COMMISSION D : Electronics and Photonics (Nov. '01 - Oct. '04)

Edited by Masayuki Izutsu and Masahiro Tsuchiya

The fields of Electronics and Photonics are huge and include many active sub-fields therein. Therefore, it is not a good idea to deal with the whole subjects of the fields in such a limited space as in the present report. On the other hand, it should be a truth that Japanese research institutions have played important roles in the past decades for the progresses of Electronics and Photonics. It should be pointed out that this trend is still continuing in the last several years, which includes the time period of the interest in this report, years from 2002 to 2005. Based upon those consideration, we, the editors of this chapter, decided to invite Japanese leading researchers to overview recent conspicuous progresses of their respective sub-fields and to contribute to the present report. In addition, we have a special review article in the beginning of the chapter on the invention and development of vertical cavity surface emitting laser, which is one of the most prominent Japanese landmarks in Electronics and Photonics. It is given by Prof. K. Iga of Japan Society for the Promotion of Science (JSPS).

The following is a list of the sub-fields that the chapter editors have taken up.

D1 Vertical Cavity Surface Emitting Lasers (Special Review)
Kenichi Iga, Japan Society for the Promotion of Science

D2 Network Devices
Yoshio Itaya, NTT Corporation

D3 Femtosecond Technology
Osamu Wada, Kobe University

D4 THz Technology
Hiromasa Ito, Tohoku University

D5 Sensor Photonics
Kazuo Hotate, University of Tokyo

D6 Photonic Signal Processing
Takashi Kurokawa, Tokyo University of Agriculture and Technology

D7 Microwave Photonics
Tadao Nagatsuma, NTT Corporation

D8 Nano-technology

D1. Vertical Cavity Surface Emitting Lasers (Special Review)

Kenichi Iga
Japan Society for the Promotion of Science

Abstract: In this chapter, we present device physics and technology based upon vertical cavity surface emitting laser (VCSEL). We will survey its progress along with the history of semiconductor lasers since the late 1960's. The VCSEL photonics is opening up a new field of applications by taking the merits of compactness, small power consumption, high speed capability, arrayed configuration, and so on.

1. Introduction

The vertical cavity surface emitting laser (VCSEL) [1]-[6] is a semiconductor laser which can be monolithically fabricated on the surface of semiconductor wafer. The light output can, therefore, be taken vertically from the surface. Its name came from these reasons suggested by K. Iga and Y. Suematsu .

The initial VCSEL as shown in **Fig. 1** was invented by K. Iga in 1977 at Tokyo Institute of Technology and the first device was demonstrated in 1979, where we used 1300nm wavelength GaInAsP/InP material for active layer. The motivation of VCSEL invention is to make a very short cavity laser as one of dynamic single mode (DSM) lasers. The DSM laser concept was suggested by Y. Suematsu in around 1975 [7] for realizing single mode fiber optical communication. Another issue is to make a semiconductor laser in terms of monolithic fabrication process.

The first room temperature continuous wave (CW) device using GaAs/AlGaAs was achieved in 1988 by F. Koyama and the present author. Since 1992, VCSELs based on GaAs have been extensively studied and 980, 850 and 780nm devices were commercialized into various photonics systems. Also, CW operation in a 1300nm GaInAsP buried-structure VCSEL was achieved in 1993. After these circumstances, 1,300-1,550nm band devices, red color GaInAlP, and blue-ultraviolet GaN-based devices have been studied.

Extensive studies and realization trials have been made on high performance devices for Gigabit

Ethernet, high speed LANs, computer links, optical interconnects, arrayed sensors, and so on. The technical progress of devices range from infrared to ultraviolet wavelengths has been achieved by world wide laboratories including expansion of operating spectra by developing advanced materials and fabrication technologies. The vertical cavity surface emitting laser (VCSEL) is emerging into market as an important device for high speed LANs and optical interconnects enabling parallelism in high speed information transmission.

In conjunction with those VCSEL related technical progresses, new areas in photonics have been proposed. For instance, inside of VCSEL devices, a lot of nano- and quantum- structures are utilized and the concept of VCSEL has been expanded into nano-and quantum photonics including photonic crystals.

2. Physics and Scaling Law

The VCSEL structure may provide a number of advantages including ultra-low threshold operation due to its small cavity volume V_a, dynamic single mode operation, high speed modulation, wide range frequency tuning, and so on. These are based upon a scaling law that is described in terms of cavity volume V_a. One of the important scaling law is to express threshold current I_{th} to achieve laser oscillation can be written as;

$$I_{th} \propto V_a \qquad (1)$$

Therefore, the actual threshold current of VCSELs can be made vary small obeying this equation being 1/100 – 1/1000 of conventional stripe lasers. Together with the improved optical cavity formation technology and the scheme for injecting electrons and holes effectively into small volume of active region, this relation has proven the scaling law.

3. Actual Devices in Various Spectral Bands

We show a typical structure of GaAs/AlGaAs VCSEL device in **Fig. 2**. An AlAs oxidation is considered to be the effective process current confinement in VCSEL's. In commercially available 850 nm devices, sub-mA thresholds and >10 mW outputs have been achieved. The power conversion efficiency of >50% has been demonstrated. The Gigabit Ethernet has already been in markets by the use of multimode-fiber-based optical links. This system is being extended to 10 Gigabits/s Ether and even faster systems. As for the reliability of VCSELs, 10^7 hours of room temperature operation is estimated. Life test of oxide-defined devices exhibited higher reliability.

The long wavelength device (1,300 nm) is developed for metropolitan area networks (MAN). A 1,550 nm VCSEL with a MEMS tunable function was considered to be introduced in a high end MAN system.

One of viable materials for long wavelength emitters is a GaInNAs system which can be formed on a GaAs substrate. A tunnel-junction is utilized in current-injection and confinement especially in long wavelength devices. The polarization control technology in VCSELs have been established by using (311)B substrate as shown in **Fig. 3** [8]. The orthogonal polarization suppression ratio (OPSR) of >30dB was obtained even in high speed modulation condition.

4. VCSEL-Related Sub-Systems

A wide variety of functions, such as frequency tuning, amplification, and filtering should be integrated. Another possible way of moduling is to use the micro-optical bench (MOB) concept to ease the assembling of components without precise alignment. Moreover, a 2-D parallel optical logic system can deal with a large amount of image information with high speed. To this demand, the VCSEL will be a key device. High power capabilities from VCSEL's is very interesting by featuring largely extending 2-D arrays. For the purpose of realizing coherent arrays, coherent coupling of these arrayed lasers has been tried by using a Talbot cavity and phase compensation is considered. It is pointed out that 2-D arrays are more suitable to make a coherent array than a linear configuration, since we can take the advantage of 2-D symmetry. The research activity is now forwarded to monolithic integration of VCSEL's taking the advantage of small cavity dimensions. A densely packed array has also been demonstrated for the purpose of making high power lasers and coherent arrays. Into VCSEL's, surface operating photonic elements using quantum wells such as an optical switch, frequency tuner, optical filter, and super-lattice functional devices are now tried to be integrated.

To establish an appropriate module technology utilizing VCSELs, a micro optical bench (MOB) has been investigated together with planar microlens array. Micro Electro Mechanical Systems (MEMS) will be very helpful.

5. Applications

The application areas of VCSELs are summarized in **Table I**. The possible materials are displayed in **Fig. 4**. In low power consumption and high speed modulation is inevitable low power interconnect applications enabling >10Gbits/s transmission or 1Gbits/s zero-bias operation [6]. Actually, transmission experiments over 10Gbits/s and zero-bias transmission have been reported. A 10 Gbits/s transmission experiment through a 100m multimode fiber was performed [6]. VCSEL's in long wavelength may find the market in 10 Gigabit metropolitan networks together with high-speed detectors and silica fibers. Actually, GaInAs and GaInNAs VCSEL's show preferable performances.

A 780 nm VCSEL array has been introduced into a high speed laser printer. A laser printer has been developed by using 4x8 VCSEL array enabling 2,400 DPI high speed printer.

The red color VCSEL emitting 650-680 nm can match to the low loss band of plastic fibers. Short distance data links are considered by using 1 mm diameter plastic fibers having graded-index have been developed. This system provides us of very easy optical coupling. VCSEL's can very nicely match to this application.

Green to UV VCSEL's will be useful in the optoelectronics field as in ultra-high density optical memories. A VCSEL pick-up may be good for high density optical memories and variety of sensors. Full color flat displays and large area projectors, illuminations and light-signals, light decorations, UV-lithography, laser processes, medical treatment, and so on.

By taking the advantages such as wide-band and small-volume, the optical interconnect is considered to be inevitable in the digital technology. Some parallel interconnect scheme is wanted and new concepts is being researched. Vertical optical interconnect of LSI chips and circuit boards may be another interesting issue. A recent application includes high speed optical wireless data transfer to digital display.

Lightwave sensing is one of the important applications of VCSELs. An optical mouse for computer is an interesting application. Several schemes for optical computing have been considered by utilizing 2-D arrays of VCSEL's and surface operating switches. The application for image recognition has been considered. Very low threshold VCSEL's have been developed, and stack integration together with 2-D photonic devices are now actually considered.

6. Toward Nano-Photonics and Beyond

The scaling law of semiconductor lasers is still considered toward a nano-scale laser. A dust laser is one of the interesting examples. A single photon emitter is an extreme case. A photonics crystal is the extension of VCSELS structure to 3-D. The strain control has been applied to highly strained GaInAs/GaAs quantum well to elongate wavelength. A quantum dot active region is effective to prevent lateral diffusion of carriers to make a laser very small. A nano-scale super lattice is applied for a tunneling junction in sophisticated carrier injection scheme. A near field VCSEL may be applicable to nano-scale sensing. In summary, the ultra-parallel and ultra-high speed photonics based upon sophisticated VCSEL's will open up a new era of millennium [9].

References

[1] K. Iga, Laboratory Notebook, March 22 (1977) .

[2] K. Iga, T. Kambayashi, and C. Kitahara: The 26th Spring Meeting of Applied Physics Societies 27p-C-1 1 (1978).

[3] H. Soda, K. Iga, C. Kitahara and Y. Suematsu: Jpn. J. Appl. Phys. **18** (1979) 2329.

[4] K. Iga, F. Koyama, and S. Kinoshita: IEEE J. Quant. Electron. **QE-24** (1988) 1845.

[5] K. Iga and F. Koyama: "Fundamentals and Application of Surface Emitting Laser" Kyouritsu Pub. Co. Ltd. Tokyo (1999).

[6] K. Iga: IEEE J. STQE **6** (2000) 1201.

[7] Y. Suematsu, M. Yamada, and K. Hayashi：Proc. IEEE, **63** (1975) 208.

[8] N. Nishiyama, A. Mizutani, N. Hatori, M. Arai, F. Koyama, and K. Iga: IEEE JSTQE, **5** (1999) 530.
[9] K. Iga: IEICE Trans. Electron. **E85**, (2002) 10.

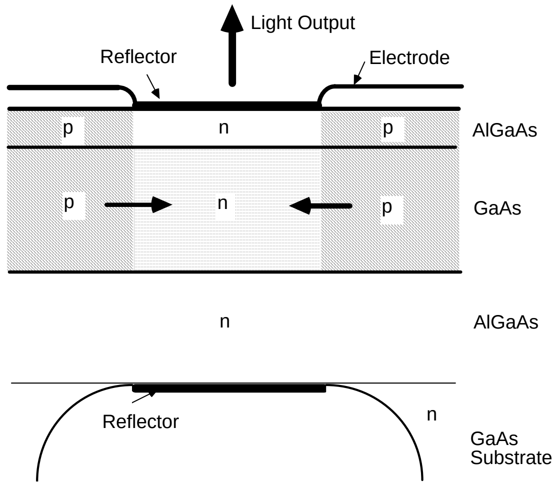


Fig. 1 An initial idea of surface emitting laser invented by K. Iga in 1977 [1].

