

Femtosecond compression and wavelength-tuning of semiconductor optical amplifier fiber laser mode-locked by backward-optical-injection

Femtosecond nonlinear pulse compression of a wavelength-tunable, backward dark-optical-comb injection harmonic-mode-locked semiconductor optical amplifier based fiber laser (SOAFL) is demonstrated for the first time. Shortest mode-locked SOAFL pulsewidth of 15 ps at 1 GHz is generated, which can further be compressed to 180 fs after linear chirp compensation, nonlinear soliton compression, and birefringent filtering. A maximum pulsewidth compression ratio for the compressed eighth-order SOAFL soliton of up to 80 is reported. The pedestal-free eighth-order soliton can be obtained by injecting the amplified pulse with peak power of 51 W into a 107.5m-long single-mode fiber (SMF), providing a linewidth and time-bandwidth product of 13.8 nm and 0.31, respectively. The tolerance in SMF length is relatively large (100-300 m) for obtaining <200fs SOAFL pulsewidth at wavelength tuning range of 1530-1560 nm.

Figure 1 illustrates the backward-optical-injection mode-locked SOAFL system with a ring cavity length of 14 m, which consists of one traveling-wave typed SOA at 1530 nm, an optical circulator, a faraday isolator, a polarizer, an 50% output coupler (OC), an optical tunable band-pass filter (OBPF), a 1/4 wave plate, and a polarization controller. The SOA with central wavelength and spectral linewidth of 1530 nm and 35 nm, respectively, was DC biased at 345 mA (well above threshold current of 50 mA).



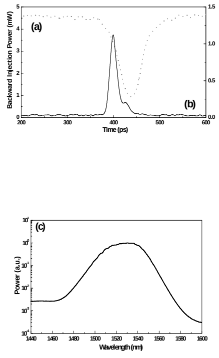


Fig. 1 The schematic diagram of the backward-optical-injection mode-locked SOAFL based femtosecond soliton generator. ATT: attenuator; Amp: power amplifier; COMB: comb generator; DFBLD: distributed feedback laser diode. EDFA: erbium-doped fiber amplifier; ISO: optical isolator; OC: optical coupler; SOA: semiconductor optical amplifier; RFS: RF synthesizer. Fig. 2 Upper: pulse shapes of the (a) injected dark-optical-comb and (b) mode-locked SOAFL; Lower: (c) the amplified spontaneous emission spectrum of SOA operated at 15 ^{o}C.

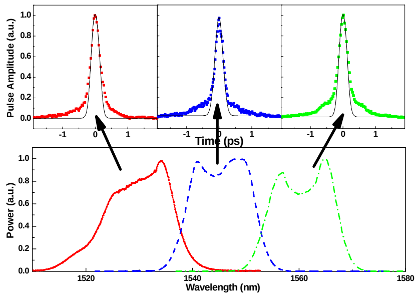


Fig. 3 The nonlinearly compressed pulse shapes and associated spectra at different SOAFL wavelengths.

To backward optical-inject the SOA for harmonic mode-locking, a butterfly-packaged DFBLD operated at 70 mA, 1535 nm, and 25oC was amplified by an EDFA with 20dB gain and externally modulated by a MZM. The electrical comb generator used to drive the MZM is triggered by an amplified microwave signal with power of 29 dBm. By operating the DC-bias level of the MZM at ~0.2 V , a dark optical-comb with average power and pulsewidth of 4.46 mW and ≤60 ps, respectively, can be obtained at the MZM output, as illustrated in Fig. 2. The dark optical-comb is backward injected into the SOAFL via an optical circulator, which then induces a gain-depletion modulation depth of nearly 100% under fine adjustment of the SOA driving current. The OBPF facilitates the mode-locking and avoids the lasing of the injected dark optical-comb in the SOAFL. The harmonic mode-locking of SOAFL is achieved when the repetition frequency of the injected dark optical-comb coincides with one harmonics of the longitudinal mode in the SOAFL. For wavelength tuning, the operating temperature of the SOA is setting at between 15oC and 35oC. This makes the gain peak of the SOA red-shifts from 1530 to 1560 nm. By setting the backward injection wavelengths at 1535 nm, 1549 nm, and 1565 nm, the optimized mode-locking of the SOAFL at wavelengths of 1530 nm, 1545 nm, and 1560 nm can be achieved, as shown in Fig. 3. At chirp compensating stage, the DCF lengths for the SOAFL at different wavelengths remain the same since the pulsewidth and linewidth of the SOAFL keep almost constant at all conditions. At nonlinear compressing stage, the estimated soliton order slightly changes from 7.8 to 8 as the central wavelength of the SOAFL red-shifts from 1530 to 1560 nm, however, the deviation in the optimized SMF length is within 10 cm. As a result, the nonlinear compressed pulsewidth and linewidth of the SOAFL are 190±10 fs and 13.7±0.1 nm, respectively. Note that a decreasing trend for the soliton pulsewidth at longer wavelengths is observed due to the slightly increased soliton order. Nevertheless, the TBP of the eighth-order SOAFL soliton at different wavelengths are controlled at 0.31~0.34.

E. Prof. Po-Tsung Lee

I. Fabrication

Two different epitaxial structures are employed in the fabrication process. One is the dielectric membrane structure and the other is the wafer-bonding structure. The membrane structure consists of a 220 nm dielectric slab suspended in air with a defect cavity defined by a two-dimensional triangular photonic crystal lattice etched through the membrane. The epitaxial layers shown in Figure 1 were deposited by metal-organic chemical vapor deposition (MOCVD). There are four 0.85% compressively strained InGaAsP quantum wells with 3 unstrained InGaAsP barriers layers. The photoluminescence spectrum of these quantum wells shows emission between 1420 and 1630 nm and is peaked at 1.55 μm at room temperature. After the epitaxial growth, an etch mask (1400-nm-thick silicon nitride) is deposited. Finally, a 3000-nm-thick 5% polymethylmethacrylate (PMMA) layer is deposited by spin coating.

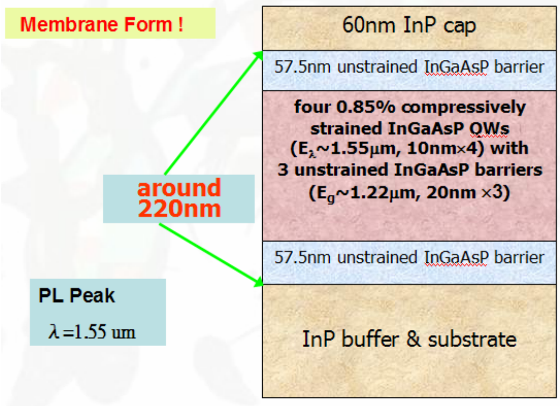


Figure 1: The dielectric membrane epitaxial structure grown by MOCVD.

The photonic crystal pattern is defined in the PMMA layer using electron beam lithography. We have written triangular lattice photonic crystals with lattice constants ranging from 460 to 560 nm and with r/a ratios varying from 0.31 to 0.40. Here, r is the hole radius and a is the lattice constant. A typical pattern after electron beam lithography is shown in Figure 2.

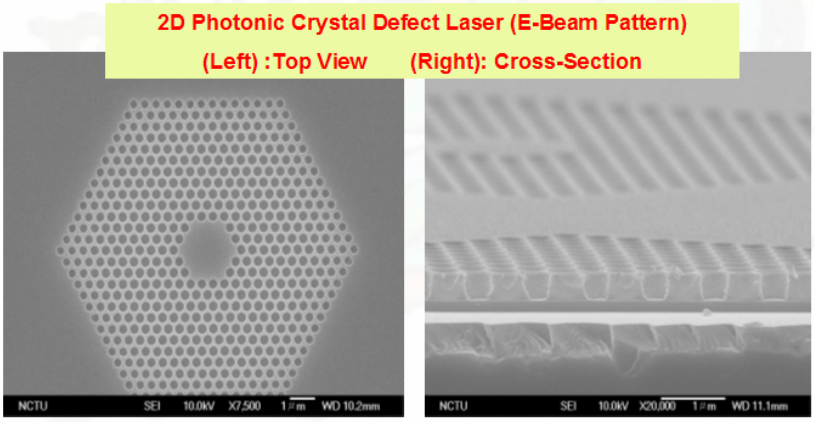


Figure 2: Two-dimensional photonic crystal pattern after electron beam lithography.

The epitaxial structure of the other sample for wafer bonding is similar to the membrane structure. The differences are that there are a 40 nm InGaAs etching stop layer and a 50 nm InP cap layer on top of the InP substrate.

To integrate the InGaAsP/InP dielectric membrane structure with the sapphire substrate, wafer-bonding technique is needed. We have developed a wafer bonding procedure which includes Photolithographic process and clean & bonding process. The purpose of the photolithographic process in wafer bonding is to create channels and prevent the appearance of rainbow and bubbles after bonding. The pictures of samples without channels and with channels after bonding were shown in Figure 3.

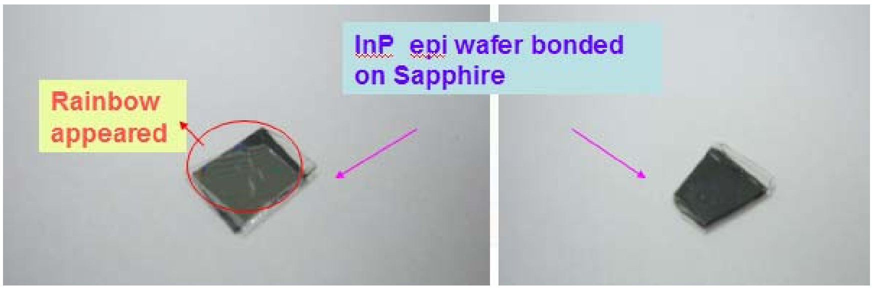


Figure 3 (a): Samples without channels after wafer-bonding.

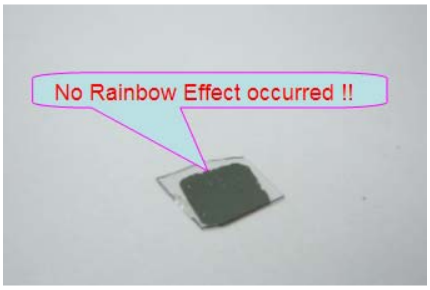
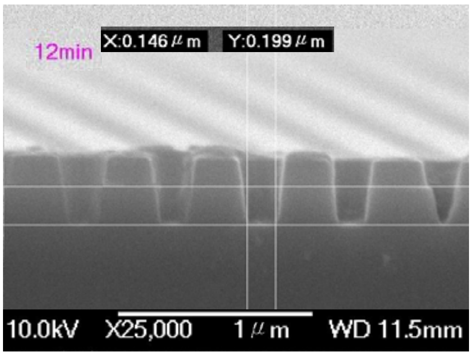


Figure 3 (b): Sample with channels after wafer-bonding.



After the successful development of electron beam lithography and wafer bonding techniques, we have integrated our epi wafer with the sapphire substrate and defined the photonic crystal defect cavity patterns. Next is to develop recipes to transfer these patterns in the mask layer and then into the epi layers. We used reactive ion etch (RIE) for silicon nitride etch and high density plasma etch (HDP) for InGaAsP/InP etch (with the help of Prof. Chen at NCU). The results are shown in Figure 4. We have established a complete fabrication process for photonic crystal patterns with nanometer-scale feature sizes.

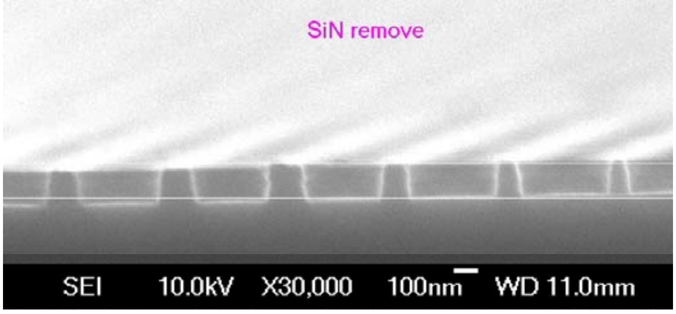


Figure 4: (left) cross-sectional SEM picture after silicon nitride etch. (right) cross-sectional SEM picture after transferring patterns into epi layers using HDP.