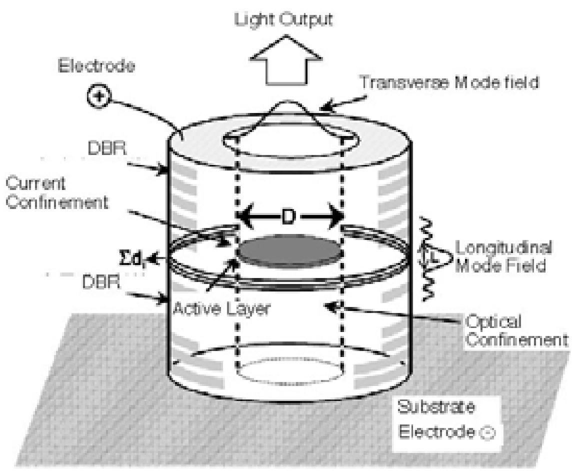


Fig. 2 A realistic model of VDSEL device.

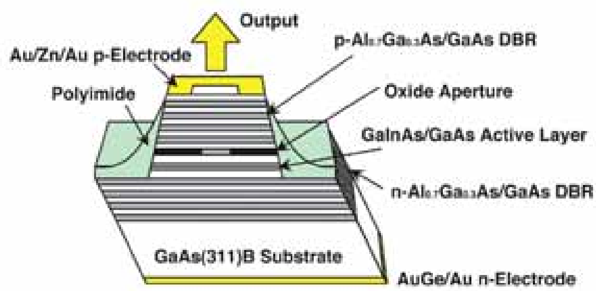


Fig. 3 A structure of 1,200nm wavelength GaInAs/GaAs VCSEL frown on (311)B GaAs. [8]

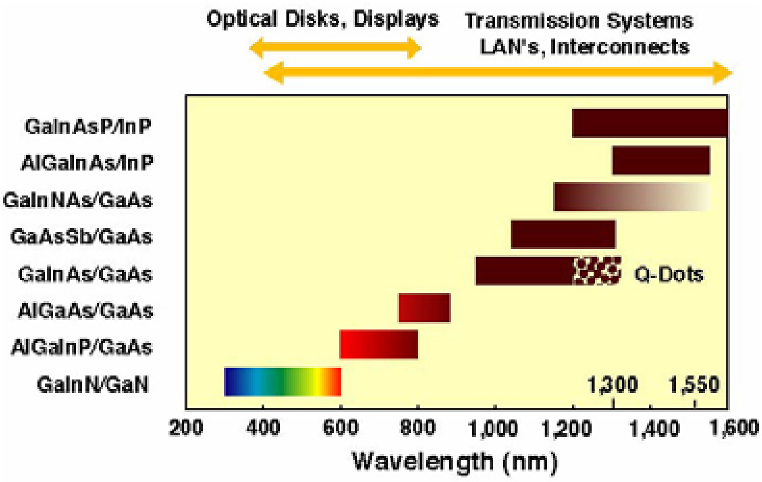


Fig. 4 Semiconductor materials for VCSELs

Table I Application of vertical cavity surface emitting lasers and related photonics

Technical Fields:	**Systems**
1. Communications:	LANs, MANs, Optical links, Mobile links, VSR, etc.
2. Computer Optics:	Computer links, Optical interconnects, High speed/Parallel data transfer, etc.
3. Optical Memory:	CD, DVD, Near-field disks, Multi-beam, Initializer, etc.
4. Opto-Equipments:	Laser printer, Laser pointer, Mobile tools, Home appliances, etc.
5. Information Processing:	Optical processors, Parallel processing, etc.
6. Optical Sensing:	Optical fiber sensing, Bar code readers, Encoders, VCSEL mouse, etc.
7. Displays:	Array light sources, High efficiency light-sources, etc.
8. Illuminations:	Multi-beam search-lights, Micro illuminators, White light VCSELs, Adjustable illuminations, etc.

D2. Network Devices

Yoshio Itaya

NTT Corporation

The establishment of a high-speed Internet environment through ADSL, FTTH and other schemes continues to progress. The technology supporting the networks of this broadband/ubiquitous era is optical communication. This technology has been advancing steadily in parallel with the development of optical devices. These include optical fiber for carrying light long distances, semiconductor lasers for high-speed generation of many optical signals, optical receivers for high-speed reception of optical signals and optical circuit components for adding/dropping optical signals. The laying of optical fiber started with the trunk network and is now reaching even individual homes enabling the exchange of large volumes of data among users. The maturing of optical technology accelerates price competition in optical device and promote the creation of new value-added optical-component technologies. The main results of optical devices are listed below.

1. Uncooled and directly modulated DFB laser module in the high speed operation of 10Gb/s
2. DFB-lasers integrated with electronabsorption modulator operating at 10 Gb/s
3. Wavelength tunable lasers with a wide tuning range
4. Low driving voltage InP-based n-i-n Mach-Zehnder modulator
5. 100Gb/s operations of Uni-Travelling-Carrier photodiode
6. Planar Lightwave Circuit (PLC) type optical switch for Reconfigurable Optical Add/Drop Multiplexer (ROADM)
7. Variable power level equalizing array waveguide (AWG) multiplexer
8. Wideband AWG multiplexer and demultiplexer for coarse WDM systems

References

K. Kasaya, K. Tsuzuki, H. Shibata and Y. Tohmori [2003], “SOA direct modulation in wavelength-selectable laser array light sources,” OECC, pp. 431-432, July

S. Shirai, Y. Tatsuoka, C. Watatani, T. Ota, K. Takagi, T. Aoyagi, E. Omura, and N. Tomita [2004], “120□ uncooled operation of direct modulated 1.3 μm AlGaInAs-MQW DFB laser diodes for 10Gb/s telecom applications,” Proc. OFC2004, ThD2

J. Klamkin, J. T. Getty, J. M. Hutchinson, L. A. Johannson, E. J. Skogen, and L. A. Coldren [2004], “Widely-Tunable Single-Mode Bipolar Cascade SGDBR Lasers,” Proc. 19th IEEE International Semiconductor Laser Conference, WC2, Takamatsu

Y. Muramoto, K. Yoshino, S. Kodama, Y. Hirota, H. Ito, and T. Ishibashi [2004], “100- and 160-Gbit/s operations of uni-traveling-carrier photodiode module,” Electron. Lett., Vol. 40, No. 6, pp. 378-380

K. Tsuzuki, T. Ishibashi, T. Ito, S. Oku, Y. Shibata, R. Iga, Y. Kondo, and Y. Tohmori [2003], “40-Gbit/s n-i-n InP Mach-Zehnder modulator with a π-voltage of 2.2 V,” Electron. Lett., Vol.39, No. 20, pp.

1464-1466, Oct.

Y. Hashizume, H. Takahashi, T. Watanabe, S. Sohma, T. Shibata, and M. Okuno [2003], “Compact 32-channel 2×2 optical switch array based on PLC technology for OADM systems,” ECOC 2003, Mo3-5-4, Sep.

K. Suzuki, T. Mizuno, M. Oguma, T. Shibata, H. Takahashi, and A. Himeno [2004], “Fully-reconfigurable wavelength-selective optical 1×N switch based transversal filter configuration, “Proc. OFC2004, WC2,Feb.

Y. Hashizume, Y. Inoue, T. Kominato, T. Shibata, and M. Okuno [2004], “Low-PDL 16-channel Variable Optical Attenuator Array using Silica-based PLC, “ Proc. OFC2004, WC4, Feb.

H. Takahashi [2003], “Recent progress on silica-based AWG waveguide multi/demultiplexers,” trans of IEICE, Vol. J86-C, No. 5, pp. 491-499, May

D3. Femtosecond Technology

Osamu Wada
Kobe University

Research and development project organization named Femtosecond Technology Research Association (FESTA) was established under the support of NEDO in 1995, and extensive research activities have been pursued at Tsukuba Lab. in Tsukuba as well as at different satellite laboratories organized by member companies. One of the most important aims of FESTA is to develop novel solid state photonic devices suitable for optical time-division multiplexing (OTDM) systems working in the femtosecond time domain. Conventional semiconductor-based optoelectronic devices and electronic ICs cannot function in the femtosecond time domain due to the limit of electronic lifetime in semiconductors. To overcome this limit, new device physics based on novel ultrafast phenomena should be investigated. Eleven research groups have devoted their efforts for developing new ultrafast devices including monolithic mode-locked semiconductor lasers, waveguide-type dispersion control devices for pulse compression, and a variety of all-optical switches such as symmetric Mach-Zehnder (SMZ) switches, intersubband transition switches, optical semiconductor amplifier (SOA)-based switches and wavelength converters, and also novel vertical structure optical switch based on organic film.

All the developed devices have shown basic capabilities of ultrafast operation and 1 Tbps class operation has been demonstrated in some of them. For example, monolithic mode-locked lasers with short cavity length have demonstrated 500 GHz and 1 THz repetition rate operation with extremely low jitter. Also 160 Gbps clock extraction function has been demonstrated for practical applications in real systems. SOA-based SMZ switch has been shown 160 and 320 Gbps-to-10 Gbps DEMUX operation and many more useful functions including 3R and wavelength conversion. It has been achieved to fabricate intersubband transition (ISBT) switches by developing new heterostructure materials based on AlAsSb/InGaAs/InP as well as AlGaN/GaN, both having large enough conduction band discontinuity in optical communication wavelength band. Waveguide-structure Sb-based ISBT switches have shown 1 THz DEMUX operation. Further efforts to lower the switching energy will make these devices practical in real systems. An interesting approach of all-optical switch has been demonstrated by a surface-normal switch based on J-aggregate dye film. Time-to-space conversion has been achieved; a series of 1-ps pulses has been extracted as light spots which are developed spatially on a 1-mm square switching plane. Such new switch function could be useful for packet header recognition for packet routing in OTDM systems. Novel physics and materials such as qunatum dots and photonic crystal have been extensively developed at FESTA. Quntum dot SOAs have been demonstrated to function as very fast response gate switch over 100 Gbps and also wavelength conversion switch through four-wave mixing in femtosecond speed. We have demonstrated that the polarization-insensitive operation can be achieved by controlling the dot shape, which would be extremely important for making these devices used in practical systems.

Details of FESTA works and related references have been summarized in a publication by Wada, O. in 2004.

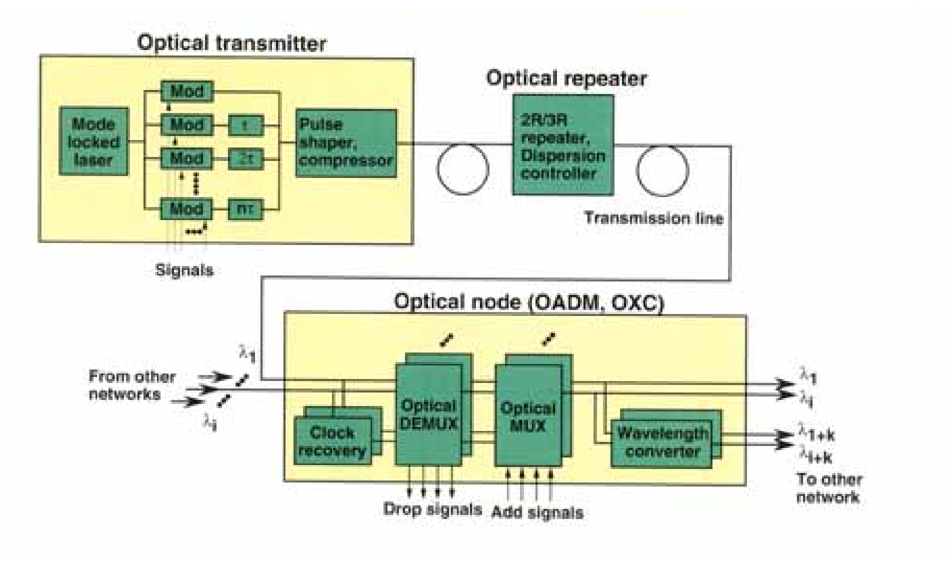


Fig. 1 Basic diagram of OTDM system.

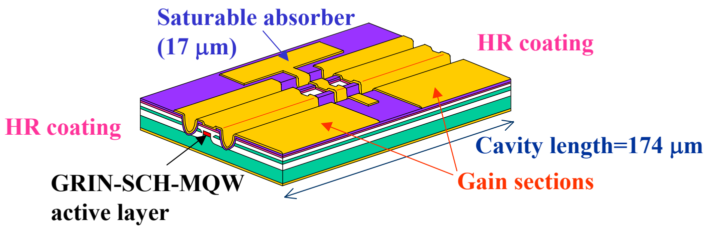


Fig.2 Structure of monolithic colliding pulse mode-locked laser for high repetition rate operation.

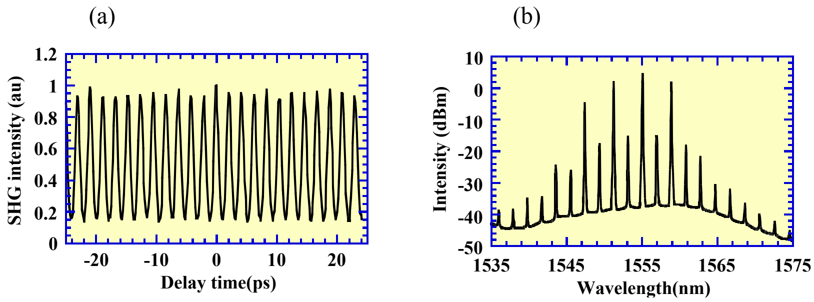


Fig. 3 Operation characteristics of mode-locked laser.

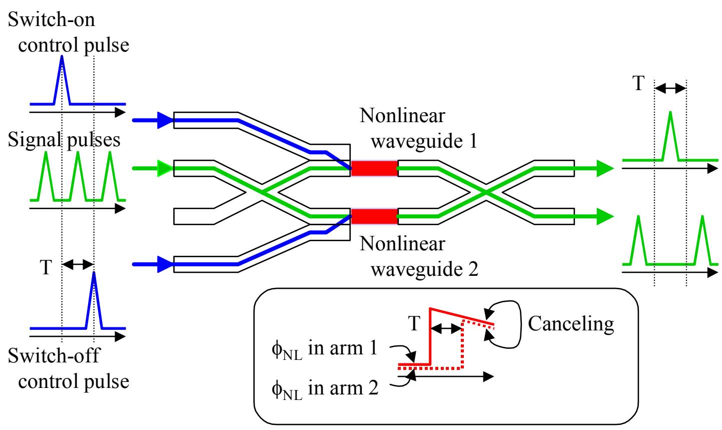


Fig. 4 Structure and operation principle of symmetric Mach-Zehnder interferometer all-optical switch using SOA nonlinear waveguides.

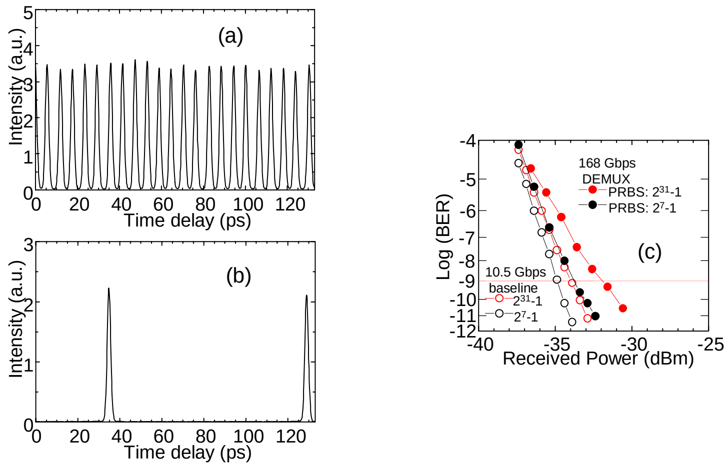


Fig. 5 Input and output signals and bit error rate data for 168 Gbps-to-10 Gbps DEMUX operation using SMZ all-optical switch.

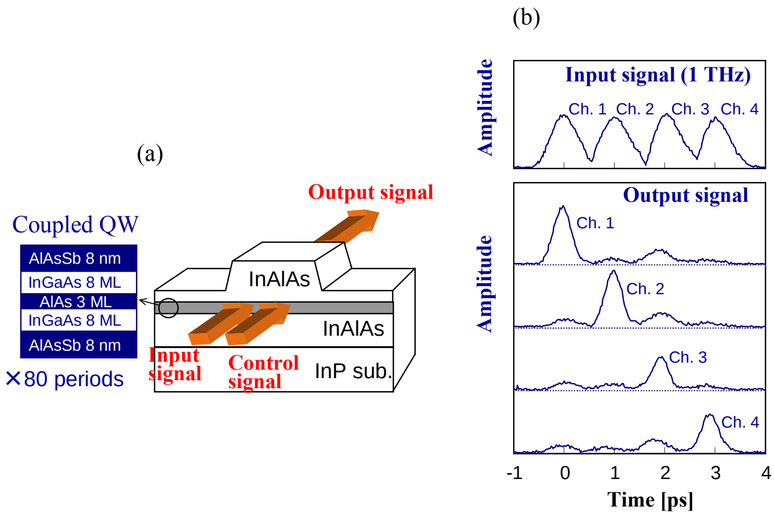


Fig. 6 Waveguide device structure of intersubband all-optical switch and demonstarated DEMUX operation for 1 THz signal.

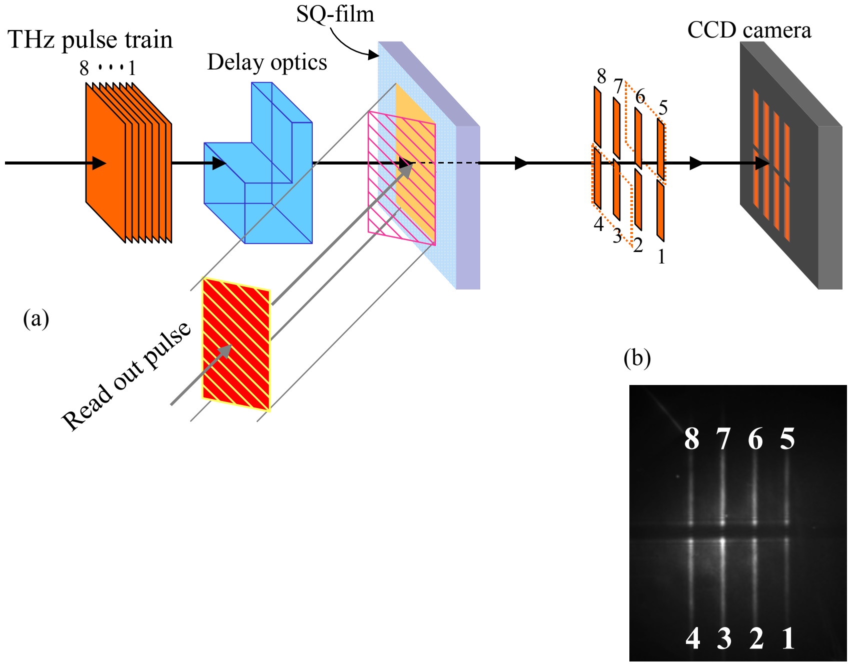


Fig. 7 Time-to-space conversion applied to DEMUX function for ultrafast pulses using organic (SQ) film-based surface normal all-optical switch.

References

Akiyama, T., Nikolai Georgiev, Teruo Mozume, Haruhiko Yoshida, Achanta Venu Gopal, and Osamu Wada [2001a]: "Nonlinearity and recovery time of 1.55 □m intersubband absorption in InGaAs/AlAs/AlAsSb coupled quantum wells", Electron. Lett. Vol.37, p.129

Akiyama, T., N. Georgiev, T. Mozume, H. Yoshida, A. V. Gopal, and O. Wada [2001b]: "Nonlinearity and recovery time of 1.55 □m intersubband absorption in InGaAs/AlAs/AlAsSb coupled quantum wells", Electron. Letts. Vlol.37, 129

Akiyama, T., N. Georgiev, T. Mozume, H. Yoshida, A. V. Gopal, and O. Wada [2002]: "1.55 um picosecond all-optical switching by using absorption in InGaAs-AlAs-AlAsSb coupled quantum wells", IEEE Photon. Tech. Letts. Vol.14, 495

Arahira, S., and Y. Ogawa [2002], '480-GHz subharmonic synchronous mode locking in a short-cavity colliding-pulse mode-locking laser diode', IEEE Photon. Technol. Lett., vol.14, no.4, p.537

Arahira, S., S. Sasaki, K. Tachibana, and Y. Ogawa [2004], 'All-optical 160-Gb/s clock extraction with a mode-locked laser diode module', IEEE Photon. Technol. Lett., vol.16, no.6, p.15658.

Dorren, , X. Yang, D. Lenstra, H. de Waardt, G. D. Khoe, T. Simoyama, H. Ishikawa, H. Kawashima, and T. Hasama[2003], "Ultrafast refractive-index dynamics in a multiquantum-well semiconductor optical amplifier ", JIEEE Photon. Technol. Lett., vol.15, pp.792-794

Fiuruki, M., I. Iwasa, S. Tatsuura, Y. Sato, M. Tian, T. Matsubara, H. Mitsu, M. Naruse(NICT), F. Kubota(NICT) [2004], "Ultrafast time-serial space-parallel converter using organic dye films," IEICE Trans. Electron.., Vol. E87-C, No. 7, p. 1161-1165

Gopal, A. V., H. Yoshida, T. Akiyama, A. Neogi, T. Mozume, N. Georgiev, and O. Wada [2001a]: "Absorption saturation of intersubband transition in InGaAs/AlAsSb quantum well characterized by absorption spectral analysis" Jpn. J. Appl. Phys. Lett. Vol.40, L1015

Gopal, A. V., H. Yoshida, A. Neogi, T. Mozume, N. Georgiev, T. Simoyama, O. Wada, and H. Ishikawa [2001b]: "Large improvement in intersubband saturation intensity in InGaAs/AlAsSb quantum well", Electron. Letts. Vol.37, 1265

Gopal, A. V., H. Yoshida, A. Neogi, T. Mozume, N. Georgiev, T. Simoyama, O. Wada, and H. Ishikawa [2002a]: "Intersubband absorption saturation in InGaAs/AlAsSb quantum wells", IEEE J. Quant. Electron vol.38, no.11, pp.1515-1520

Gopal, A. V., H. Yoshida, T. Simoyama, T. Mozume, and H. Ishikawa [2002b]: "Well width and doping density dependence of the 1.35 um intersubband transition in InGaAs/AlAsSb quantum wells", Appl. Phys. Letts. Vol.80, 4696

Gopal, A. V., H. Yoshida, T. Simoyama, T. Mozume, and H. Ishikawa [2002c]: "1.35 um intersubband transition in InGaAs/AlAsSb single quantum wells", Electron. Letts. Vol.38, p.600

Gopal, A. V., H. Yoshida, T. Simoyama. N. Georgiev, T. Mozume, H. Ishikawa[2003], "Understanding the ultra-low intersubband saturation intensity in InGaAs-AlAsSb quantum wells", IEEE J. Quantum Electron., vol.39, pp.299-305

IWASA, I., Makoto FURUKI, Minquan TIAN, Yasuhiro SATO, Lyong Sun PU, Satoshi TATSUURA, Osamu WADA[2002] "Ultrafast optical demultiplexer using a spincoated squarylium-dye film", IEICE Transaction of Electronics, Volume E85-C, No. 1, p. 167

Kanamoto, K., S. Lan, N. Ikeda, Y. Tanaka, Y. Sugimoto, K. Asakawa, and H. Ishikawa[2004], “Single photonic-crystal defect switch for all-optical ultrafast operation using two photon absorption”, IEICE Trans. Electron.,, Vol. E87-C, No. 7, p.1142

Lan, S., Satoshi Nishikawa, and Osamu Wada [2001a]: “Leveraging deep photonic bandgaps in photonic crystal impurity bands”, Applied Physics Letters, Vol. 78, p.2101

Lan, S., Satoshi Nishikawa, Osamu Wada[2001b], Kouichi Akahane, Yoshitaka Okada, and Mitsuo Kawabe: “Different responses of localized and extended excitons to exciton-exciton scattering manifested in excitation density-dependent photoluminescence excitation spectra”, Journal of Applied Physics, Vol. 89, p.6171

Lan, S., Satoshi Nishikawa, Hiroshi Ishikawa, and Osamu Wada[2001c]: “Design of impurity band-based photonic crystal waveguides and delay lines for ultrashort optical pulses”, Journal of Applied Physics, Vol. 90, p.4321

Lan, S., Satoshi Nishikawa, Hiroshi Ishikawa, and Osamu Wada[2002a]:“Engineering photonic crystal impurity bands for waveguides, all-optical switches and optical delay lines”, IEICE Transactions on Electronics, Vol. E85-C, p.181

Lan, S., and Hiroshi Ishikawa[2002b]: “Coupling of defect pairs and generation of dynamical band gaps in the impurity bands of nonlinear photonic crystals for all-optical switching”, Journal of Applied Physics, Vol. 91, p.2573

Lan, S., Satoshi Nishikawa, Yoshimasa Sugimoto, Naoki Ikeda, Kiyoshi Asakawa, and Hiroshi Ishikawa [2002c]: “Analysis of defect coupling in one- and two-dimensional photonic crystals”, Physical Review B, Vol. 65, p.165208

Lan, S., Satoshi Nishikawa, Hiroshi Ishikawa, Osamu Wada, Kouichi Akahane, Hai-Zhi Song, Yoshitaka Okada, and Mitsuo Kawabe [2002d]: “Comparison of the optical properties of InGaAs/GaAs(311)B two-dimensional quantum dot superlattices and quantum wells”, Japanese Journal of Applied Physics, Vol. 41, p.2807

Lan, S., and Hiroshi Ishikawa [2002e]: “Reflection type all-optical switch for ultrashort pulses by modulating the absorption of a single asymmetrically confined photonic crystal defect”, Optics Letters, Vol.