II. Measurement Results

In order to measure the characteristics of 2D photonic crystal lasers, we setup a micro-PL system shown in Fig. 1. In this system, a 50x long working distance NIR objective lens mounted on a 3-axis stage focuses the pump beam to a spot size about 3.5μm in diameter. It also collects the output light from the top of the sample. We use a collective lens to focus the signal into the slit of our spectrum analyzer, TRIAX-320, with 0.06nm resolution.

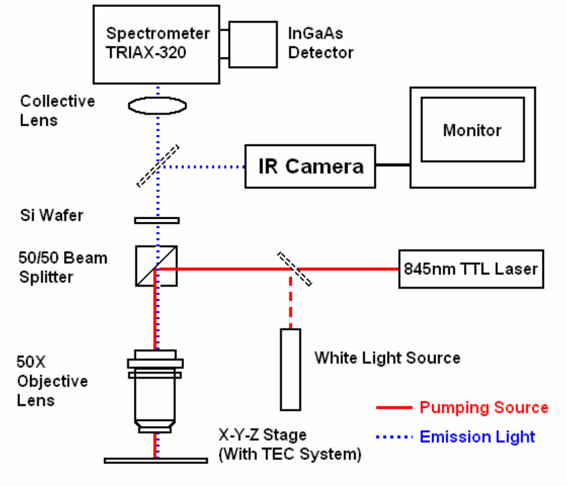
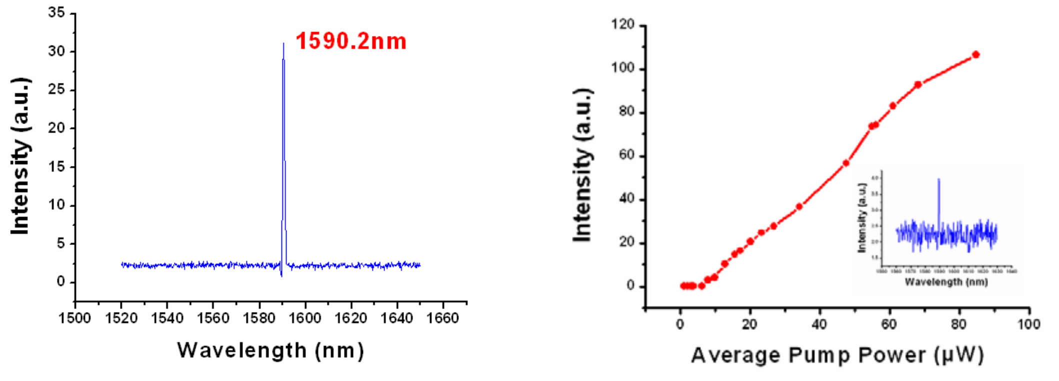


Fig. 1. The schematic illustration of the micro-PL system.

A typical lasing spectrum is shown in Fig. 2 (a). The lasing wavelength is 1590.2nm and FWHM is about 0.33nm. The SMSR is more than 19dB above threshold. The L-L curve pumped with 2% duty cycle and 0.5MHz repetition rate is shown in Fig. 2 (b). The average threshold pump power is about 6.4µW. All measurements so far are done at room temperature.



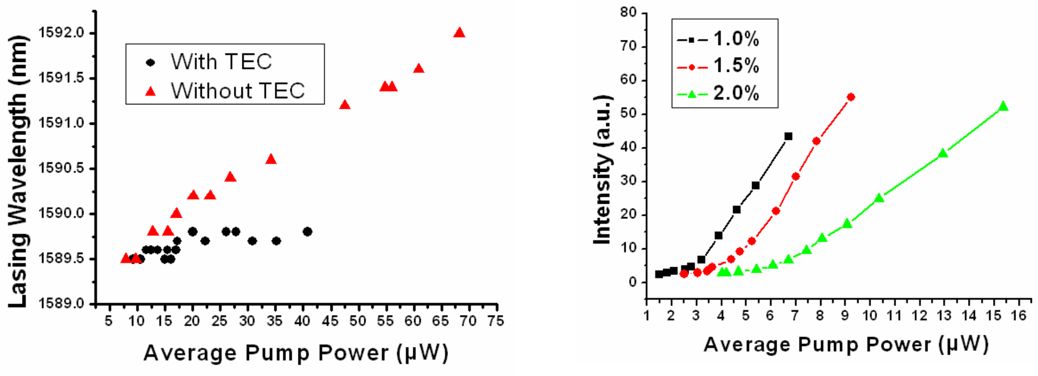
(a) (b)

Fig. 2. (a) The PL spectrum of a 2D photonic crystal laser pumped with 2% duty cycle at 0.5MHz repetition rate. The lasing wavelength is 1590.2nm. (b) The corresponding L-L curve. The threshold pump power is about 6.4µW. The inset is the PL spectrum near threshold.

The plot of lasing wavelength variation versus different pump power is shown in Fig. 3 (a). The red shift of lasing wavelength is approximately linear proportional to the pump power. The rate of red shift is about 0.043nm/µW. In order to improve the variation of lasing wavelength, we put the sample on a copper that is mounted on a TE cooler to stabilize the substrate temperature at room temperature. In this TEC system, a 10kΩ thermistor with ±0.01°C accuracy is used to monitor the temperature of the sample. We observe the significant improvement of the red shift effect, which is also shown in Fig. 3 (a). The variation of lasing wavelength due to pump power increasing can be controlled to within 0.3nm.

Threshold dependence on substrate temperatures of the photonic crystal laser is also investigated. The substrate temperature is fixed at different values using the TEC system. The threshold pump powers for substrate temperatures of 24°C, 30°C, 36°C, and 42°C are 6.8μW, 10.3μW, 14.8μW, and 20.2μW with 1.5% duty cycle and 0.5MHz repetition rate. It is obvious that the threshold of the laser cavity increases with the substrate temperature. The red shift rate of lasing wavelength caused by increasing substrate temperature is 0.067nm/K.

We also investigate threshold dependence on different pumping conditions. We turn off the TEC system and change the condition of our pumping source for three different duty cycles, 1%, 1.5%, and 2%. With these three conditions, we obtain three corresponding L-L curves shown in Fig. 3 (b). An ultra-low threshold power about 3.4μW is measured with 1% duty cycle pumping condition. The threshold pump powers for 1.5% and 2% duty cycles are 4.3μW and 6.1μW, respectively.



(a) (b)

Fig. 3. (a) The red shift of lasing wavelength is about 2.6nm when the average pump power increases 60μW. The variation of lasing wavelength is improved to within 0.3nm when a TEC system is used. (b) There is strong dependence of threshold pump power on the duty cycle of pump power. The threshold pump powers for 1%, 1.5%, and 2% duty cycles are 3.4μW, 4.3μW, and 6.1μW, respectively.

The lasing wavelength and threshold pump power both depend on the thermal effects caused by different pumping conditions and substrate temperatures. These thermal effects are significant due to poor heat dissipation of air. It can be improved by using a low-index substrate with higher thermal conductivity as the heat sink.

4. A SUMMARY OF THE POST-PROJECT PLAN （IF THERE ARE ANY PLAN OR BUDGET ADJUSTMENT FOR FY 2006, PLEASE PROVIDE DETAILED DESCRIPTION AND ASSOCIATION WITH THE PROJECT IN APPENDIX I）

NEXT GENERATION OPTICAL COMMUNICATION TECHNOLOGIES

(I) Coherent and THz Photonics

For system applications, we will attempt to demonstrate transmission of video signals through the THz communication link. For this purpose, we continue to improve the characteristics of the THz emitter in the following categories:

(1) Compactness;
(2) Radiation Power;
(3) System efficiency;
(4) Wavelength tunability
(5) Radiation direction controllability.

In additional to the THz emitter, various THz quasi-optic components e.g., phase shifters, filters, phase gratings, and so on with liquid crystal and photonic crystals enabled functionalities. For the design and optimization of these THz components, existing THz instrumentation will be used to investigate the optical and optoelectronic properties of the required material and devices. We also expect to make progress on high-power harmonic mode-locked fiber laser for highly efficient fiber-based THz system at 1550 nm.

(II) Quantum (Photonic Crystal) structures and Enabling devices

(1) Design and optimize the defect cavity structure to obtain high quality factor and small mode volume.
(2) Integrate the fabrication technology of 2D photonic crystals and the wafer bonding technique of InGaAsP wafer and sapphire substrate developed in the previous year to fabricate various defect cavity structures.
(3) Measure the characteristics of these laser cavities and achieve CW-operation.
(4) Growth of nitride based UV-material and device
(5) Laser lift-off technique applied on nitride based UV-material
(6) Development process of nitride based LEDs and Lasers
(7) Study of optical properties of nano-rod nitride based LED/ surface emitting laser
(8) Process development of electrical-pump nano-LEDs
(9) Development of nitride based single-emitter
(10) Development of laser action in GaN vertical micro-cavity under optical pumping at room temperature
(11) Development of high reflectivity and crack-free AlN/GaN DBR
(12) Process development of electric pumping of LW-VCSEL
(13) Development of Long wavelength photonic crystal VCSEL
(14) Development of singlemode Quantum-Dot VCSEL in 1.3 um with Side-mode

Suppression Ratio over 30dB

(15) Development of 1.3 μm Quantum Dot Vertical Cavity Surface Emitting Laser with External Light Injection

(16) Development of Singlemode InAs quantum dot photonic crystal VCSELs

(III) Photorefractive Materials and Enabling devices

By combining the theoretical and experimental results achieved in the first two years, we hope to develop a model of the physics of the recording mechanism and optimize our holographic materials. The results can provide the guidelines for designing new materials. In addition, we plan to explore the novel applications of optical spectral filters for bio-medical sensing, 3-D optical interconnections, and dynamic information processing.

5. INTERNATIONAL COOPERATION ACTIVITIES (OPTIONAL)

Our research group has been collaborating with Professor Yamamoto of Stanford University during past several years, and will collaborate on the microcavity QD GaN-based VCSEL device development and controlled photon emission experiment. We believe a room temperature operating GaN-based mesoscopic GaN quantum confined structures with controllable photon emission can be realized under this project.

Prof. S. C. Wang visited TIT Prof. K. Iga for collaboration of GaN materials
Prof. C.L. Lin form CUHK (Hong Kong) visit us for discussion on QDs Laser
Prof. S. L. Chuang from UIUC for QD VCSEL slow light
Prof. M. Feng from UIUC for LW – Photo detector and Transistor Laser
Prof. Connie Chang from UC Berkley – injection locking on VCSEL
Prof. H.C. Kuo visited Hong Kong University of Science and Technology for collaboration of GaN nanotechnology

Prof. S.C. Wang, H.C. Kuo and T. C. Lu visited Professor Yamamoto of Stanford Jan. 2006 during Photonics West 2006 (San Jose) to discuss collaboration of GaN based nanostructures in high Q micro-cavity.

III. STATISTICS on Research Outcomes of this Project (Form 3)

[1] Indicate the number of items that are significant. The criterion for “significant” is defined by the PIs of the program. For example, it may refer to Top journals (i.e., those with impact factors in the upper 15%) in the area of research, or conferences that are very selective in accepting submitted papers (i.e., at an acceptance rate no greater than 30%). Please specify the criteria in Appendix IV.

[2] Indicate the number of citations. The criterion for “citations” refers to citations by other research teams, i.e., exclude self-citations.

[3] Refers to the workshop and conferences hosted by the program.

[4] Includes Laureate of Nobel Prize, Member of Academia Sinica or equivalent, fellow of major international academic societies, etc.

[5] Refers to industry standards approved by national or international standardization parties that are proposed by PIs of the program.

[6] Refers to research outcomes used to provide technological services, including research and educational programs, to other ministries of the government or professional societies.