27, p.1259

Lan, S., and Hiroshi Ishikawa [2002f]: “Broadband waveguide intersections with low cross-talk in photonic crystal circuits”, Optics Letters vol.27,no.17, pp.1567

Lan, S., K. Kanamoto, T. Yang, S. Nishikawa, Y. Sigimoto, N. Ikeda, H. Nakamura, K. Asakawa, and H. Ishikawa[2003]: “Similar role of waveguide bend in photonic crystal circuit and disordered defects in coupled cavity waveguides: An intrinsic problem in realizing photonic crystal circuits”, Phys. Rev., vol.B67, pp.115208-115215

Nakamura, S., Y. Ueno, and K. Tajima [2001], "168-Gb/s all-optical wavelength conversion with a Symmetric-Mach-Zehnder-type switch", IEEE Photon. Technol. Lett., Vol. 13, No. 10, pp. 1091-1093.

Neogi, A., H. Yoshida, T. Mozume, N. Georgiev and O. Wada [2001a]: "Temperature-insensitive intersubband-transitions in InGaAs/AlAsSb multiple quantum well designed for optical communication wavelength" Jpn. J. Appl. Phys. Lett., vol. 40, p. L558

Neogi, A., H. Yoshida, and O. Wada [2001b]: "Effect of thermally induced charge-carrier transfer on near-infrared intersubband transitions in $In_xGa_{1-x}As/AlAs/AlAs_{1-y}Sb_y/InP$ coupled quantum-well structure", Phys. Rev. B. Vol.63, p.235320

Neogi, A., H. Yoshida, T. Mozume, N. Georgiev, T. Akiyama, O. Wada, A. Tackeuchi [2001c]: "Ultrafast all-optical modulation by near-infrared intersubband transition in n-doped InGaAs/AlAsSb quantum wells", Opt. & Quantum Electron., Vol.33, (2001).

Neogi, A, H. Yoshida, T. Mozume, N. Georgiev, T. Akiyama and O. Wada [2001d]: "Intersubband Transition in InGaAs/AlAsSb/InP coupled double quantum well structures optimized for communication wavelength operation", Electron. Lett. vol. 36, 1972 (2000); Eratta - vol. 37, p.203

Neogi, A., H. Yoshida, T. Mozume, N. Georgiev, and O. Wada [2001e]: "Intersubband transition and Ultrafast all-optical switching in coupled InGaAs/AlAsSb quantum well" Select. Top. J. of Quant. Electron, p. 710

Nishikawa, S., S. Lan, N. Ikeda, Y. Sugimoto, H. Ishikawa, K. Asakawa [2002a], “Optical characterization of photonic delay lines based on one-dimensional coupled defects”, Optics Lett., vol.27, no.23, pp.2079-2081

Nishikawa, S., S. Lan, N. Ikeda, Y. Sugimoto, H. Ishikawa, K. Asakawa [2002b], “Design and fabrication of impurity band-based photonic crystal waveguide for optical delay lines”, Appl. Phys. Lett.,vol.81, no.11, pp.1946-1948

Nishikawa, S., S. Kohmoto, H. Nakamura, Y. Sugimoto, N. Ikeda, T. Ishikawa,T. Akiyama, H. Ishikawa, O. Wada [2002c]: "Dephasing time characterization of InAs quantum dots by degenerate four-wave mixing measurement", Physica E, Vol.13, p.273

Nishikawa, S., S. Lan, O. Wada, T. Nishimura, K. Akahane and M. Kawabe [2002d]: "Lateral-Coupling-Induced Modification of Density of States and Exciton Dynamics in High-Density Ordered In0.4Ga0.6As/GaAs(311)B Quantum Dot Arrays", Jpn. J. Appl. Phys., Vol.41, p.3766

Tajima, K., S. Nakamura, A. Furukawa, and T. Sasaki [2004], “Hybrid-integrated Symmetric Mach-Zehnder all-optical switches and ultrafast signal processing”, IEICE Trans. Electron. Vol. E87-C, No. 7, pp. 1119-1125

Tatsuura, S., Osamu Wada, Makoto Furuki, Minquan Tian, Yasuhiro Sato, Izumi Iwasa, Lyong Sun Pu [2001a]:” Femtosecond two-dimensional serial□to□parallel pulse converter using a squarylium Dye J-aggregate film”, Opt.Quantum Electron. Vol.33, p.1089

Tatsuura, S., Osamu Wada, Makoto Furuki, Minquan Tian, Yasuhiro Sato, Izumi Iwasa, Lyong Sun Pu [2001b]: “All-optical two-dimensional serial□to□parallel Pulse converter using an organic film with femtosecond optical response”, Jpn.J.Appl.Phys. Vol.40, p.2731

Tatsuura, S., O.Wada, M.Tian, M.Furuki, Y.Sato, I.Iwasa, L.S.Pu, and H.Kawashima [2001c]: “Large kai(3) of squarylium dye J-aggregates measured using the Z-scan technique” Appl.Phys.Lett. Vol.79, p.2517 (2001)

Tatsuura, S., M. Tian, M. Furuki, Y. Sato, I. Izawa, L. S. Pu, H. Kawashima, H. Ishikawa [2002]: “Microstructure of squarylium dye J aggregate films examined on the basis of optical behavior at low temperature”, Appl. Phys. Lett., vol.81, p.2704-2706

Yoshida, H., T. Simoyama, A. V. Gopal, J. Kasai, T. Mozume, and H. Ishikawa [2004]: "Ultrafast All-Optical Switching and Modulation Using Intersubband Transitions in Coupled Quantum Well Structures", IEICE Trans. Electron., Vol.E-87C, p.1134 (Invited paper)

Wada, O. [2004]: "Femtosecond all-optical devices for ultrafast communication and signal processing," New J. Phys., Vol. 6, p.183, http://stacks.iop.org/1367-2630/6/183

D4.THz Technology

Hiromasa Ito

Tohoku University

The THz-wave region has attracted significant interest in these years. The generation of THz radiation by optical rectification or photo-conductive switching has been extensively studied by using femto-second laser pulses. Applied research, such as time domain spectroscopy (TDS), makes use of the high time resolution of THz-waves and ultra broad bandwidth up to the THz region.

In contrast, monochromatic THz-wave source developments have been extensively performed. Widely tunable monochromatic THz source based on the polariton mode scattering of LiNbO3 or MgO: LiNbO3 crystals showed great advancement. Those are THz parametric oscillator (TPO) and THz parametric generator (TPG). The TPO/TPG has proved to be a useful coherent THz-wave source which operates at room temperature. It is wide tunable and also random fast frequency access in 100- to 300 μm (1- to 3 THz) range and can emit peak powers of up to several tenths of a milli-Watt or more.

The difference between a TPO and a TPG is that the former has an idler cavity while the latter has not. TPO requires only one pump source, and its linewidth is several tens of GHz. Recently developed ring cavity TPO with galvano scanner makes the TPO's frequency response possible up to 1ms (1 kHz), and variety of new spectroscopic imaging and analyzing applications are expected.

The linewidth of TPG is in nature wider than that of TPO. However, by introducing an injection seeding technique to the idler, TPG spectrum is narrowed to the Fourier transform limit of the pulsewidth (~100MHz or less). The purity of the THz-wave frequency was dramatically improved to $\Delta\nu/\nu < 10^{-4}$. Simultaneously, oscillation with higher output power, wider tenability and good stability, was demonstrated.

Surface-emitted THz-wave generation using bulk slanted-PPLN and slab optical waveguided PPLN was successfully demonstrated. The QPM condition of the slanted-PPLN works well in both pulsed and cw operation. Dual wavelength sources foe excitation of DFG were constructed from all telecom components worked at 1.55 μm. The waveguided structure is key for increasing conversion efficiency especially under the CW operation.

Remarkable advancements were reported for quantum cascaded laser (QCL) research. Lower than 3

THz operation is one of the big target right now especially for homeland security purpose. QCL with new materials of InAs/GaSb has been investigated extensively. Though relatively limited tuning range of one single tip QCL, there are no doubts that it will efficiently work if the THz application targets are clearly fixed.

References

Imai, K., K. Kawase, J. Shikata, H. Minamide, and H. Ito [2001], "An injection-seeded terahertz-wave parametric oscillator", Applied Physics Letters, vol. 78, pp. 1026-1028

Kawase, K., J. Shikata, K. Imai, and H. Ito [2001], "A Transform-limited, Narrow-Linewidth, THz-wave Parametric Generator", Applied Physics Letters, vol. 78 no. 19, pp. 2819-2821

Imai, K., K. Kawase, and H. Ito [2001], "A frequency-agile terahertz-wave parametric oscillator", Opt. Express 8, pp. 699-704

Ito, H., T. Hatanaka, S. Haidar, K. Nakamura, K. Kawase, and T. Taniuchi [2001], "Periodically poled $LiNbO_3$ OPO for generating Mid IR to terahertz waves", Ferroelectrics, vol.253, pp.95-104

Sato, A., K. Kawase, H. Minamide, S. Wada, and H. Ito [2001], "A Tabletop Terahertz-Wave Parametric Generator Using a Diode-Pumped Solid-State Laser", Trends in Optics and Photonics Series (TOPS), vol. 50, pp. 456-460

Sato, A., K. Kawase, H. Minamide, S. Wada, and H. Ito [2001], "Tabletop terahertz-wave parametric generator using a compact, diode-pumped Nd:YAG laser", Review of Scientific Instruments, vol. 72, No. 9, pp. 3501-3504

Kawase, K., J. Shikata, H. Minamide, K. Imai, and H. Ito [2001], "Arrayed silicon prism coupler for a THz-wave parametric oscillator", Applied Optics, vol.40, No.9, pp.1423-1426

Avetisyan, Y., Y. Sasaki, and H. Ito [2001], "Analysis of THz-wave surface-emitted difference-frequency generation in periodically poled lithium niobate waveguide", Applied Physics B, vol.73, pp.511-514

Kawase, K., H. Minamide, K. Imai, J. Shikata, and H. Ito [2002], "Injection-seeded terahertz-wave parametric generator with wide tunability", Applied Physics Letters, vol.80, no.2, pp.195-197

Kawase, K., J. Shikata, and H. Ito [2002], "Terahertz wave parametric source (Topical Review)", Journal of Physics D: Applied Physics, vol.35, no.3, pp.R1-R14

Karino, K., J. Shikata, K. Kawase, H. Ito, and I. Sahashi [2002], "Terahertz-wave parametric generation characteristics of MgO: $LiNbO_3$", Electronics and Communications in Japan, Part 2, vol.85, no.4, pp.22-29

Kawase, K., S. Ariyoshi, C. Otani, H. Minamide, K. Imai, J. Shikata, and H. Ito [2002], "Widely tunable THz-wave parametric generator for imaging system", RIKEN Review, no.47, pp.48-51

Sato, A., K. Imai, K. Kawase, H. Minamide, S. Wada, and H. Ito [2002], "Narrow-linewidth operation of a compact THz-wave parametric generator system", Optics Communications, vol.207, no.1-6, pp.53-359

Ito, H., and K. Kawase [2002], "Tunable compact THz sources and their application", Trends in Optics and Photonics (TOPS), vol.79, pp.75-77

Imai, K., K. Kawase, H. Minamide, and H. Ito [2002], "Achromatically injection-seeded terahertz-wave parametric generator", Trends in Optics and Photonics (TOPS), vol.79, pp.233-235