Listing		Total	Domestic/ International	Significant[1]	Citations[2]	Technology Transfer
Published Articles	Journals		**D: 4**			
			I: 107	55	**29**	
	Conferences		**D: 73**			
			I: 102	**I: 30**		
	Book Chapters		**1**			
Patents	Pending		**D: 4**	**-**		
			I: 5			
	Granted		**D: 6**	**-**		
			I:			
Copyrighted Inventions	Item					
Workshops/ Conferences[3]	Item		**D:**			
			I:			
	Participants		**D:**			
			I:			
Training Courses（Workshops/ Conferences）	Hours					
	Participants					
Personal Achievements	Honors/ Awards[4]		**D:**			
			I:			
	Keynotes Given by PIs		**D:**			
			I: 1			
	Editor for Journals		**D:**			
			I: 2			
Technology Transfers	Item		**3**			
	Licensing Fee		**1,000,000+**			
	Royalty					
Industry Standards[5]	Item					
Technological Services[6]	Item			**-**	**-**	**-**
	Service Fee			**-**	**-**	**-**

IV. LIST OF WORKS, EXPENDITURES, MANPOWER, AND MATCHING SUPPORTS FROM THE PARTICIPATING INSTITUTES (FORM 4)

Serial No.: Sub-Project 1	Program Title: Fundamental Studies on Photonic Science and Technology for the Tera Era 兆位元時代光電科技之基礎研究

Research Item (Include sub projects)	Major tasks and objectives	Expenditures (in NT$1,000)					Manpower (person-month)					Matching Supports from the Institutes (in English & Chinese)
		Salary	Seminar/ Conference-related expenses	Project-related expenses	Cost for Hardware & Software	Total	Principal Investigators	Consultants	Research/ Teaching Personnel	Supporting Staff	Total	
Fundamental Studies on Photonic Science and Technology for the Tera Era	Ultrafast Lasers in Nanotechnology	296.2	88	310	50	744.2	5		3	7	15	
	TFT device fabrication; Er:Si ablation install	294	87.1	312	60	753.1	4		5	8	17	
	THz spectroscopy, imaging and communication	298	89	311.17	55	753.17	2		6	12	20	
	All-fiber-based E-O sampler	293	87	311	60	751	2		5	12	19	
	OPA-FROG establishment	297	87	309	55	748	3		5	10	18	
	GaN quantum dots	298	89	311	55	753	2			12	14	
	InAs QDs and InGaAsN nanostructure for LW-VCSEL	296.43	87	313	50	746.43	1			11	12	
	Nanocrystallite Si based material growing	295	88.11	312	55	750.11	1			9	10	
	1.55 um InGaAsP photonic crystal laser	299	88	312	55	754	2			12	14	
	multilevel photo-refractivity of doped photopolymer, BTO &BGO	296.205	88	312	55	751.205	2			12	14	
										12	12	
SUM		2962.835	878.21	3113.17	550	7504.215	24		24	117	165	

V. APPENDIX I

DESCRIPTION OF BUDGET AND PROJECT ADJUSTMENTS FOR FY 2006

NONE.

VI. APPENDIX II

1. PUBLICATION LIST (CONFERENCES, JOURNALS, BOOKS, BOOK CHAPTERS, etc.）

[International Journals]

A. Coherent and THz Photonics

1. Chun-Jung Lin, Y.-L. Chueh, L.-J. Chou, C.-W. Chang, E. W. G. Diau, H.-C. Kuo, and G.-R. Lin, "Countinuous-Wave and Time-Resolved Photoluminescence Analysis of Silicon Nanocrystals Formed by Thermal Annealing of Amorphous Silicon Oxides at Different Times", *Japanese Journal of Applied Physics*, Vol. 45, No. 2A, pp. 1040-1043, Feb 2006
2. Chun-Jung Lin, Chao-Kuei Lee, Eric Wei-Guang Diau, and Gong-Ru Lina, "Time-resolved Photoluminescence Analysis of Multidose Si-ion-implanted SiO_2", *Journal of Electrochemistry Society*, Vol. 153, pp. E25-E32, January 2006, selected by the Virtual Journal of Ultrafast Sciences, Vol. 5, No. 1, January 2006.
3. Chun-Jung Lin, Gong-Ru Lin, Yu-Lun Chueh, and Li-Jen Chou, "Analysis of Silicon Nanocrystals in Silicon-rich SiO_2 Synthesized by CO_2 Laser Annealing", *Electrochemical and Solid-State Letters*, Vol. 8, No. 12, pp. D43-D45, December 2005
4. Tze-An Liu, Gong-Ru Lin, Yung-Cheng Chang, Ci-Ling Pan, "A wireless audio and burst communication link with directly modulated THz photoconductive antenna," Optics Express, Vol. 13, No. 25, pp. 10416-10423, 12 December, 2005.
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9. Chao-Kuei Lee, Tze-An Liu, Kai-Fung Huang and Ci-Ling Pan, "Frequency Resolved Optical Gating Studies of Strained Saturable Bragg Reflector: Anomalous dispersion near Resonance Absorption of the Exciton Resonance," Jpn. J. Appl. Phys., Vol. 44, No. 9A, pp. 6553-6557, September 2005
10. Yung-Cheng Chang and Gong-Ru Lin, "Optically gain-switched laser diode based 10Gbit/s all-optical data format converter", *Optics Letters*, Vol. 30, No. 16, pp. 2704-2706, 15 August 2005.
11. Jin-Wei Shi, H.-C. Hsu, F.-H. Huang, W.-S. Liu, J.-I. Chyi, Ja-Yu Lu, C.-K. Sun, and Ci-Ling Pan, "Separated-Transport-Recombination p-i-n Photodiode for High-Speed and High-Power Performance," IEEE Photon. Technol. Lett., Vol. 17, No. 8, pp. 1722-1724, August 2005.
12. Tze-An Liu, Gong-Ru Lin, Yen-Chi Lee, Shing-Chung Wang, Masahiko Tani, Hsiao-Hua Wu, and Ci-Ling Pan, "Dark Current and Trailing Edge Suppression in Ultrafast Photoconductive Switches and THz Spiral Antennas Fabricated on Multi-Energy Arsenic-Ion-Implanted GaAs", *Journal of Applied Physics*, Vol. 98, No. 1, pp. 013711, July 2005, selected article in *Virtual Journal of Ultrafast Science*, Vol. 4, No. 8, August 2005

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15. Gong-Ru Lin, Yung-Cheng Chang, Yu-Huang Lin, and J. H. Chen, "All Optical Data Format Conversion in Synchronously Modulated Single-Mode Fabry-Perot Laser Diode Using External Injection-Locking Induced Nonlinear Threshold Reduction Effect", *IEEE Photonics Technology Letters*, Vol. 17, No. 6, pp. 1307-1309, June 2005.
16. Ming C. Chen, Jung Y. Huang, Qiantso Yang, C. L. Pan, and Jen-Inn Chyi, "Freezing phase scheme for fast adaptive control and its application to characterization of femtosecond coherent optical pulses reflected from semiconductor saturable absorber mirrors," Journal of The Optical Society Of America B, Vol. 22, No. 5, pp. 1134-1142, May 2005, selected by the Virtual Journal of Ultrafast Science, Vol. 4, No. 6, June 2005.
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21. Bor-Yuan Shew, Han-Chieh Li, Ci-Ling Pan and Cheng-Hao Ko, " X-ray micromachining SU-8 resist for a terahertz photonic filter," Journal Of Physics D-Applied Physics Vol. 38, No. 7, pp. 1097-1103, Apr 7 2005
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23. Gong-Ru Lin and Yu-Sheng Liao, "Sensitivity evaluation of fiber optic OC-48 p-i-n transimpedance amplifier receivers using sweep-frequency modulation and intermixing diagnostics", *Optical Engineering*, Vol. 44, pp. 044002, April 2005.
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23. Gong-Ru Lin, “Retrospect on the Research of Silicon Nanocrystal Embedded Silicon Oxide Materials and Light-Emitting Devices in NCTU/IEO”, *3rd Symposium on Nanophotonics Science and Technology*, Hwalian, Taiwan, September 13-17, 2005.
24. Cheng Lo(羅誠), Cho-Fan Hsieh, Ru-Pin Pan and Ci-Ling Pan, “Effects of Hole Material on Enhanced Terahertz Transmission through Metallic Hole Arrays”, C-FR-V 1-2, presented at OPT2005 (Optics and Photonics Taiwan), Dec. 9-10, 2005, Tainan, Taiwan.
25. Ching-Wei Chen (陳晉瑋), Wen-Jr Jiang and Ci-Ling Pan, “Phase Retrieval Of Ultrafast Optical Pulses From Interferometric Autocorrelation Measurement By Population-Split Genetic Algorithm (PSGA)”, C-FR-V2-7, presented at OPT2005 (Optics and Photonics Taiwan), Dec. 9-10, 2005, Tainan, Taiwan.(2005年光電科技研討會學生論文獎).
26. Tzung-Han Wu(吳宗翰), Chin-Rung Chung, Chao-Kuei Lee and Ci-Ling Pan, “Enhancement of Tera-Hertz Radiation by modulation of carrier dynamics with optical pulses in photoconductive antennas”, C-FR-V2-8, presented at OPT2005 (Optics and Photonics Taiwan), Dec. 9-10, 2005, Tainan, Taiwan.
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35. Tze-An Liu(劉子安) , Sheng-Lung Wu, Ci-Ling Pan, “Burn-Depth Detection Of Pork With T-Ray Technology,” PF-FR2-30, presented at OPT2005 (Optics and Photonics Taiwan), Dec. 9-10, 2005, Tainan, Taiwan.
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B. Quantum (Photonic Crystal) structures and Enabling devices

1. M. Y. Tsaia(蔡敏瑛), M. Youa (游敏), T. C. Wangb(王德宗) H. C. Kuoa (郭浩中)* and S. C. Wanga (王興宗), “Optical properties of ultra-high-density InGaN quantum dots grown by metalorganic chemical vapor deposition” 物理年會2005.
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13. H. H. Yao, G. S. Huang, T. C. Lu, C. Y. Chen, W. D. Liang, H. C. Kuo and S. C. Wang*"Study The Effect of Self-Assembled INGaN/GaN Quantum Dots with Various Interruption Time" , OPT, Dec. 2005
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15. Chuan-Yu Luo, Yi-An Chang, Hao-Chung Kuo, Yen-Kuang Kuo, Shing-Chung Wang "Simulation of InGaN quantum well laser performance using quaternary InAlGaN alloy as electronic blocking layer" Optics and Photonics Taiwan 2004
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17. Y.C. Peng (彭裕鈞), C.C. Kao (高志強), J.Y.Tsai (蔡睿彥), C.F.Lin (林佳峰), H.C.Kuo (郭浩中) and S. C. Wang (王興宗)" Fabrication and characteristics of InGaN/GaN vertical cavity light emitting diodes" Optics and Photonics Taiwan 2004
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19. Min-Ying Tsai(蔡敏瑛), Min You(游敏), Te Chung Wang(王德宗) H.C. Kuo(郭浩中) and S. C. Wang(王興宗)" OPTICAL PROPERTIES OF ULTRA-HIGH-DENSITY INGAN QUANTUM DOTS GROWN BY METALORGANIC CHEMICAL VAPOR DEPOSITION" Optics and Photonics Taiwan 2004
20. Y. T. Wang(王薏婷), H. H. Yao(姚忻宏), Y. S. Chang(張亞銜), T. H. Hseuh(薛道鴻), H. C. Kuo(郭浩中) and S. C. Wang(王興宗)" Optical Characteristics of of GaN Quantum Dots Grown on AlN Nanoholes by Metal-organic Chemical Vapor Deposition" Optics and Photonics Taiwan 2004, PA-SA1-02.
21. C. P. Chu, M. Y. Tsai1, H. C. Kuo, Fang-I Lai1, Y. H. Chang1, S. Y. Kuo1, S.C. Wang, N. Tansu, Jeng-Ya Yeh and Luke J. Mawst" TEMPERATURE DEPENDENT PHOTOLUMINESCENCE OF HIGHLY STRAINED InGaAsN/GaAs QUANTUM WELL (λ=1.28-1.45µm) WITH GaAsP STRAIN-COMPENSATED LAYER" Optics and Photonics Taiwan 2004
22. Y.C. Lin (林永昌), A.T. Cho (卓恩宗) , Y.F. Lai (賴一凡) ,J.M. Shieh (謝嘉民), H.C. Kuo (郭浩中), S. C. Wang (王興宗)" Silicon Quantum-dots-embedded Mesoporous Nanoscale Silica as the new type high efficient Photonic Emitters" Optics and Photonics Taiwan 2004.
23. Hung-Wen Huang, Chih-Chiang Kao, Ya-Hsien Chang,Tao-Hung Hsueh Miaochia Ou-Yang1, Hao-Chung Kuo1 and Shing-Chung Wang, "FABRICATION OF INGAN MULTI-QUANTUM-WELL NANOROD BY NI NANO-MASK," Optics and Photonics Taiwan 2004. (獲得2004OPT論文獎)
24. Chih-Chiang Kao(高志強), Y. C. Peng(彭裕鈞), H. W. Huang(黃泓文),J. T. Chu(朱榮堂), C. C. Yu(余長治), C. F. Lin(林佳鋒), H. C. Kuo (郭浩中), and S. C. Wang(王興宗), "The Effect of ~22o Undercut Side wall on the performance of the GaN-Based Light-Emitting Diode", Optics and Photonics Taiwan 2004.