Sasaki, Y., Y. Avetisyan, K. Kawase, and H. Ito [2002], "Tunable THz-wave difference frequency generation from slant-stripe-type PPLN based on surface-emitting geometry", Trends in Optics and Photonics (TOPS), vol. 79, pp. 20-22

Imai, K., K. Kawase, M. H., and H. Ito [2002], "Achromatically injection-seeded terahertz-wave parametric generator", Optics Letters, vol.27, no.24, pp.2173-2175

Sasaki, Y., A. Yuri, K. Kawase, and H. Ito [2002], "Terahertz-wave surface-emitted difference frequency generation in slant-stripe-type periodically poled $LiNbO_3$ crystal", Applied Physics Letters, vol.81, issue 18, pp.3323-3325

Shikata, J., K. Kawase, T. Taniuchi, and H. Ito [2002], "Fourier-Transform Spectrometer with a Terahertz-Wave Parametric Generator", Japanese Journal of Applied Physics, part 1, vol.41, no.1, pp.134-138

Imai, K., S. Sugawara, J. Shikata, K. Kawase, H. Minamide, and H. Ito [2003], "The effect of injection seeding on terahertz parametric oscillation", Electronics and Communications in Japan, Part 2, vol.86, no.1, pp.26-35

Imai, K., K. Kawase, H. Minamide, and H. Ito [2003], "A rapidly tunable terahertz-wave parametric oscillator", Electronics and Communications in Japan, Part 2, vol.86, no.4, pp.18-26

Watanabe, Y., K. Kawase, T. Ikari, H. Ito, Y. Ishikawa, and H. Minamide [2003], "Spatial pattern separation of chemicals and frequency-independent components by Terahertz spectroscopic imaging", Applied Optics, vol.42, issue 28, pp.5744-5748

Kawase, K., J. Shikata, and H. Ito [2003], "Widely tunable THz-wave generation using nonlinear optics", Solid-state mid infrared laser sources, Edited by I. T. Sorokina and K. L. Vodopyanov, pp.433-461

Watanabe, Y., K. Kawase, T. Ikari, H. Ito, Y. Ishikawa and H. Minamide [2003], "Component spatial pattern analysis of chemicals using terahertz spectroscopic imaging", Applied Physics Letters, vol.83, no.4, pp.800-802

Imai, K., K. Kawase, H. Minamide, and H. Ito [2003], "A rapidly tunable terahertz-wave parametric oscillator", Electronics and Communications in Japan, part 2, vol.86, no.4, pp.18-26

Watanabe, Y., K. Kawase, T. Ikari, H. Ito, Y. Ishikawa, and H. Minamide [2003], "Spatial Pattern Separation of Chemicals and Frequency-Independent Components by Terahertz Spectroscopic Imaging", Applied Optics, vol.42, issue 28, pp.5744-5748

Sasaki, Y., H. Yokoyama, and H. Ito [2004], "Dual-wavelength optical-pulse source based on diode lasers for high-repetition-rate, narrow-bandwidth terahertz-wave generation", Optics Express, vol. 12, no. 14, pp.3066-3071

Watanabe, Y., K. Kawase, T. Ikari, H. Ito, Y. Ishikawa, and H. Minamide [2004], "Component analysis of chemical mixtures using terahertz spectroscopic imaging", Optics Communications, vol.234, pp.125-129

Ohtani, K., K. Fujita and H. Ohno [2004], "A low threshold current density InAs/AlGaSb superlattice quantum cascade laser operating at 14μm", Jpn. J. Appl. Phys., vol.43, pp.L879-881.

Takahashi, M., Y. Ishikawa, J. Nishizawa, and H. Ito [2005], "Low-frequency vibrational modes of riboflavin and related compounds", Chemical Physics Letters 401, pp.475-482

D5. Sensing Photonics

Kazuo Hotate
Univesity of Tokyo

Among various types of optical fiber sensors, fiber optic distributed and multiplexed sensing technologies have been intensively studied, which have provided schemes to measure, for example, distribution of longitudinal strain or lateral force along an optical fiber. In these systems, the fiber can act as nerve networks to sense damage of materials or structures, in which the fiber is embedded. These techniques are the key to realize “smart materials” and “smart structures” for improving reliability, safety and security of the society (see Fig.1). The 16th International Conference on Optical Fiber Sensors (OFS-16) was held in Nara, Japan, in October, 2003. In the conference, almost half of the papers were related to these technologies. Some representatives are described bellow.

A down-shifted frequency of Brillouin scattering caused in a fiber is changed in proportion to longitudinal strain applied to it. By this phenomenon, a scheme for fiber-optic distributed strain sensing was proposed and developed in Japan, in which optical time domain reflectomerty technique was used for the distribution measurement. However, in this scheme based on pulsed-lightwave, spatial resolution was limited around 1m, and long measurement time is required for obtaining enough signal to noise ratio. On the contrary, another technique based on continuous lightwave has recently been proposed also by Japanese researchers. In this technique, pump and prove lightwaves, propagating in the fiber in opposite directions, are modulated in frequency, which realizes localized excitation of stimulated Brillouin scattering. By this “Brillouin Optical Correlation Domain Analysis: BOCDA,” a spatial resolution of 1.0cm was demonstrated.

The BOCDA technique has recently been applied to find clacks caused in a concrete block, in which the sensing fiber is embedded. Clacks with sub millimeter width have successfully been recognized, for the first time, through strain distribution caused by the crack along the fiber. Another feature of this technique is fast measurement speed. About 60Hz sampling rate has been demonstrated, which is 10^4 times faster than the pulsed lightwave technique. Dynamic strain measurement at multiple arbitrary points along a fiber, which is pasted on a building model, has also been demonstrated under vibration excited by an earthquake waveform, as shown in Fig.2. Additionally, a simplified and low cost configuration for the BOCDA has also been developed. The BOCDA is only one technique that can realize both the high spatial resolution and the fast measurement speed. This technique was selected as the Hasunuma Prize in 2002 from the Society of Instrument and Control Engineers, SICE.

Basic principle of the BOCDA technique is “synthesis of optical coherence function: SOCF,” in which arbitrary shapes of optical coherence function can be synthesized by modulating optical frequency of a light source. This is invented also in Japan as a technique for distribution measurement. With the SOCF technique, a novel multiplexing way of fiber Bragg grating (FBG) strain sensors has been proposed and experimented. In traditional techniques, FBGs with different Bragg wavelength were required for wavelength division multiplexing. In these systems, number of the FBGs is limited and the system becomes expensive. On the contrary, FBGs with the same Bragg wavelength can be multiplexed by using the SOCF technique. Multiplexed and dynamic strain sensing has been successfully demonstrated by the technique.

By also applying the SOCF technique, a fiber optic distributed force sensing has been proposed and studied. Sensing mechanism is polarization mode coupling induced by lateral force in a polarization maintaining fiber. Propagation speed difference between the two polarization modes is used to resolve the force-applied position. Introducing a special laser diode, a SSG-DBR LD invented by NTT, Japan, which has quite a wide frequency tuning range, the spatial resolution has been improved to be 20cm.

Techniques for diagnosing fiber optic subscriber networks have also been studied using SOCF technique. We must measure the reflectivity distribution around the optical elements, which locate at the end of the network beyond, for example, a 5km length optical fiber, with cm order spatial resolution. Recently, it has been found that the SOCF technique can also measure reflectivity distribution at a region beyond the coherence length of a laser source. By this scheme, 10cm spatial resolution with 5km measurement range has been demonstrated.

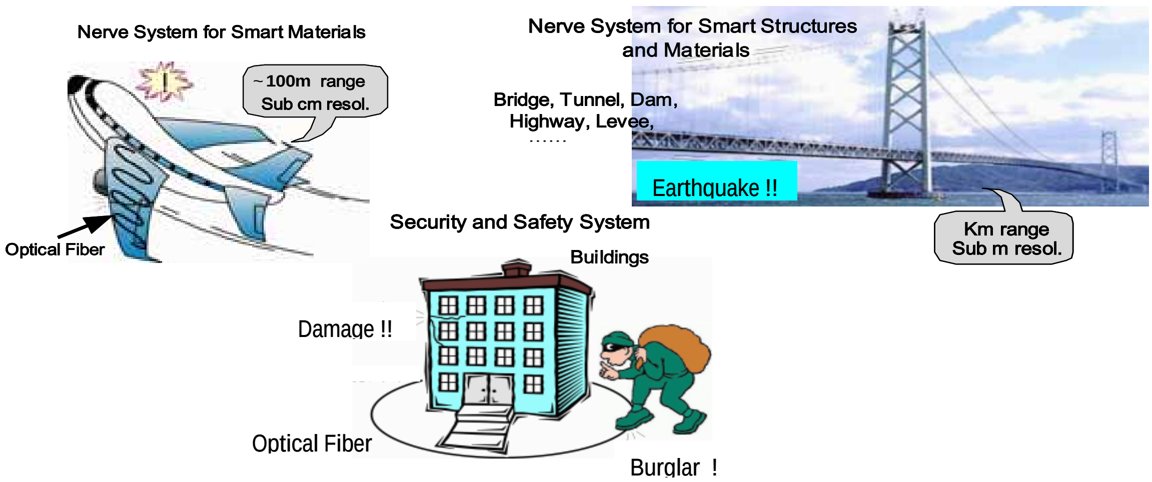


Fig. 1 Fiber optic nerve systems for smart structures and smart materials.

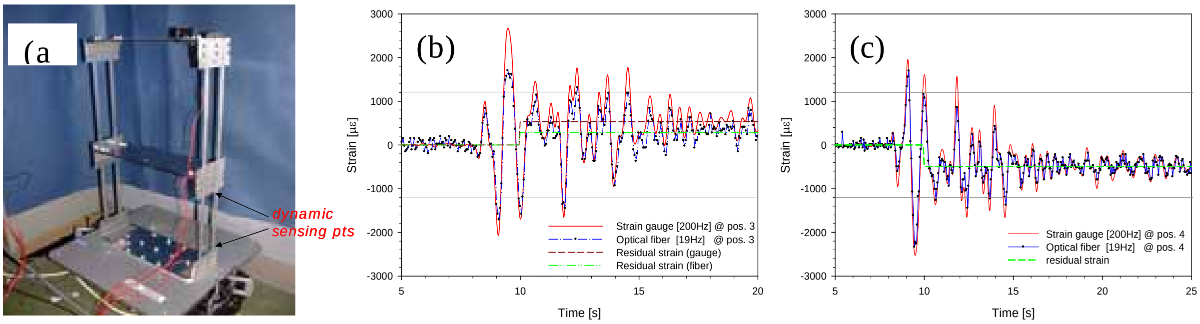


Fig. 2 Dynamic and multiple-points strain measurement of a building model by BOCDA system.
(a) Building model with a fiber, and (b) and (c) dynamic strain measurementε_y

References

Hotate, K., and M. Tanaka [2001], "Correlation-based continuous-wave techniques provide high spatial resolution for distributed fiber optic sensing", SPIE OE Magazine, 11, pp.36-40 <Invited>-ε_y

Hotate, K., and M. Tanaka [2001], "Correlation-based continuous-wave technique for fiber optic distributed strain measurement using Brillouin scattering with cm-order spatial resolution —Applications to smart materials—", IEICE Trans. on Electron., vol.E84-C, no.12, pp.1823-1828 <Invited>

Hotate, K., and M. Tanaka [2002], "Distributed fiber Brillouin strain sensing with 1cm spatial resolution by correlation-based continuous-wave Technique", IEEE Photon. Tech. Lett., vol.14, no.2, pp.179-181

Hotate, K., and M. Tanaka [2002], "Application of correlation-based continuous-wave technique for fiber Brillouin sensing to measurement of strain distribution on a Small Size Material", IEEE Photonic Technology Letters, vol.14, no.5, pp.675-677

Hotate, K. [2002], "Application of synthesized coherence function to distributed optical sensing," IOP Measurement Sci. and Tech., vol.13, no.11, pp.1746-1755

Hotate, K. [2002], "Recent progress in Brillouin based fiber sensor technology", 15th Intern. Conf. on Optical Fiber Sensors (OFS-15), Portland, WC1, pp.297-300 <Invited>

Hotate, K. and S. S. L. Ong [2002], "Distributed fiber Brillouin strain sensing by correlation-based continuous-wave technique –cm-order spatial resolution and dynamic strain measurement–", SPIE