25. T. H. Hsueh, H. C. Kuo, Y. S. Chang, H. W. Huang, M. C. Ou-yang, C. W. Chang, and S. C. Wang, "Optical and structural properties of In0.3Ga0.7N nanowires", pp-65物理年會 2004
26. S.-C. Wei, P.-T. Lee, and T.-Y. Chang, “Fabrication and Characterization of Organic Thin Film Transistors,” TDC, A037 01_023, Taiwan (2004).
27. Z.-W. Lu and P.-T. Lee, “Thermal Characteristics of Two-Dimensional Photonic Crystal Lasers,” OPT'04, B3N, Taiwan (2004).
28. Po-Tsung Lee, Hsiao-Wen Zan, Shih-Chiang Wei, Cheng-Chung Lee, Jia-Chong Ho, and Tang-Hsiang Hu, “Thermal Behavior and Self-Heating Effect in Pentacene-Based Thin Film Transistors,” International Display and Manufacturing Conference (IDMC), Wed-12-05, Taiwan (2005).
29. Kuo-His Ten, Hsiao Wen Zan, C. P. Ko, P. K. Liu, T. Y. Chang, K. H. Su, C. S. Wei, P. T. Lee, Ch. H. Chen, C. M. Yeh, and Jennchang Hwang, “Organic thin-film transistors with AlN film as a gate-insulator by RF/ICP Sputtering,” EuroDisplay 2005 Oral Presentation.
30. F. M. Tasi, P. T. Lee, and T. C. Lu, “Fabrication and characterization of two-dimensional quasi-periodic photonic crystal lasers”OPT’05, A-FR-I-1-1, Taiwan (2005)

C. Volume Holographic Materials, Technology, and Enabling Devices

1. 方建舜、林俊華、許根玉、林烜輝、莊漢聲、楊正財, "全像式微流檢測", Paper D-SA-VI 2-2, Optics and Photonics Taiwan '04, JungLi, Taiwan, Dec. 18-19, 2004.
2. 林俊華、蕭義男、林烜輝、許根玉, "新穎摻雜PQ之共基底體積全像高分子的製備研究", Paper D-SA-VI 2-3, Optics and Photonics Taiwan '04, JungLi, Taiwan, Dec. 18-19, 2004.
3. 林俊華、蕭義男、林烜輝、許根玉, "9,10-Phenanthrenequinone摻雜共基底感光高分子的體積全像特性研究", Paper PD-FR1-22, Optics and Photonics Taiwan '05, Tainan, Taiwan, Dec. 9-10, 2005.
4. 陳柏霖、蕭義男、林俊華、林烜輝、許根玉, "以PQ衍生物為光敏感劑的感光全像高分子材料製備與特性研究", Paper D-FR-VI 2-6, Optics and Photonics Taiwan '05, Tainan, Taiwan, Dec. 9-10, 2005.
5. 林俊華、蕭義男、林烜輝、許根玉, "摻雜ZnMA 與PQ分子之PMMA的感光高分子塊材的製作與其全像記錄的特性量測", Paper D-SA-VI 4-5, Optics and Photonics Taiwan '05, Tainan, Taiwan, Dec. 9-10, 2005

[Book chapter]

1. J. D. O'Brien, W. Kuang, P. T. Lee, J. R. Cao, W. Kim, and C. Kim, “Photonic Crystal Lasers,” in Encyclopedia of Nanoscience and Nanotechnology edited by H. S. Nalwa, American Scientific Publishers, California, Vol. 8, pp. 617-628 (2004).

2. PATENT LIST

A. Coherent and THz Photonics

1. Ci-Ling Pan 潘犀靈, Ru-Pin Chao 趙如蘋, and Chao-Yuan Chen 陳昭遠 “利用磁場控制液晶雙折射現象之可調兆赫波相移器或相位延遲器 Terahertz Phase Shifter or Retarder Based on Magnetically Controlled Birefringence in Liquid Crystals,” ROC patent, no. 200186, granted on April 11, 2004; US patents filed on November 12, 2003, No. 10-706,097.
2. Ci-Ling Pan 潘犀靈, Ru-Pin Chao 趙如蘋, and Yu-Ping Lan 藍玉屏, “具數位及無跳模連續微調波長機制之多波長外腔雷射系統 A multi-wavelength external-cavity laser with digital and mode-hop-free fine tuning mechanism,” ROC patent, no. I223484, granted November 1, 2004; US patents filed on Nov. 16, 2003, No. 10-738,893.
3. Ci-Ling Pan 潘犀靈, Jin-Yuen Zhang 張景園, Jung Y. Huang 黃中垚, and Chao-Kuei Lee 李晁逵, “波長可調

之藍光飛秒非共線式光參數放大器 A blue-light generating Femtosecond wavelength-tunable Non-collinear Optical Parametric Amplifier," ROC Patent, No. I239128, granted September 1, 2005; US patents filed on August 24, 2004, No. 10-926,654.

4. Ci-Ling Pan 潘犀靈, Ru-Pin Chao 趙如蘋, Min-Jay Huang 黃銘杰 and Yu-Ping Lan 藍玉屏, "具多種功能之電控液晶式可調光多工器及光解多工器 Multi-functional electrically controlled Liquid crystal based tunable optical multiplexer and demultiplexer," ROC patent filed on Feb. 2, 2005 No. 94103162.
5. Ci-Ling Pan 潘犀靈、Yi-Chao Wang 王怡超、Jia-Min Hsieh 謝嘉民、Zun-Hao Chen 陳尊豪、Bau-Tung Dai 戴寶通, "近紅外波段飛秒雷射在非晶矽退火的應用方法, Near-infrared femtosecond laser-induced crystallization of amorphous silicon," ROC patent, No. I245321, granted December 11, 2005.
6. Teh-Ho Tao 陶德和, Tze-An Liu 劉子安, Zu-sho Chow 周儒修, Sheng-Lung Wu 吳勝隆, Ci-Ling Pan 潘犀靈, "皮膚灼傷檢測系統 System for Detecting the Burned Degree of a Skin" ROC patent filed, March 23, 2005, No. 0094108924, US patent filed on October 26, 2005, No. 11/258086.
7. Ru-Pin Chao 趙如蘋, Ci-Ling Pan 潘犀靈, and Chao-Yuan Chen 陳昭遠, "利用液晶雙折射現象之可調兆赫波濾鏡或波長選擇器," Patent claim filed with the NCTU Patent Office, March 10, 2006.
8. 林恭如, "發明自耦同步調制技術以量測光接收機之等效靈敏度與誤碼率, " 中華明國專利, 專利公號:I 2 2 6 7 6 2

B. Novel Semiconductor Quantum Structures and Devices

1. S. C. Wang(王興宗), H. C. Kuo (郭浩中),G. S. Huang(黃根生)" 利用氮化鋁/氮化鎵超晶格成長無裂縫氮化鋁/氮化鎵的多層膜反射鏡"

3. INVENTION LIST

4. LIST OF WORKSHOPS/CONFERENCES HOSTED BY THE PROJECT

Prof. Ci-Ling Pan

1. Journal through Nanotechnology and Photonics, a workshop designed to provide an overview for high school students, Dec. 13, 2004, NCTU, Hsinchu, Taiwan.
2. Advanced Light Emitting Devices and Lasers, a workshop in honor of Prof. S. C. Wang, March 4, 2005.

5. LIST OF PERSONAL ACHIEVEMENTS OF THE PIS

I. Faculty awards and recognitions:

Prof. Ci-Ling Pan 潘犀靈

1. 2004 OSA Fellows;
2. 2004 SPIE Fellow;
3. 2004 Engineering Medal 工程獎章 of the ROCOES 中華民國光學工程學會;
4. 2004 Outstanding Scholar Award of the Ministry of Education 教育部第 48 屆學術獎;
5. 2005 PSROC Fellow 中華民國物理學會會士;

Prof. Ken Y. Hsu 許根玉

2004 OSA Fellow

Prof. Gong-Ru Lin, 林恭如

1. 2005 NCTU Young Scholar Research Award 交大年輕學者研究獎
2. 2005 Senior Member of IEEE

II. Student awards and recognitions:

1. Kuen-Chie Yo, Yung-Cheng Chang, and Gong-Ru Lin, “An OC-48 transmission based on a mutual injection-locked Fabry-Perot laser diode and Erbium doped fiber amplifier link”, Optics Express, submitted, July 2005. (游昆潔榮獲九十三年度國科會大專學生參與專題研究計畫研究創作獎).
2. Yung-Cheng Chang, Yu-Huang Lin, J. H. Chen, and Gong-Ru Lin, “All-optical NRZ-to-PRZ format transformer with an injection-locked Fabry-Perot laser diode at unlasing condition”, Optics Express, Vol. 12, No. 19, pp. 4449-4456, September 2004. (張詠誠榮獲財團法人徐有庠基金會第三屆通信光電類科技論文獎).
3. 林鈺晃，2004 中華民國光學工程學會碩士論文獎.
4. 林鈺晃，2004 中國電機工程師學會青年論文獎.
5. 葉建宏，2004 中華民國光學工程學會博士學生論文獎.
6. 彭朋群，Best student paper award in OPT 2004.
7. Sheng-Lung Wu (吳勝隆), Tze-An Liu, Zu-sho Chow, Jia-Huey Tsao, Teh-Ho Tao, and Ci-Ling Pan, “Burn-Depth Detection Of Pork With T-Ray Technology,” PF-SA2-02, presented at OPT2004, , Dec.18-19, 2004, Taipei, Taiwan, (2004 年台灣光電科技研討會壁報論文獎).
8. Ching-Wei Chen (陳晉瑋), Wen-Jr JIANG and Ci-Ling Pan, “Phase Retrieval Of Ultrafast Optical Pulses From Interferometric Autocorrelation Measurement By Population-Split Genetic Algorithm (PSGA)”, C-FR-V2-7, presented at OPT2005 (Optics and Photonics Taiwan), Dec. 9-10, 2005, Tainan, Taiwan.(2005 年光電科技研討會學生論文獎).
9. Ching-Wei Chen(陳晉瑋), Yu-Kuei Hsu, J. Y. Huang, C. S. Chang, Ci-Ling Pan, Jing-Yuan Zhang,“Intense picosecond infrared pulses tunable from 2.4 m to 38 m for nonlinear optics applications”, paper # CFI3-1, IQEC/CLEO-PR 2005, Tokyo, Japan, July 11-15, 2005 (Student Travel Support Award).
10. Chao-Kuei Lee (李晁逵) , J. Y. Huang, Ci-Ling Pan, and Jing-Yung Zhang, “Novel Method for Generation of Tunable UV/Blue Femtosecond Pulses,” presented at the 2005 Advanced Solid-State Photonics Meeting, paper WB24, Vienna, Austria, Feb. 6-9, 2005, proceeding paper to be published in ASSP2005 TOPS vol. 98, Optical Society of America (young scientist traveling support Award).
11. Chao-Yuan Chen 陳昭遠, Recipient of The 2005 Bor-Uei Chen Memorial Scholarship Award of the Photonic Society of Chinese Americans (PSC，華人光電學會). This is the first time a Ph.D. student from outside of U.S. has been awarded this prestigious award.