Photonics Asia, Shanghai, 4920-51, pp.299-310 <Invited>

Hotate, K. and M. Kashiwagi [2003], “High spatial resolution reflectometry for optical subscriber networks by synthesis of optical coherence function with measurement range enhancement”, IEICE Trans. on Electron., volE86-C, no.2, pp.213-217

Hotate, K. and S. S. L. Ong [2003], “Distributed dynamic strain measurement using a correlation-based Brillouin sensing system”, IEEE Photon. Technol. Lett., vol.15, no.2, pp.272-274

Hotate, K. [2003], “Optical Fiber Sensors for Smart Materials/Structures and Optical Communicaitons”, International Meeting on New Frontiers for Ubiquitous IT Services, Atsugi <Invited>

Hotate, K. [2003], “Fiber Optic Distributed Sensing for Smart Materials and Structures by Optical Correlation Domain Technique with Continuous Lightwave”, 16th Intern. Conf. on Optical Fiber Sensors (OFS-16), Nara, SS-6, pp.510-513 <Invited>

Hotate, K., M. Enyama, S. Yamashita and Y. Nasu [2004], “A multiplexing technique of fiber Bragg grating sensors with the same reflection wavelength by the synthesis of optical coherence function”, Measurement Sci. and Technol., vol. 15, no.1, pp. 148-153

Hotate, K., A. Kuramoto and Z.-Y. He [2004], “Optical fiber stress-location measurement by synthesis of binary optical coherence function,” IEEE Photon. Technol. Lett., vol. 16, no.2, pp. 578-580

Hotate, K. [2004], “Trends and prospects for optical distributed sensing －Fiber-optic nerve systems for smart materials and smart-structures－”, SPIE Vol.5502, Second European Workshop on Optical Fiber Sensors, Santander, pp.51-58 <Invited>

Hotate, K. [2004], “Potential applications of optical fiber sensing technology for future society”, International Symposium on Network and Center-Based Research for Smart Structures Technologies and Earthquake Engineering, Osaka <Invited>

Hotate, K. [2004], “Fiber optic nerve systems for smart materials and smart structures”, SPIE Optics East 2004, Philadelphia, 5604-1, pp.1-10 <Invited>

Hotate, K. [2004], “Optical Fiber Sensors for Smart Materials/Structures and Optical Communicaitons”, Chapter 9 in “New Photonics Technologies for the Information Age”, ed., by S. Sudo and K. Okamoto, Artech House, pp.159-179

He, Z. and K. Hotate [2002], “Distributed Fiber-optic stress-location measurement by arbitrary shaping of optical coherence function”, Jour. of Lightwave Tech., vol.20, no.9, pp.1715-1723

Zhu, B., T. Saida and K. Hotate [2003], “Variable optical filter using dynamic grating in Er doped fiber controlled by synthesis of optical coherence function: Proposal and experimental verification”, IEICE Trans. on Electron., IEICE Trans., vol.E86-C, no.1, pp.97-99

Kashiwagi, M. and K. Hotate [2004], “Elongation of Measurement Range by Successively Shifting Measurement Window in a High Spatial Resolution Reflectometry for Optical Subscriber Networks by Synthesis of Optical Coherence Function”, Measurement Sci. and Technol., vo.15, no.8, pp. 1512-1518

Enyama, M. and K. Hotate [2004], “Dynamic and random-access strain measurement by fiber Bragg gratings with synthesis of optical coherence function”, SPIE Optics East 2004, Philadelphia, 5589-20, pp.144-153 <Invited>

D6. Photonic signal processing

Takashi Kurokawa
Tokyo University of Agriculture and Technology

The use of ultra-short optical pulses has been highly expected in various fields of technology such as high-speed fiber optic communication system, high-precision optical measurement, and laser processing. These applications have increased the demands for synthesizing the optical short pulses with arbitrary waveforms and evaluating the quality of ultra-short optical pulses. So we are constructing optical short pulse synthesizers and analyzers.

Frequency decomposed parallel photonic signal processing using arrayed-waveguide grating is very suitable for Tbit/s signals because the most high-speed electronics can be operated at 100 Gbit/s or less. Figure 1 shows the operation principle. The input optical pulse or the light from the optical frequency comb is decomposed by the first AWG, the phase and the amplitude of each frequency component is modulated, and synthesized by the second AWG. Various kinds of photonic signal processing, including waveform shaping, arbitrary waveform generation, optical code division multiplexing, can be achieved. For such an application, we have developed analogue and digital type optical pulse synthesizers using

AWGs. The analogue type optical synthesizer has advantages that it can be operated for an optical pulse train with any repetition frequency and has almost flat transmission profile. On the other hand, the digital type optical synthesizer is usually applied to arbitrary waveform pulse generation in combination with optical frequency comb and the frequency domain optical code division multiplexing (OCDM).

We also have demonstrated a novel waveform measurement system of ultra-short optical pulses based on the two-photon absorption process in a Si-image sensor. Using an interferometer with a tilt mirror in the reference path, the relative time difference between the signal and reference pulses is spatially distributed on the Si-image sensor, so the intensity auto-correlation is monitored as an image at a time without using moving parts.

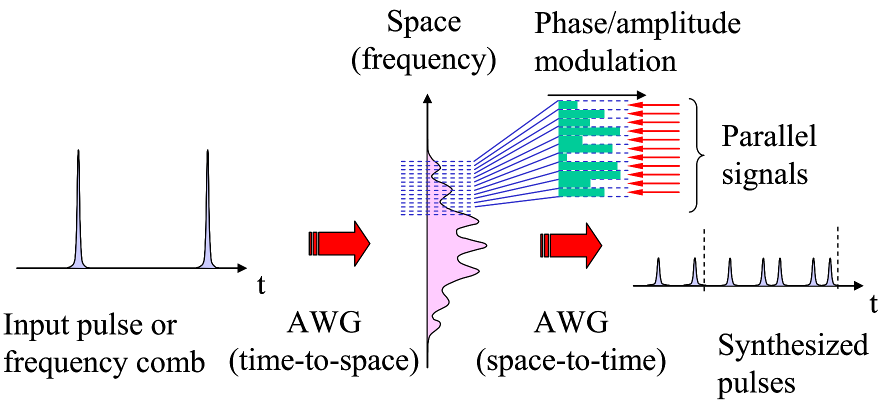


Fig. 1 Principle of frequency decomposed parallel photonic signal processing .

References

Kurokawa, T.[2001], "Optical Signal Processing for Communication and Information Systems", Proc. CLEO/Pacific Rim, Makuhari, Vol.□, pp.532-534 <Tutorial, Invited>.

Sakai, F., Y. Tanaka, and T. Kurokawa [2001], "Two-photon absorption in a Si-photodiode array and its application to ultrafast optical pulse waveform measurement", OSA Annual Meeting and Exhibit, WE2, Long Beach,.

Tanaka, Y., P. G. Chua, T. Kurokawa, H. Tsuda, M. Naganuma, and M. Takeda [2002], “Reflectometry based on two-photon absorption of a silicon avalanche photodiode”, Proc. 15th Optical Fiber Sensors Conference, Portland, pp.577-580.

Tanaka, Y., T. Kurokawa [2002], “Profilometry using two-photon absorption of silicon avalanche photodiode”, Proceedings of SPIE, Vol. 4919, pp.102-109 <Invited>.

Itoh, Y., K. Aizawa, Y. Tanaka, H. Tsuda [2003], “Measurement of short optical pulse spectra using arrayed waveguide grating”, Proc. 6th International Symposium on Contemporary Photonicsn Technology, Post-Deadline papers, p.7.

Tanaka, Y., N. Sako, T. Kurokawa, H. Tsuda and M. Takeda [2003], “Profilometry based on two-photon absorption in a silicon avalanche photodiode”, Optics Letters, vol.28, no.6, pp402-404.

Yamanaka, A., M. Yamamoto, Y. Tanaka, T. Kurokawa, T. Kawanishi and M. Izutsu [2003], “A Multi-wavelength light source using an optical single-side band modulator an arrayed waveguide grating”, Proc. 5th Pacific Rim Conference on Lasers and Electro-Optics, Taipei, p.714.

Sako, N., S. Imoto, Y. Tanaka and T. Kurokawa [2003], “Measurement accuracy of profilometry based on two-photon absorption”, Proc. 5th Pacific Rim Conference on Lasers and Electro-Optics, Taipei, p.299.

Itoh, Y., K. Aizawa, Y. Tanaka, H. Tsuda and T. Kurokawa [2003], “Optical Spectrum analyzer for optical short pulses”, Proc. 5th Pacific Rim Conference on Lasers and Electro-Optics, Taipei, p.41.

Imoto, S., N. Sako, Y. Tanaka and T. Kurokawa [2003], “Accuracy improvement of two-photon absorption based measurement by temperature controlled Si-photodetecter”, Proc. 5th Pacific Rim Conference on Lasers and Electro-Optics, Taipei, p.516.

Nezu, T., Y. Tanaka and T. Kurokawa [2003], “Delayed self-heterodyne linewidth measurement of fiber Bragg grating laser”, Proc. 5th Pacific Rim Conference on Lasers and Electro-Optics, Taipei, p.388.

Suzuki, T., Y. Shibata and H. Tsuda [2003], “Design and the fabrication of the small v-bend optical waveguide using an elliptic mirror”, Proc. 11th European Conference on Integrated Optics, Prague, Czech.

Suzuki, T., Y. Shibata and H. Tsuda [2003], “Small v-bend optical silica-waveguide using an elliptic mirror for planar lightwave circuits”, Proc. 9th Microoptics Conference, Tokyo, H-20.

Tate, A., T. Suzuki, Y. Shibata and H. Tsuda [2004], “Proposal of WDM multi/demultiplexer with deep grooves and parabolic mirrors”, Proc. 7th International Symposium on Contemporary Photonics Technology, Tokyo, PDP-1.

Hakamata, M., and H. Tsuda [2004], “Diffractive optical elements using the sub-wavelength scale pillar array structure," SPIE Photonics West, San Jose, pp.5360-5363.

Aizawa, K., H. Aoki, Y. Ito, Y. Tanaka and T. Kurokawa [2004], "Waveform measurement of ultra-short optical pulses based on two photon absorption in Si-image sensor", ICO International Conference on Optics & Photonics in Technology Frontier, Tokyo, pp.331-332.

Suzuki, T., K. Mandai, H. Tsuda, T. Kurokawa and T. Kawanishi [2004], "Optical pulse generation by controlling the sidebands of the phase modulated light", OECC/COIN2004 (9th Optoelectronics and Communications Conference/ 3rd International conference on Optical Internet, Yokohama, pp.738-739.

Ishida, M., T. Suzuki and H. Tsuda [2004], "180 degree-bend structures using a double elliptic mirror in a slab waveguide", OECC/COIN2004 (9th Optoelectronics and Communications Conference/ 3rd International conference on Optical Internet, Yokohama, 13F1-4.

Suzuki, T., Y. Shibata, K. Masuda and H. Tsuda [2004], "Compact arrowhead arrayed waveguide grating using v-bend optical waveguides," Topical Meeting on Integrated Photonics Research, San Francisco, IFH2.

Mandai, K., T. Suzuki, H. Tsuda, T. Kurokawa and T. Kawanishi [2004], "Arbitrary optical short pulse generator using a high-resolution arrayed-waveguide grating", International Topical Meeting on Microwave Photonics, Ogunquit, pp.107-110.

D7. Microwave Photonics

Tadao Nagatsuma
NTT Corporation

Microwave photonics, which merges radio-wave (microwave) and photonics technologies, has made a steady progress since 1990's. The first use of the term microwave photonics was at International Microwave Photonics (MWP) Conference held at Kyoto in 1996. The International MWP Conference has subsequently been held yearly in the U.S., Europe and Asia-Pacific region, and came back to Japan (Awaji Island) in 2002. Moreover, between Japan and Korea, a joint workshop on MWP has been held yearly since 2000.

Research goals for MWP technology up to now can be very roughly categorized as

(1) achieving higher performance and higher functionality for telecommunications system applications by introducing photonics technology to conventional radio-wave technology, and

(2) exploring new applications in telecommunications and other fields as well through the use of photonics technology by breaking through the frequency limit from microwave to millimeter waves and further on to the submillimeter-wave region in radio-wave technologies.