III. International Invited Papers and Presentations (APRIL 2004-FEBRUARY 2006)

1. Ci-Ling Pan, “NCTU Photonics Programs: an Overview,” invited talk, presented at the 2005 NRC-IME-ITRI Trilateral Photonics Workshop, Ottawa, Canada, Sept. 27-29, 2004.
2. Ci-Ling Pan, Ru-Pin Pan, Chao-Yuan Chen, T. R. Tsai, C. H. Wang, Cho-Fan Hsieh, “Liquid Crystal THz Optics,” invited talk, presented at the Croucher Advanced Study Institute on “Frontiers of Photonics Research: Nanophotonics, Femtosecond Photonics and Biophotonics,” Hong Kong, December 6-10, 2004.
3. Ci-Ling Pan, “Ultra-broadband THz field detection by Ion-implanted III-V PC Antenna,” invited talk, presented at the Photonics West 2005, San Jose, California, USA, Jan. 22-27, 2005.
4. Ci-Ling Pan, “An Overview of THz Research Activities in Taiwan,” invited talk, presented at the Photonics West 2005, San Jose, California, USA, Jan. 22-27, 2005.
5. Ci-Ling Pan, “Progress in Liquid Crystal THz Optics,” keynote speech, presented at Workshop On Global Perspectives In Frontiers Of Photonics: Computational Imaging, Biophotonics And Nanophotonics,” Durham, North Carolina, USA, May 18-19, 2005.
6. Ci-Ling Pan, “Recent Progress in Liquid Crystal THz Optics,” invited paper, presented at "Frontiers of Laser and Optical Sciences", October 1 - 2, 2005, Faculty of Science, Hongo Campus, The University of Tokyo, Tokyo, Japan.
7. Ci-Lin Pan and Ru-Pin Pan, “Recent progress in liquid crystal THz optics,” invited talk, presented at Photonics West 2006, San Jose, California, USA, Jan. 21-26, 2006, invited paper to be published in Proceedings of SPIE Vol. #6135, Liquid Crystal Materials, Devices, And Applications XI, Liang-Chy Chien, ed..
8. Po-Tsung Lee "Next-Generation Nano-Photonics Workshop" Invited Speaker, Korea (2005)

9. Ken Y. Hsu, Shiuan Huei Lin, and Vera Marinova, “Dynamic Intensity, polarization,and phase holograms,” Paper 14B1-1(Invited), ICO’04 International Conference Optics & Photonics in Technology Frontier, Tokyo, Japan, 12-15 July, 2004.
10. Yi-Nan Hsiao, Wha Tzong Whang, Shiuan Huei Lin, and Ken Y. Hsu, “Holographic characteristics of organo-metallic compound doped PQ:PMMA photopolymers,” Paper 5560-05 (Invited), SPIE Photorefractive Fiber and Crystal Devices: Materials, Optical Properties, and Applications IX, Denver, Colorado, 2-3 August, 2004.
11. S. H. Lin and K. Y. Hsu, “Studies on doped PMMA photopolymers for holographic recording,” (Invited), Information Optics and Photonics Technolog, Conference 5642, Photonics Asia, Beijing, China, 8-12 November, 2004.
12. Shiuan-Huei Lin, and Ken Y. Hsu, "Investigation on new PQ:PMMA photopolymers for holographic recording," invited paper, presented at "Global Perspectives in Frontiers of Photonics, Computational Imaging, Biophotonics and Nanophotonics", May 18-20, 2005, Duke university, USA.
13. Shiuan Huei Lin, Vera Marinova and Ken Yuh Hsu, "Doped Bi12TiO20 and Bi4Ge3O12 photorefractive crystals for holographic applications," invited paper, presented at "International Conference on Holography, Optical Recording and Processing of Information", Varna, Bulgaria, 21-25 May, 2005.
14. Shiuan Huei Lin, Vera Marinova and Ken Yuh Hsu, "Bi12TiO20:Ru Crystals for two-wavelength holographic recording," invited paper, presented at "Photorefractive Fiber and Crystal Devices: Materials, Optical Properties, and Applications X", San Diego, USA, 31 July-4 August, 2005.
15. Ken Yuh Hsu, "Photorefractive and photopolymer materials for volume holographic recording," invited paper, presented at "5th International Symposium on Modern Optics and Its Applications (ISMOA 2005)", Bandung, Indonesia, 15-20 August, 2005.

IV. Editorial Activities:

1. Ken Yuh Hsu（許根玉）, Editor, Optical Memory & Neural Network (Information Optics).
2. Ken Yuh Hsu（許根玉）, Advisory Editor, Optics Letters.
3. Proceeding guest editor, 2005 IEEE International Microwave Photonics, (Hao-chung Kuo 郭浩中).

V. International Committee Activities:

1. Ci-Ling Pan（潘犀靈）, Program Committee , Ultrafast Phenomena XIV, Niigita, Japan, 2004
2. Ci-Ling Pan(潘犀靈), Program Committee, Joint Conference on Ultrafast Optics V and Applications of High Field and Short wavelength Sources XI, UFO/HFSW 2005, Nara, Japan, Sept. 25-30, 2005
3. Ci-Ling Pan（潘犀靈）, Program Committee, Ultrafast Phenomena in Semiconductors and Nanostructure Materials IX, Photonics West 2006, San Jose, California, USA, Jan. 21-26, 2006.
4. Ken Yuh Hsu(許根玉), Program Committee, Symposium on Photorefractives X, SPIE’s 50 Annual Meeting, San Diego, USA, 31 July-4 August, 2005.
5. Ken Yuh Hsu（許根玉）, Program Committee, International Conference on Holography, Optical Recording and Processing of Information, Varna, Bulgaria, 21-25 May, 2005.
6. Ken Yuh Hsu(許根玉), Program Committee, Symposium on Photorefractives XI, SPIE’s 51 Annual Meeting, San Diego, USA, 13-17 August, 2006.
7. Gong-Ru Lin （林恭如）member of the SPIE Awards Committee.
8. Shiuan Huei Lin（林烜輝）, Program Committee, Symposium on Photorefractives XI, SPIE’s 51 Annual Meeting, San Diego, USA, 13-17 August, 2006.

6. LIST OF TECHNOLOGY TRANSFERS

1. Technology transfer to CMC corp. for NT$ 1,000,000, “Fabrication on PQ:PMMA Holographic disk”.
2. GOC 全球光通: Tapped Fiber Splicing Process for Reduction Splicing Loss between Single-Mode & Erbium-Doped Fibers
3. 聖威光電: Sensitive Evaluation of Fiber-Optic SONET OC-48 PIN-TIA Receivers Using Sweep-Frequency Modulation and Inter-Mixing Diagnostics

7. LIST OF TECHNOLOGY SERVICES

8. PAPERS SELECTED BY AIP VIRTUAL JOURNALS

1. Time-Resolved Photoluminescence Analysis of Multidose Si-Ion-Implanted SiO_2
   Chun-Jung Lin, Chao-Kuei Lee, Eric Wei-Guang Diau, and Gong-Ru Lin
   J. Electrochem. Soc. 153, E25 (2006)
   Virtual Journal of Ultrafast Science -- January 2006 Volume 5, Issue 1

2. Femtosecond wavelength tunable semiconductor optical amplifier fiber laser mode-locked by backward dark-optical-comb injection at 10 GHz
   Gong-Ru Lin and I-Hsiang Chiu
   Opt. Express 13, 8772 (2005)
   Virtual Journal of Ultrafast Science -- January 2006, Volume 5, Issue 1

3. Dark current and trailing-edge suppression in ultrafast photoconductive switches and terahertz spiral antennas fabricated on multienergy arsenic-ion-implanted GaAs
   Tze-An Liu, Gong-Ru Lin, Yen-Chi Lee, Shing-Chung Wang, Masahiko Tani, Hsiao-Hua Wu, and Ci-Ling Pan
   J. Appl. Phys. 98, 013711 (2005)
   Virtual Journal of Ultrafast Science -- August 2005, Volume 4, Issue 8

4. Suppression of phase and supermode noise in a harmonic mode-locked erbium-doped fiber laser with a semiconductor-optical-amplifier-based high-pass filter
   Gong-Ru Lin, Ming-Chung Wu, and Yung-Cheng Chang
   Opt. Lett. 30, 1834 (2005)
   Virtual Journal of Ultrafast Science -- Volume 4, Issue 7, July 2005

5. Freezing phase scheme for fast adaptive control and its application to characterization of femtosecond coherent optical pulses reflected from semiconductor saturable absorber mirrors
   Ming C. Chen, Jung Y. Huang, Qiantso Yang, C. L. Pan, and Jen-Inn Chyi
   J. Opt. Soc. Am. B 22, 1134 (2005)
   Virtual Journal of Ultrafast Science -- June 2005 Volume 4, Issue 6

6. 1.2-ps mode-locked semiconductor optical amplifier fiber laser pulses generated by 60-ps backward dark-optical comb injection and soliton compression
   Gong-Ru Lin, I-Hsiang Chiu, and Ming-Chung Wu
   Opt. Express 13, 1008 (2005)
   Virtual Journal of Ultrafast Science -- Volume 4, Issue 5 May 2005

7. Stimulated emission and lasing of random-growth oriented ZnO nanowires
   Hsu-Cheng Hsu, Chun-Yi Wu, and Wen-Feng Hsieh
   J. Appl. Phys. 97, 064315 (2005)
   Virtual Journal of Nanoscale Science & Technology -- Volume 11, Issue 12 March 28, 2005

8. Two-photon resonance assisted huge nonlinear refraction and absorption in ZnO thin films
   Ja-Hon Lin, Yin-Jen Chen, Hung-Yu Lin, and Wen-Feng Hsieh
   J. Appl. Phys. 97, 033526 (2005)

Virtual Journal of Ultrafast Science -- Volume 4, Issue 2, February 2005

9. Time-resolved photoluminescence and capacitance–voltage analysis of the neutral vacancy defect in silicon implanted SiO_2 on silicon substrate
Gong-Ru Lin, Chun-Jung Lin, and Kuo-Chen Yu
J. Appl. Phys. 96, 3025 (2004) Virtual Journal of Ultrafast Science -- October 2004, Volume 3, Issue 10

10. Near-infrared femtosecond laser-induced crystallization of amorphous silicon
Jia-Min Shieh, Zun-Hao Chen, Bau-Tong Dai, Yi-Chao Wang, Alexei Zaitsev, and Ci-Ling Pan
Appl. Phys. Lett. 85, 1232 (2004)
Virtual Journal of Ultrafast Science -- September 2004, Volume 3, Issue 9

11. Theoretical and experimental studies of tunable ultraviolet–blue femtosecond pulses in a 405-nm pumped type I -BaB_2O_4 noncollinear optical parametric amplifier and cascading sum-frequency generation
Chao-Kuei Lee, Jing-Yuan Zhang, J. Y. John Huang, and Ci-Ling Pan
J. Opt. Soc. Am. B 21, 1494 (2004)
Virtual Journal of Ultrafast Science -- September 2004, Volume 3, Issue 9

12. Magnetically tunable room-temperature 2 pi liquid crystal terahertz phase shifter
Chao-Yuan Chen, Cho-Fan Hsieh, Yea-Feng Lin, Ru-Pin Pan, and Ci-Ling Pan
Opt. Express 12, 2625 (2004)
Virtual Journal of Ultrafast Science -- September 2004 Volume 3, Issue 9

13. Ultrabroadband terahertz field detection by proton-bombarded InP photoconductive antennas
Tze-An Liu, Masahiko Tani, Makoto Nakajima, Masanori Hangyo, Kiyomi Sakai, Shin-ichi Nakashima, and Ci-Ling Pan
Opt. Express 12, 2954 (2004)
Virtual Journal of Ultrafast Science -- August 2004, Volume 3, Issue 8

14. Dynamics of optical backward-injection-induced gain-depletion modulation and mode locking in semiconductor optical amplifier fiber lasers
Gong-Ru Lin, Yu-Sheng Liao, and Quang-Qun Xia
Opt. Express 12, 2017 (2004) Virtual Journal of Ultrafast Science -- July 2004, Volume 3, Issue 7

VII. APPENDIX III

LIST OF PUBLICATIONS IN "TOP" JOURNALS AND CONFERENCES (LIMIT TO 3-5)

1. The criteria for top journals and conferences should be defined and stated briefly at the beginning of this section.
2. Please provide electronic files for these publications

"Top" journals are defined by their SCI Impact factor ranking in 2004. Those ranked in the top 1/3 of their catergory are listed as top journals.