(3)

The primary motivation of the former is to make positive use of special merits in optical fibers as transmission media, such as low loss, high capacity (broad bandwidth), light weight, flexible, and non-inductive properties. The latter involves making use of not only optical fibers, but all of optical communication technology and its peripheral technology (high-speed devices, measurement technologies, etc.), which have made terabit-class data signal processing possible, in the radio-wave technologies.

On the basis of the above categorization, we have seen a number of examples of research and development accomplished recently. Radio-on-fiber, optical remote-antenna and optically-controlled antenna are typical examples of the first category, while microwave and millimeter-wave measurement as well as millimeter-wave and submillimeter-wave signal generation are in the second category.

Radio-on-fiber (RoF) technology continues to steadily advance in a form that supports the need for high-speed and ubiquity in telecommunications. At present, the cellular phone frequencies (around 1-2 GHz) are the focus of commercial attention, and RoF in wireless LAN (2-5 GHz) is expected to appear in the next market place. The implementation of millimeter-wave RoF, which is currently at the hottest research stage, will be linked to the development of millimeter-wave wireless (60-GHz band, for example), because public application of that technology has become active in recent years. As for higher millimeter-wave frequency RoF, NTT has developed a 10-Gbit/s wireless link system using 120-GHz-band millimeter waves, and the license was given to it as the first experimental radio station in Japan by the Ministry of Public Management, Home Affairs, Posts and Telecommunications in 2004. In that system, photonics technologies are effectively used for generation, modulation and emission of millimeter-wave signals.

In addition, technology for the optical generation and detection of radio-wave signals has become essential for various fields of measurement, as it facilitates the handling of ultrahigh-frequency radio-waves, which has been difficult with previous technologies. One example is a project that is attempting to introduce a millimeter and submillimeter-wave oscillator that employs photonics technology to a receiver for use in radio-astronomy. Low-noise photonic local oscillators have been successfully applied in the observation of millimeter-wave signals from the universe. Generation of over 1-THz radio-wave signal is now possible by using an ultrafast photodiode called Uni-Traveling-Carrier Photodiode (UTC-PD), although the emitted average power is still low, on the order of microwatts at that frequency.

As for the optical measurement of microwave and millimeter-wave signals, an electric-field sensor based on electro-optic (EO) effect has become the most common, mainly because of its broad bandwidth (from MHz to THz) and small invasiveness. It has been widely applied to, for example, LSI testing, antenna characterization, EMC measurement, detectors in the imaging and spectroscopy. A magnetic-field sensor based on magneto-optic (MO) effect has also been studied to measure a current in place of an electric field or a voltage.

References

Hirata, A., T. Nagatsuma, R. Yano, H. Ito, T. Furuta, Y. Hirota, T. Ishibashi, H. Matsuo, A. Ueda, T. Noguchi, Y. Sekimoto, and S. Matsuura[2002], "Output power measurement of photonic millimeter-wave and sub-millimeter-wave emitter at 100-800 GHz", Electron. Lett., vol. 38, no. 15, pp. 798-800

Hirata, A., M. Harada, and T. Nagatsuma[2003a], "120-GHz wireless link using photonic techniques for generation, modulation, and emission of millimeter-wave signals", IEEE J. Lightwave Technol., vol. 21, no.10, pp. 2145-2153

Hirata, A., M. Harada, K. Sato, and T. Nagatsuma[2003b], "Low-cost millimeter-wave photonic techniques for gigabit/s wireless link", IEICE Trans. on Electronics, E86-C, no. 7, pp. 1123-1128

Hirata, A., H. Ishii, and T. Nagatsuma[2004a], "Design and characterization of ultra-broadband photonic emitters for microwave and millimeter-wave applications", Japan-Korea workshop on microwave and millimeter-wave photonics 2004 Dig, pp. 63-66

Hirata, A., H. Togo, N. Shimizu, H. Takahashi, K. Okamoto, and T. Nagatsuma[2004b], "Low-phase noise photonic millimeter-wave generator using an AWG integrated with a 3-dB combiner", MWP 2004 Dig., TD-3, pp. 209-212

Ikeda, K., T. Kuri, Y. Takahashi, and K. Kitayama[2003], "Full-duplex transmission using 2-RF-port electroabsorption transceiver with photonic up-and downconversions for millimeter-wave radio-on-fiber system", IEICE Trans. on Electronics, E86-C, no. 7, pp. 1138-1145

Ito, H., T. Furuta, A. Hirata, T. Kosugi, Y. Muramoto, M. Tokumitsu, T. Nagatsuma, T. Ishibashi[2004], "Pre-amplifier-integrated uni-traveling-carrier photodiode module with a rectangular waveguide-output port for operation in the 120-GHz band", LEOS2004 Dig., MN2, pp. 128-129

Iwanami, M., E. Yamazaki, K. Nakano, T. Sudo, S. Hoshino, S. Wakana, M. Kishi, and M. Tsuchiya[2003], "Magnetic near-field measurements over LSI package pins by fiber-edge magnetooptic probe", IEEE J. Lightwave Technol., vol. 21, no. 12, pp. 3273-3281

Izutsu, M.[2004], "Electrooptic light modulation technology for microwave photonics", MWP2004 Dig., MA-2, pp. 12-15

Kitayama, K.[2003], "Dense wavelength division multiplexing radio-on-fiber system", MWP2003 Dig., pp. 129-134

Kosugi, T., M. Tokumitsu, T. Enoki, M. Muraguchi, A. Hirata, and T. Nagatsuma[2004], "120-GHz Tx/Rx chipset for 10-Gbit/s wireless applications using 0.1-□m-gate InP HEMTs", IEEE CSIC Dig., pp. 171-174

Mizuno, M., A. Hirata, K. Kawase, C. Otani, and T. Nagatsuma[2004], "Analysis of Pheochromocytoma (PC12) membrane potential under the exposure to millimeter-wave radiation", AIP Conference Proc., no. 716, pp. 164-166

Nagatsuma, T.[2002], "Photonic measurement technologies for high-speed electronics", Meas. Sci. Technol. vol. 13, no.11, pp. 1655-1663

Nagatsuma, T., H. Ito[2003], "Ultrafast applications of uni-traveling-carrier photodiodes from measurement to signal processing", Proc. SPIE, vol. 4992, pp. 90-104

Nagatusma, T., H. Togo, K. Narahara, N. Shimizu, and A. Sasaki[2004], "Recent progress in optical measurement of radio-wave signals from gigahertz to terahertz", MWP2004 Dig., MB-1, pp. 20-23

Nakajima, F., T. Furuta, and H. Ito[2004],"High-power terahertz-wave generation from a resonant-antenna-integrated uni-traveling-carrier photodiode", MWP2004 Dig., WD-4, pp. 313-316

Niiho, H., M. Nakaso, K. Masuda, H. Sasai, K. Utsumi, and M. Fuse[2004], "Multi-channel wireless LAN distributed antenna system based on radio-over-fiber techniques", LEOS2004 Dig., MF2, pp. 57-58

Sasaki, A., and T. Nagatsuma[2002], "Reflection-type CW- millimeter-wave imaging with a high-sensitivity waveguide-mounted electro-optic sensor", Jpn. J. Appl. Phys., vol. 41,part 2, no. 1A/B, pp. L83-L86

Sato, T., M. Tsuchiya, M. Iwanami, S. Hoshino, and M. Kishi[2003], "Current profiling for □m-class planar circuit patterns by fiber-edge magneto-optic probe", MWP 2003 Dig., pp. 341-344

Shoji, Y., and H. Ogawa[2003],"Experimental demonstration of 622 Mbps millimeter-wave over fiber link for broadband fixed wireless access system", IEICE Trans. on Electronics, E86-C, no. 7, pp. 1129-1137

Suzuki, H., M. Fujiwara, K. Iwatsuki, A. Hirata, and T. Nagatsuma[2005], "Photonic millimetre-wave generator using intensity and phase modulators for 10 Gbit/s wireless link", Electron. Lett., vol. 41, no. 6, pp. 89-90

Takano, S., A. Ueda, T. Yamamoto, S. Asayama, Y. Sekimoto, T. Noguchi, M. Ishiguro, H. Takara, S. Kawanishi, H. Ito, A. Hirata, and T. Nagatsuma[2003], "The first radioastronomical observation with photonic local oscillator", Publ. Astron. Soc. Japan, vol. 55, pp. L53-L56

Togo, H., A. Sasaki, A. Hirata, and T. Nagatsuma[2004], "Characterization of millimeter-wave antenna using photonic measurement techniques", Int. J. RF and Microwave Computer-aided Engineering., vol. 14, no. 5, pp. 290-297

Tsuchiya, M., E. Yamazaki, M. Iwanami, S. Mitani, T. Sato, S. Wakana, S. Hoshino, and M. Kishi[2003], "High-speed and high-spatial resolution fiber-optic measurement technique for RF magnetic field distribution", LEOS2003 Dig., ThS1, pp. 929-930

Tsukamoto, K., T. Higashino, T. Nakanishi, and S. Komaki[2003], "Direct optical switching code-division multiple-access system for fiber-optic radio highway networks", IEEE J. Lightwave Technol., vol. 21, no. 12, pp. 3209-3220

Usami, M., R. Fukasawa, M. Tani, M. Watanabe, and K. Sakai[2003], "Calibration free terahertz imaging based on 2D electro-optic sampling technique", Electron. Lett., vol. 39, no. 24, pp. 1746-1747

Yamamoto, T., and S. Kawanishi[2004], "Generation of low-noise optical frequency comb and optical beat signal using phase modulator", Japan-Korea workshop on microwave and millimeter-wave photonics 2004 Dig., pp. 15-19

D8. Nanotechnology

Katsuyuki Utaka
Waseda University

Nanotechnology covers very vast fields, such as materials, chemistry, physics, electronics, photonics, mechanics, biotechnology, atom manipulation, fabrication technology and so on. The research and development in these fields seem to have been carried out in their individual academic society and industrial groups, and nanotechnology in these fields shall still continue to grow. In order to create and incubate new fields and novel devices for future prosperous society, however, cross-communication and, in some cases, fusion between various fields of nanotechnology should be required. For this purpose, the new technical group, named as "Next-Generation Nanotechnology (NNN) Group", has been established in April, 2004, to discuss next-generation nanotechnology under the Electronics Society (ES) of Institute of Electronics, Information Communication Engineers (IEICE). The activity of various nanotechnology is over-viewed through the topics in the meetings of the NNN Group, which are a very limited examples.

1. Photonics: Photonic crystal (PhC) devices have been gathering increasing attention, and by the improvement of fabrication technology using electron beam lithography well-controlled PhC functional devices have been fabricated and reported such as very high-Q cavity and group-velocity controlled devices for the application to narrow-band integrated WDM filter and quasi-optical memory, respectively. A compact photonic integrated circuits combined with well-controlled quantum dots exhibited a high-speed wavelength converter. As for quantum dots (QD), its size and density have begun to be controlled by the development of crystal growth of molecular beam epitaxy (MBE) and metal-organic vapor phase epitaxy (MO-VPE). Generation of single photon emission and its application to quantum communication is intensively investigated.

2. Electronics: Due to the approaching limit of the size reduction in Si ULSI, further improvement of fabrication process and material aspects are required. From a viewpoint of fabrication technology of nano-strucutures, the bottom-up methods such as self-organization and atom-manipulation have been spotlighted, as well as increasing development of the conventional top-down methods such as electron beam lithography and etching. QD mentioned above is one of the promising examples. From the material aspects, carbon nano-tube (CNT) is gathering increasing attention as a post-Si material due to its larger electron mobility and larger maximum current density. CNT-gated transistors and application to through-hole vias were reported. Fabrication control of CNTs from viewpoints of wall number, diameter, density, position and so on for designed performances have been highly investigated.

3. Biotechnology: Application of nanotechnology to biotechnology is highly spotlighted, since bio-cell and bio-molecular themselves are in the range of nanometer size. Some of the promising applications are sensing and marking of cells or proteins such as cancer, delivering of medicine to target cells or killing them, and so on. These technologies lead to the remedy of incurable diseases with reduced pains through the nanotechnology. As such nanotechnologies, the followings have been reported; micelling of

self-organized nano-capsules, nano-pillars to detect proteins with high sensitivity by CNT or polymer and their fabrication by nano-inprinting, nano-particles for marking killing of cancer cells. Hereafter, collaboration between nanotechnology and medical engineering has been further required with taking the advantages of each nanotechnology.