Partial List of "Top" Journals (journals that the P.I. published in the period of Apr. 2004 – Feb. 2006) in alphabetical order:

1. Appl. Phys. B [impact factor: 2.215, ranked 13/79 (Physics, Applied), 10/54 (Optics)]
2. Appl. Phys. letters. [impact factor: 4.308, ranked 4/79 (Physics, Applied)]
3. Eelctrochemistry and Solid State Letters [impact factor: 2.271, ranked 22/177 (Materials, Multidisciplinary)]
4. IEEE J. of Lightwave Technology [impact factor: 2.113, ranked 24/209 (EE), 11/54 (Optics)]
5. IEEE Journal of Quantum Electronics [impact factor: 3.675, ranked 3/209 (EE), 5/79 (Physics, Applied)]
6. IEEE Journal of Sel. Top. In Quantum Electron. [impact factor: 3.048, 8/209 (EE), 6/54 (Optics)]
7. IEEE Photonics Technology Letters [impact factor: 2.552, ranked 14/209 (EE), 9/54 (Optics)]
8. Journal of Applied Physics [impact factor: 2.255, ranked 12/79 (Physics, Applied)]
9. Journal of Electrochemical Society [impact factor: 2.356, ranked 1/19 (Materials, Coating and Films)]
10. Journal of Optical society of America B [impact factor: 2.649, ranked 8/54 (Optics)]
11. Nanotechnology [impact factor: 3.332, ranked 8/79 (Physics, Applied), 17/177 (Materials, Multidisciplinary)]
12. Optics Express [impact factor: 3.797, ranked 4/54 (Optics)]
13. Optics Letters [impact factor: 3.882, ranked 3/54 (Optics)]
14. Semiconductor Science and Technology [impact factor: 2.152, ranked 22/209 (EE), 23/177 (Materials, Multidisciplinary)]

Out of the 109 journal papers published by the group, about half or 55 appeared in these top "journals".

Those Conferences with a high reputation and high rejection ratio are considered "top" conferences.

Partial List of "Top" Conferences (conferences that the P.I. published in the period of Apr. 2004 – Feb. 2006) in alphabetical order:

1. CLEO/QELS/IQEC
2. MRS
3. OFC
4. Ultrafast phenomena

Out of the 74 international conference papers presented by members of the group, 30 appeared in these top "conferences".

A. Coherent and THz Photonics

1. Tze-An Liu, Gong-Ru Lin, Yung-Cheng Chang, Ci-Ling Pan, "A wireless audio and burst communication link with directly modulated THz photoconductive antenna," Optics Express, Vol. 13, No. 25, pp. 10416-10423, 12 December, 2005.

2. Gong-Ru Lin, Ming-Chung Wu, Yung-Cheng Chang, and Ci-Ling Pan, "Ultrahigh supermode noise suppressing ratio of a semiconductor optical amplifier filtered harmonically mode-locked Erbium-doped fiber laser," Optics Express, Vol. 13, No. 18, pp. 7215–7224, September 5, 2005.
3. Tze-An Liu, Gong-Ru Lin, Yen-Chi Lee, Shing-Chung Wang, M. Tani, Hsiao-Hua Wu, and Ci-Ling Pan, "Multi-Energy Arsenic-Ion-Implanted GaAs Photoconductive THz Spiral Antenna with Suppressed Dark Current and Trailing Edge," J. Appl. Phys., Vol. 98, 013711-1 to -4, July 15, 2005, selected by the Virtual Journal of Ultrafast Science, Vol. 4, No. 8, August 2005.
4. Ming C. Chen, Jung Y. Huang, Qiantso Yang, C. L. Pan, and Jen-Inn Chyi, "Freezing phase scheme for fast adaptive control and its application to characterization of femtosecond coherent optical pulses reflected from semiconductor saturable absorber mirrors," *Journal of The Optical Society Of America B*, Vol. 22, No. 5, pp. 1134-1142, May 2005, selected by the Virtual Journal of Ultrafast Science, Vol. 4, No. 6, June 2005.
5. Ci-Ling Pan, Cho-Fan Hsieh, and Ru-Pin Pan, Masaki Tanaka, Fumiaki Miyamaru, Masahiko Tani, and Masanori Hangyo, "Control of enhanced THz transmission through metallic hole arrays using nematic liquid crystal," *Optics Express*, Vol. 13, No. 11, pp. 3921 - 3930, May 30, 2005.

B. Quantum (Photonic Crystal) Structures and Enabling Devices

1. Huang GS, Lu TC, Yao HH, Kuo HC, Wang SC, Lin CW, Chang L "Crack-free GaN/AlN distributed Bragg reflectors incorporated with GaN/AlN superlattices grown by metalorganic chemical vapor deposition" *Applied Physics Letters* 88 (6): Art. No. 061904 Feb 6 2006.

2. Kao CC, Peng YC, Yao HH, Tsai JY, Chang YH, Chu JT, Huang HW, Kao TT, Lu TC, Kuo HC, Wang SC, Lin CF "Fabrication and performance of blue GaN-based vertical-cavity surface emitting laser employing AlN/GaN and Ta_2O_5/SiO_2 distributed Bragg reflector" *Applied Physics Letters* 87 (8): Art. No. 081105 Aug 22, 2005.

3. Hsueh TH, Huang HW, Lai FI, Sheu JK, Chang YH, Kuo HC, Wang SC "Photoluminescence from $In_{0.3}Ga_{0.7}N$/GaN multiple-quantum-well nanorods" Nanotechnology 16 (4): 448-450 Apr 2005.

4. Gong-Ru Lin, Hao-Chung Kuo, Chi-Kuang Lin, and M. Feng, "Ultralow Leakage $In_{0.53}Ga_{0.47}As$ p-i-n Photodetector Grown on Linearly Graded Metamorphic $In_xGa_{1-x}P$ Buffered GaAs Substrate", *IEEE Journal of Quantum Electronics*, Vol. 41, No. 6, pp. 749-752, June 2005

5. Kuo HC, Chang YH, Chang YA, Lai FI, Chu JT, Tsai MN, Wang SC "Single-mode 1.27-mu m InGaAs : Sb-GaAs-GaAsP quantum well vertical cavity surface emitting lasers" *IEEE Journal of Selected Topics in Quantum Electronics* 11 (1): 121-126 Jan-Feb 2005.

C. Volume Holographic Materials, Technology and Enabling Devices

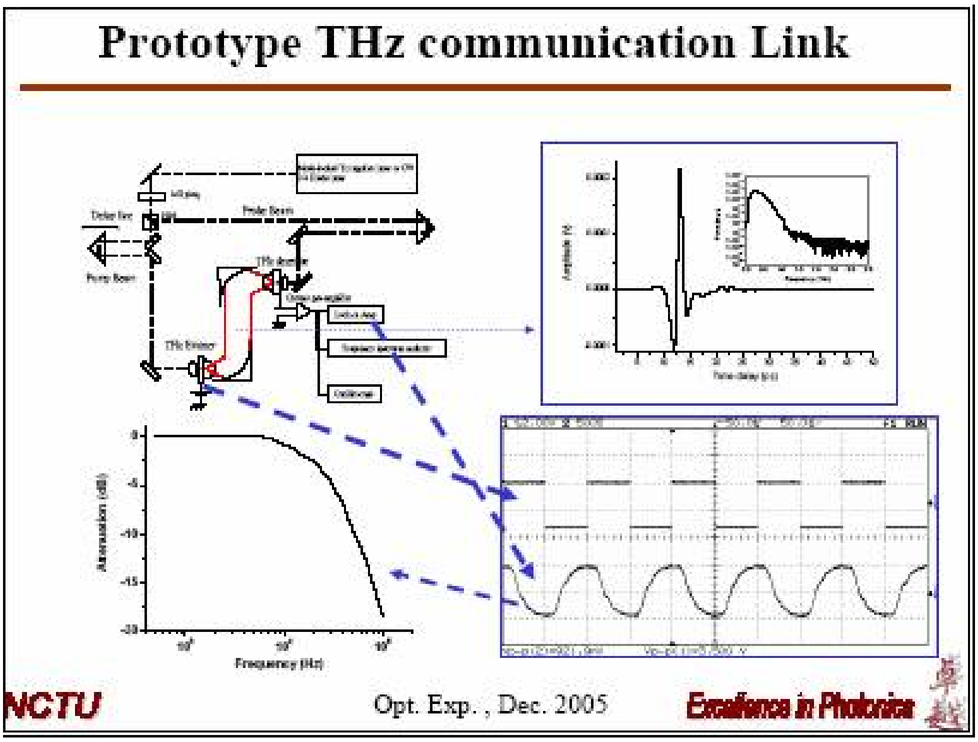
1. Jian-Shuen Fang, Qi Hao, David J. Brady, Mohan Shankar, Bob D. Guenther, Nikos P. Pitsianis, and Ken Y. Hsu, "Path-dependent human identification using a pyroelectric infrared sensor and Fresnel lens arrays", Optics Express Vol. 14, 609-624, 2006, selected by OSA's Virtual J. for Biomedical Optics, Vol. 1, Issue2, Feb. 10, 2006.

2. V. Marinova, S. H. Lin, and Ken Y. Hsu "Light-induced properties of ruthenium-doped $Bi_4Ge_3O_{12}$ crystals" J. Appl. Phys. 98, 113527, 2005.

VIII. APPENDIX IV

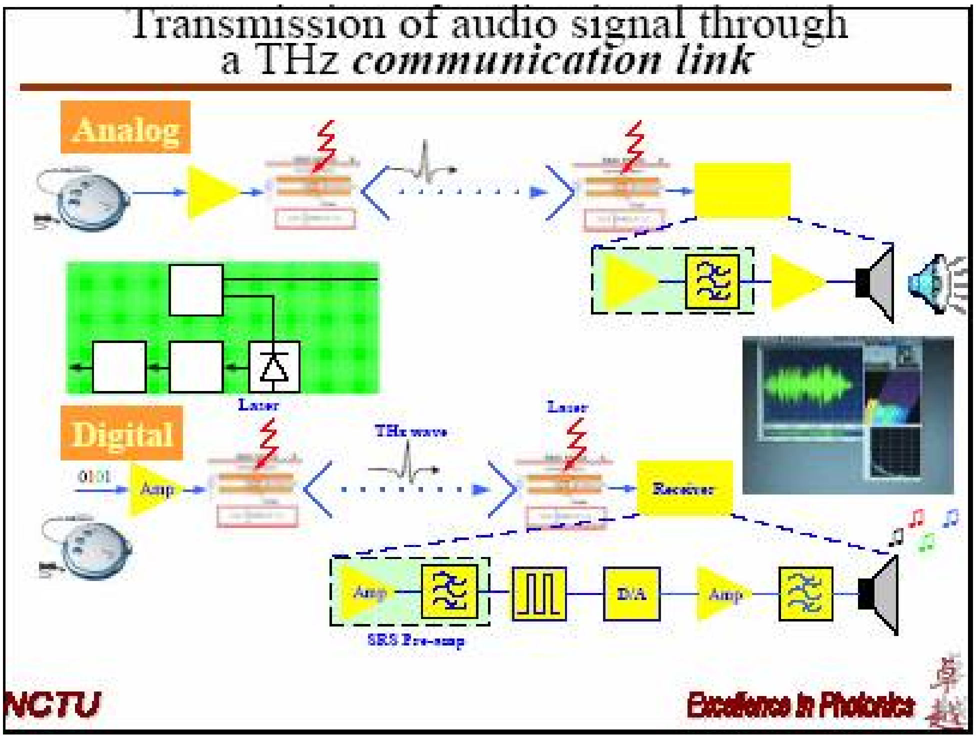
Slides on Science And Technology Breakthroughs (Two Slides for each Breakthrough)

(I) Coherent and THz Photonics

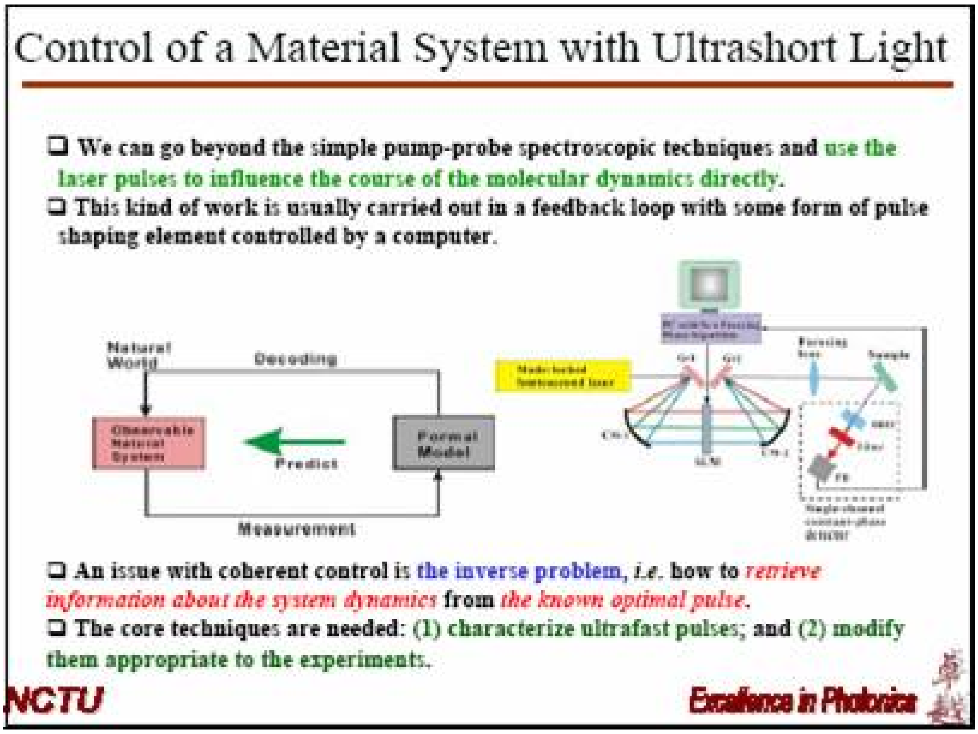


Prototype THz communication Link

Opt. Exp. , Dec. 2005



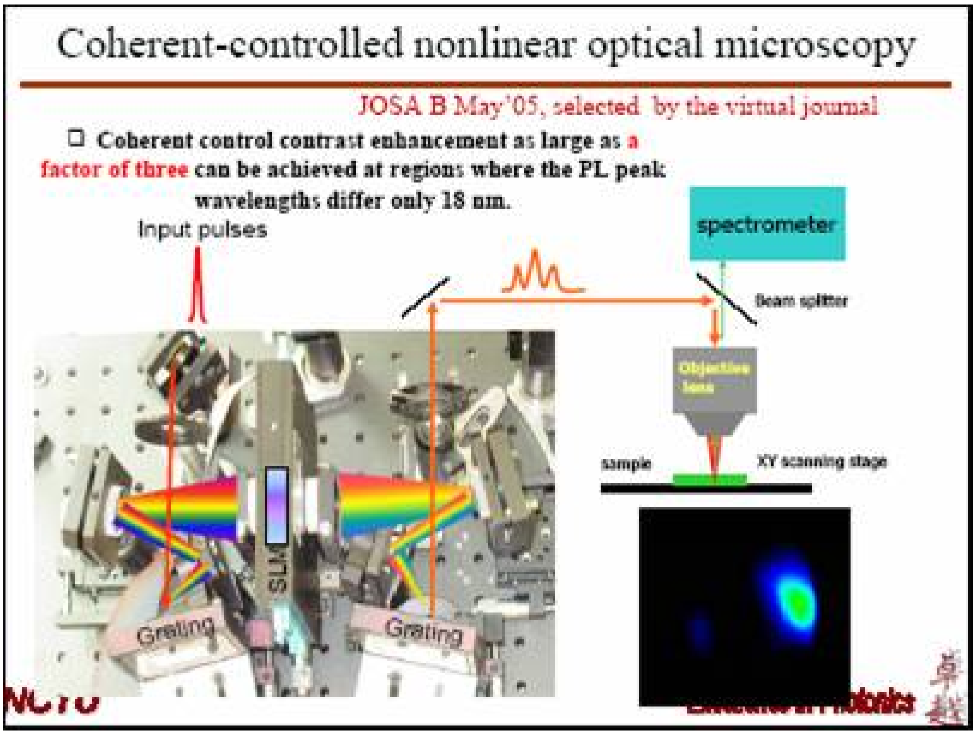
Transmission of audio signal through a THz *communication link*



Control of a Material System with Ultrashort Light

- ❑ We can go beyond the simple pump-probe spectroscopic techniques and use the laser pulses to influence the course of the molecular dynamics directly.
- ❑ This kind of work is usually carried out in a feedback loop with some form of pulse shaping element controlled by a computer.

- ❑ An issue with coherent control is the inverse problem, *i.e.* how to *retrieve information about the system dynamics* from *the known optimal pulse*.
- ❑ The core techniques are needed: (1) characterize ultrafast pulses; and (2) modify them appropriate to the experiments.

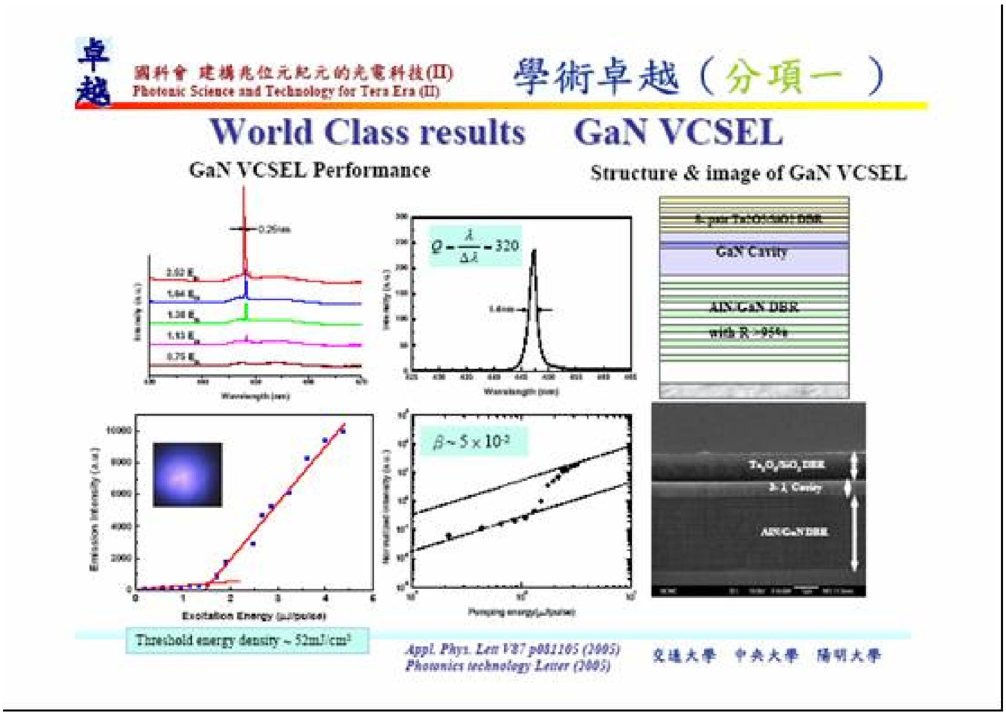


Coherent-controlled nonlinear optical microscopy

JOSA B May'05, selected by the virtual journal

- ❑ Coherent control contrast enhancement as large as a factor of three can be achieved at regions where the PL peak wavelengths differ only 18 nm.

(II) Quantum (Photonic Crystal) structures and Enabling devices



卓越 國科會 建構兆位元紀元的光電科技(II)
Photonic Science and Technology for Tera Era (II)
學術卓越（分項一 ）

World Class results GaN VCSEL

GaN VCSEL Performance

Structure & image of GaN VCSEL

Threshold energy density ~ 52mJ/cm²

Appl. Phys. Lett V87 p081105 (2005)
Photonics technology Letter (2005)

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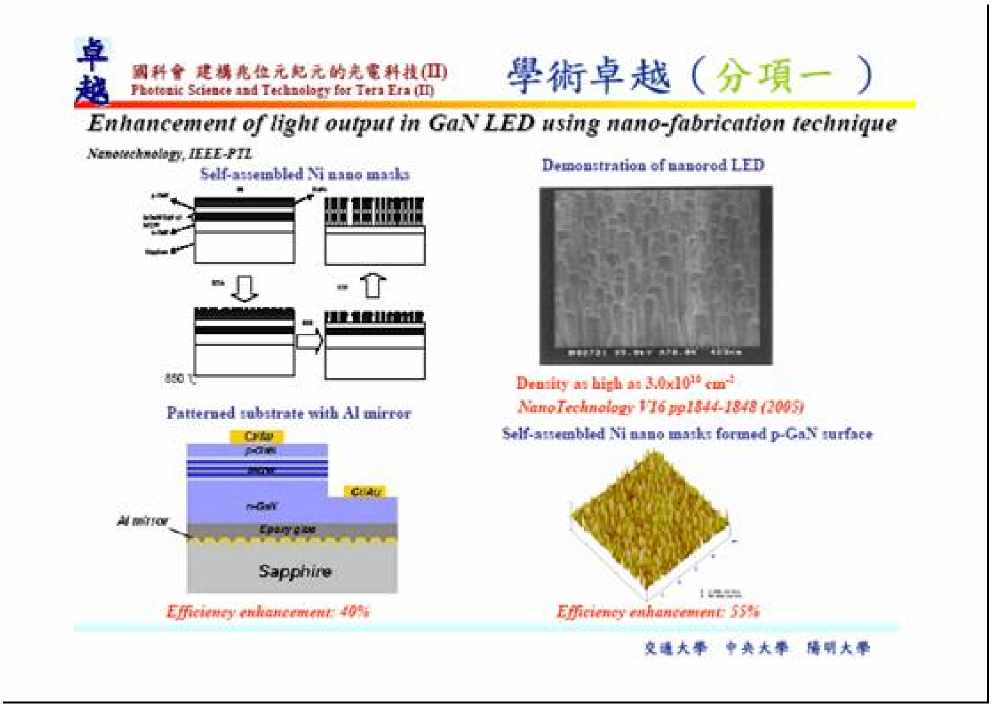

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Photonic Science and Technology for Tera Era (II)
學術卓越（分項一 ）

Enhancement of light output in GaN LED using nano-fabrication technique

Nanotechnology, IEEE-PTL

Self-assembled Ni nano masks

Demonstration of nanorod LED

Density as high as 3.0×10^{10} cm^{-2}
NanoTechnology V16 pp1844-1848 (2005)

Patterned substrate with Al mirror

Self-assembled Ni nano masks formed p-GaN surface

Efficiency enhancement: 40%

Efficiency enhancement: 55%

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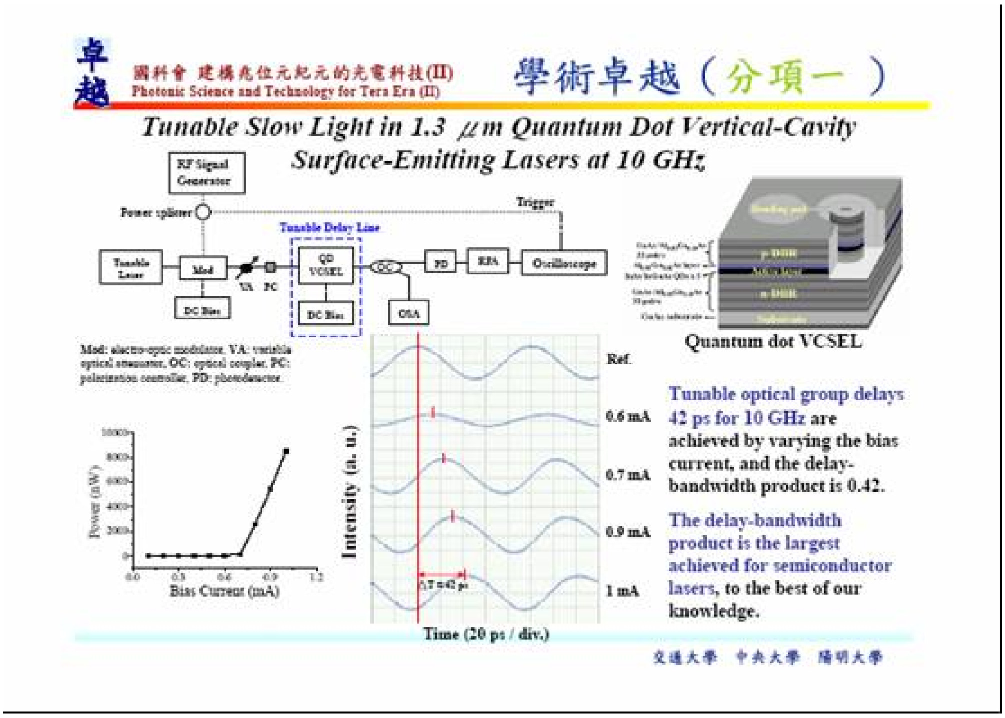

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Photonic Science and Technology for Tera Era (II)

學術卓越（分項一）

Tunable Slow Light in 1.3 μm Quantum Dot Vertical-Cavity Surface-Emitting Lasers at 10 GHz

Mod: electro-optic modulator, VA: variable optical attenuator, OC: optical coupler, PC: polarization controller, PD: photodetector.

Tunable optical group delays 42 ps for 10 GHz are achieved by varying the bias current, and the delay-bandwidth product is 0.42.

The delay-bandwidth product is the largest achieved for semiconductor lasers, to the best of our knowledge.

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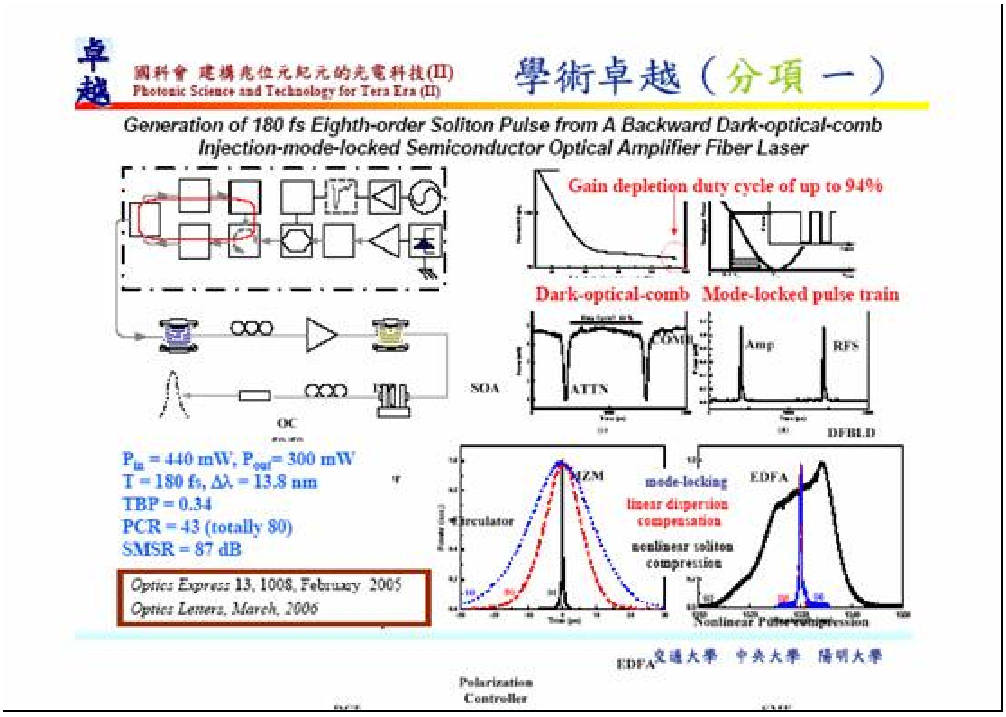

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Photonic Science and Technology for Tera Era (II)

學術卓越（分項 一）

Generation of 180 fs Eighth-order Soliton Pulse from A Backward Dark-optical-comb Injection-mode-locked Semiconductor Optical Amplifier Fiber Laser

P_{in} = 440 mW, P_{out} = 300 mW
T = 180 fs, Δλ = 13.8 nm
TBP = 0.34
PCR = 43 (totally 80)
SMSR = 87 dB

Optics Express 13, 1008, February 2005
Optics Letters, March, 2006

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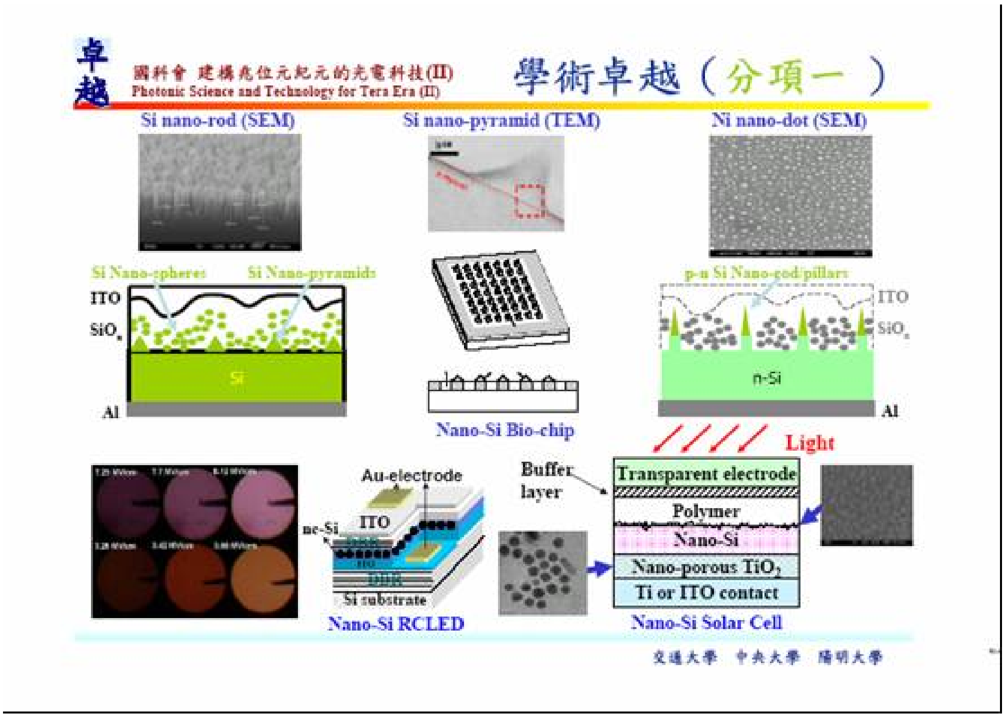

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Photonic Science and Technology for Tera Era (II)

學術卓越（分項一 ）

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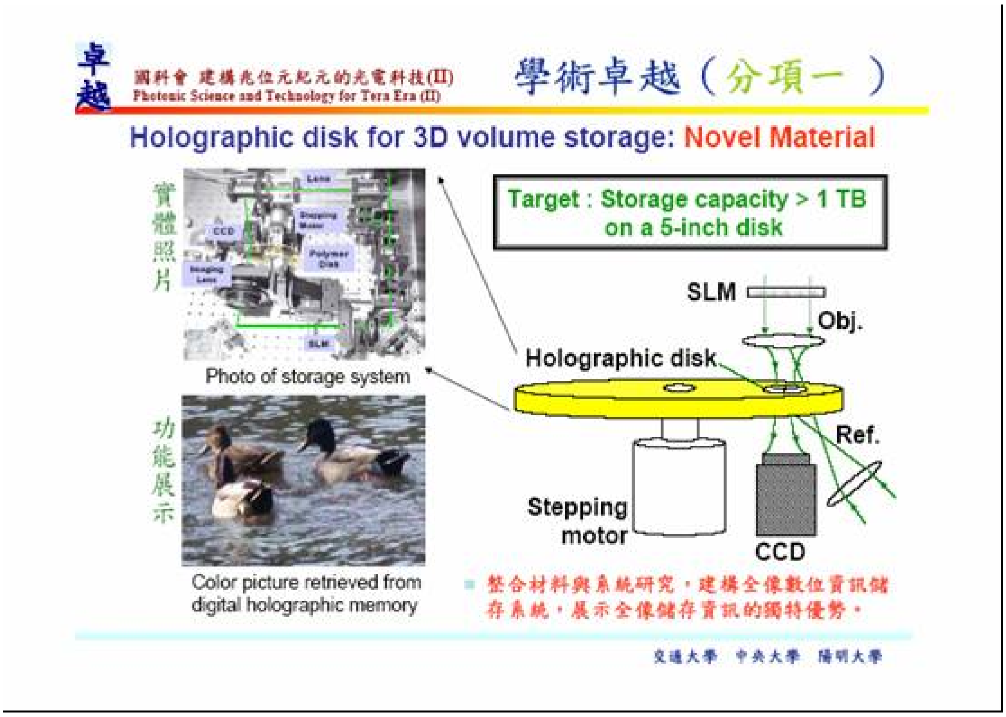
(III) Photorefractive Materials and Enabling devices



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Photonic Science and Technology for Tera Era (II)

學術卓越（分項一 ）

Holographic disk for 3D volume storage: Novel Material

Target : Storage capacity > 1 TB on a 5-inch disk

- 整合材料與系統研究，建構全像數位資訊儲存系統，展示全像儲存資訊的獨特優勢。

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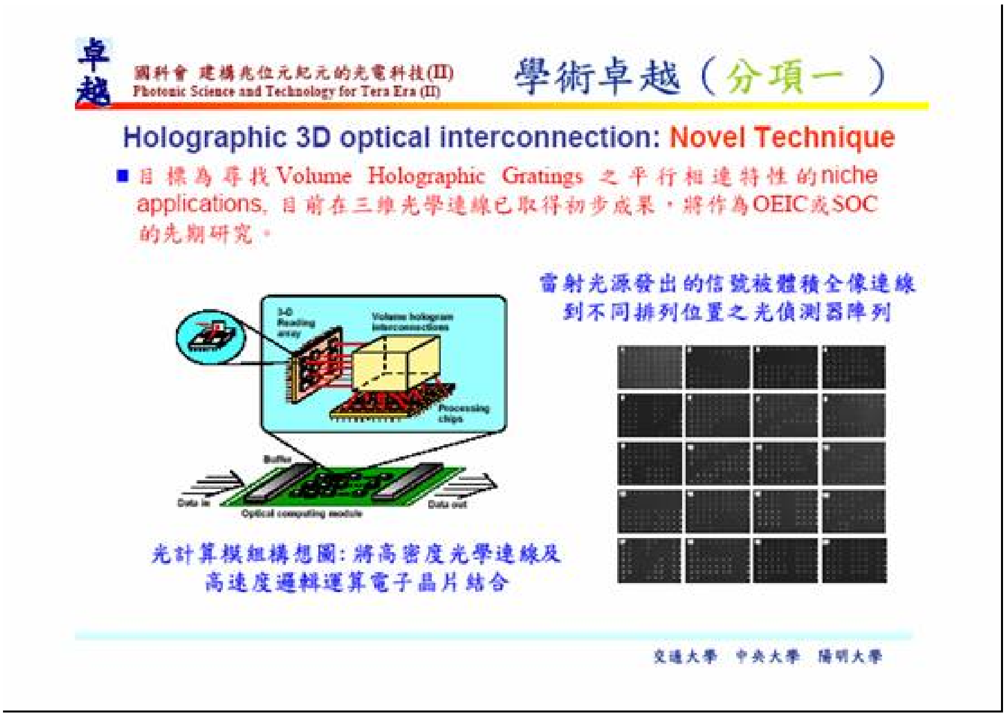

卓越 國科會 建構兆位元紀元的光電科技(II)
Photonic Science and Technology for Tera Era (II)

學術卓越（分項一 ）

Holographic 3D optical interconnection: Novel Technique

- 目標為尋找Volume Holographic Gratings 之平行相連特性的niche applications, 目前在三維光學連線已取得初步成果，將作為OEIC或SOC的先期研究。

雷射光源發出的信號被體積全像連線到不同排列位置之光偵測器陣列

光計算模組構想圖: 將高密度光學連線及高速度邏輯運算電子晶片結合

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IX. Appendix V: Self-Assessment

PROJECT TITLE: ____

	ASSESSMENT SUBJECT	**SCORE** **（1～5, LOW TO HIGH）**
PROJECT'S CONTENTS & PERFORMANCE	Importance & Innovation of the Project's Major Tasks	**4**
	Clarity and Presentation of the Report	**4**
	Viability of the Project's Approaches & Methodologies	**4**
	Principle Investigator's Competence for Leading the Project	**5**
	Interface & Integration with the main project	**4**
	Interface & Integration with other Sub-Projects	**3-4**
	Manpower & Expenditures	**-**
PROJECT'S RESULTS	Contribution in Enhancing the Institute's International Academic Standing	**4**
	Impact on Advancing Teaching or on Technology Development	**4**
	OVERALL	**4**

REVIEWER'S COMMENTS & SUGGESTION:

1. **Basic studies related to overall goals are excellent. Work in THz photonics and GaN VCSEL for blue light emission are particularly exciting. Publications of such results will enhance the fame of the research institution.**

2. **Holographic recording using PMMA is interesting even though the storage density needs is still far from desired. Material stability for practical applications may become a problem. Much follow-up work remains to improve the storage density.**

3. **Other research including Si-Rich SiO_2 for light emission has been very good. In general, the project has produced a number of exciting results. Prospects of good and exciting results from this project are expected.**

PRINCIPAL INVESTIGATOR'S FEEDBACK: (AVAILABLE)

We would like to thank the reviewer for appreciating our work on THz Photonics and GaN VCSEL. We shall continue to perform follow-up studies on the Holographic recording using PMMA.

Project Reviewer's Signature:________________________________