4. Mechanics: Micro electro-mechanical systems (MEMS) machines have been further down-sized to reach the level to handle nano-size materials such as cells through the improvement of fabrication technology. This opens the way to the application of the nano electro-mechanical systems (NEMS) to realization of novel artificial materials and structures by controlled bottom-up technology in the fields of electronics and bio-science such as molecular motors and DNA capturing, which have been partly demonstrated. Improving of flexibility and motion-freedom dimensions and further utilization of NEMS machines are highly required.

D9. Polymeric Photonics

Toshikuni Kaino
Tohoku University

Polymeric optical materials are of great interest for applications in optical telecommunication and data communication devices because of their ease in processing, excellent flexibility, low cost, and high volume production in comparison with silica-based materials. One of the important polymer photonic devices is optical waveguides that can be fabricated using very simple and cost effective methods. The use of soft-lithography instead of standard photolithography and dry etching technologies is attractive because inexpensive optical device can be realized. Polymerization or decomposition using multi-photon absorption of materials is also a good method for optical waveguide fabrication. Direct waveguide patterning can be done using this method. Laser induced self-writing technology of optical waveguide is also very simple and attractive. Using these processes, it is possible to fabricate and interconnect multiple optical devices at once.

Polymers are also easy to functionalize where high speed optical switching and signal modulation can be attained. Ultra fast and highly efficient optical processing requires nonlinear optical (NLO) materials where high-speed signals will be operated. For that, EO polymers have been paid a lot of attention because of their high potential for next generation EO modulators and/or switches. It is reported that higher bandwidth, lower drive voltage EO modulators than that of typical inorganic EO crystal, $LiNbO_3$. were fabricated using a chromophore-shape-controlled EO polymer. However, in general, EO polymer has a large optical loss (more than a few dB/cm), and it is necessary to reduce the total insertion loss for a practical EO device. So an EO polymer device serially grafted with a passive waveguide composed of a high transparent polymer was fabricated using soft-lithography, photolithography and spin-coating techniques. Monolithically integration of passive waveguide with active devices such as EO-modulator on a single substrate is possible. If the entire structure is on one circuits, the manufacturing, packaging, and assembly costs are reduced dramatically.

Azo-dye, stilbene-dye, or polyene-dye functionalized polymers have been investigated as 2nd-order NLO materials, showing efficient NLO characteristics with low absorption loss. In this case, dye in the polymer should be aligned in a specific direction to possess 2nd-order optical nonlinearity. So, poling process to align dyes in the polymer is inevitable i.e., electric field poling is used to obtain 2-nd order NLO polymers. The polymer films on glass substrates were poled by parallel electrode poling or corona poling. The nonlinear electronic polarization of the dye-functionalized polymers originates from mesomeric effects that usually depend on the size of the □-conjugated systems of the dye. The □-conjugation length dependence of the 2nd-order NLO hyperpolarizability □ has been investigated.

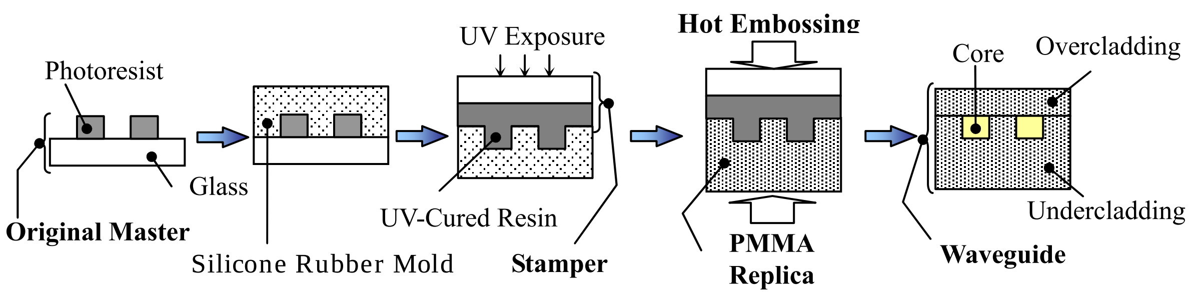
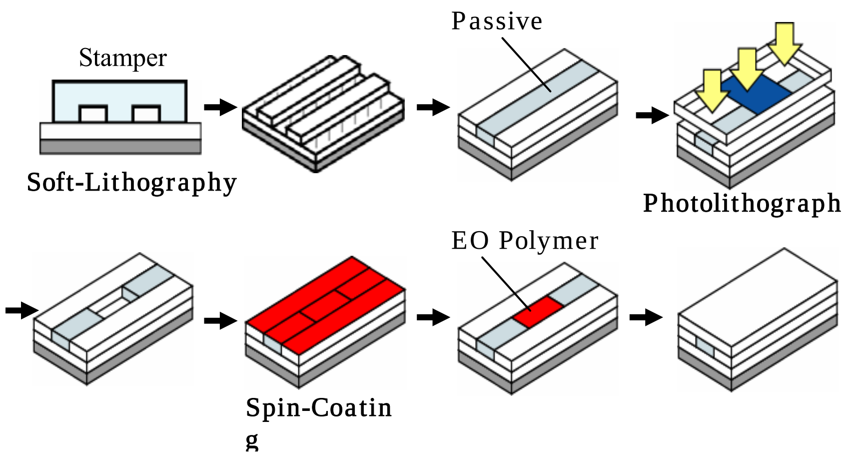


Figure 1. Fabrication process of polymer optical waveguide using hot embossing technology



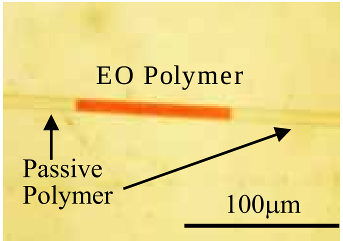


Figure 2. Process flow for serially grafted EO polymer waveguide (Serially grafted structure)

Waveguide grating, that is an important device in optical communication and signal processing systems, has such functions as input-output coupler, wavelength filter, and wavelength division multiplexer. An azo-dye functionalized polymer is one of the candidates for fabricating grating through the photochemical reaction of the azo-dye through two laser beam interference. This reaction can be explained by following two mechanisms. The first mechanism is reversible trans-cis-trans isomerization of the dye where strong interference beam was irradiated. A surface relief grating can be fabricated through the movement of the azo-dye attached matrix polymer due to the conformational change of the dye through its isomerization. These surface relief gratings based on the isomerization mechanism were optically or thermally erasable. The second mechanism is irreversible photobleaching of the dye that occurs under higher energy irradiation. In this case, π-conjugated system in azo dye is broken and as a result, permanent refractive index change of the polymer occurs,

Compact polymer optical amplifier devices also have of special attention that can be incorporated into integrated optical circuits. Incorporation of laser dyes into polymers as active gain region is effective for the amplification. These doped polymers provide a convenient method of creating high gain with wide range of visible wavelength. Rare-earth doped polymers are also used for longer wavelength amplification. Waveguide amplifier devices have the potential to be used in compact optical system such as monolithically integrated photonic circuits.

References

A. Yeniary, R.Y. Gao, K. Takayama, R.F. Gao, A.F. Garito, (2004) Ultra-Low Loss Polymer Waveguides, J. Lightwave Technol., **22**, 154-158

H. Ma, A.K-Y. Jen, L.R. Dalton, Polymer-Based Optical Waveguides; Materials, Processing and Devices, Advanced Mater., **14**, 1339-1365,

H. Mizuno, S. Jordan, O. Sugihara, T. Kaino, N. Okamoto, M.Ohama, (2004) Polymeric Optical Waveguides with Plastic Optical Guides for Passive Alignment Fabricated by Hot Embossing, Jpn. J. Appl. Phys., **43**, L1496-L1498

H. Mizuno, O. Sugihara, T. Kaino, Y. Ohe, N. Okamoto, M.Hoshino, (2004) Thick Photoresist Original Master: A New Tool for Fabrication of Polymeric Optical Waveguides with Large Core by Hot Embossing, J. Nonlinear Optical Phys. Mater., **13**, 513-517

H. Mizuno, O. Sugihara, T. Kaino, N. Okamoto, M. Tomiki, M. Hoshino, (2004) Fabrication method of large core polymeric optical waveguide through replication process using anisotropically etched silicon, Optics Letters, **28**, 2378-2380

H. Mizuno, O. Sdugihara, T. Kaino, N. Okamoto, M. Hoshino, (2003) Low-loss polymeric optical waveguides with latge cores fabricated by hot embossing, Proc. SPIE Organic Photonics Materials and Devices VI, San Jose, **5351**, 268-275

T.Shioda, (2002) Fluorinated Polyimide Waveguide Fabricated Using Replication Process with Antistacking, Appl. Phys. Lett., **41**, 1379-1381

O. Sugihara, H. Tsuchie, H. Endo, N. Okamoto, T. Yamashita, M. Kagami, T. Kaino, (2004) Light-Induced Self-Written Polymeric Optical Waveguides for Single-Mode Propagation and for Optical Interconnection, IEEE Photon. Tech. Lett., **16**, 804-806

B. Cai, O. Radmer, C. Zawadski, H. H. Yao, N. Keil, T. Kaino, (2004) DAST Crystal Waveguide Fabrication by Photobleaching Method, Nonlinear Optical Phys. Mat., **13**, 195-208

B. Cai, T. Ushiwata, K. Komatsu, T. Kaino, (2004) Fabrication of Serially Grafted 4-(4-dimethyl-aminostyryl)-1-methylpyridinium Tosylate Crystal Waveguide by Photobleaching, Jpn. J. Appl. Phys., **41**, L390-L392

T. Kaino, B. Cai, K. Takayama, (2002) Fabrication of DAST Channel Optical Waveguides, Adv, Funct. Mater, **12**, 599-603

T. Kaino, K. Takayama, B. Cai, K. Komatsu, (2001) Fabrication of Nonlinear Optical Waveguide, Ferroelectrics, **257**, 13-26

K. Takayama, K. Komatsu, T. Kaino, (2001) Serially Grafted Waveguide Fabrication of Organic Crystal and Transparent Polymer, Jpn. J. Appl. Phys., **40**, 5149-5150

Y. Suzuki, K. Komatsu, T. Kaino, and Y. Honda, (2003). “Serially grafted optical waveguide fabrication of NLO polyimide and transparent polymers”, Opt. Mater., **21,** 521-524

T. Ushiwata, E. Okamoto, T. Kaino, (2002) Development of Thermally Stable Novel EO-polymers, Mol. Cryst. Liq. Cryst., **374**, 303-314

T. Ushiwata, E. Okamoto, K. Komatsu, T. Kaino, (2001) Synthesis and optical properties of azo dye attached novel second order NLO polymers with high thermal stability, Proc. SPIE Organic Photonics Materials and Devices III, San Jose, **4279**, 17-24

A. Kaneko, E. Okamoto, T. Kaino, (2002) Synthesis and Characterization of Novel Side-Chain Nonlinear Optical Polymers with Furan Derivative as an Acceptor, Jpn. J. Appl. Phys., **41**, L559-L561

T. Taima, K. Komatsu, T. Kaino, C.P. Franceschina, L. Tartara, G.P. Banfi, V. Degiorgio, (2003) Third-order nonlinear optical properties of 2-adamanthyl amino-5-nitropyridine caused by cascaded second-order nonlinearity, Optical Materials, **21**, 83-86

T. Hattori, T. Shibata, S. Onodera, T. Kaino, (2004) Thermo-optically Tunable Wavelength Filter with Permanent Refractive Index Grating into Azo-Polymer Waveguide, Jpn. Jpn. App. Phys., **43**, 1492-1495

B. Cai, T. Hattorit, H-H. Deng, K. Komatsu, C. Zawadski, N. Keil, T. Kaino, (2001) Refractive Index Control and Grating Fabrication of 4-(4-dimethyl-aminostyryl)-1-methylpyridinium Tosylate Crystal, Jpn. J. Appl. Phys., **40**, L964-L966

F.L. Labarther, T. Buffeteau, C. Sourisseau, (2001) Time dependent analysis of the formation of a half-period surface relief grating on amorphous azopolymer films, J. Appl. Phys., **90**. 3149-3158

J.Y. Kim, T.H. Kim, T. Kiura, T. Fukuda, H. Matsuda, (2002) Surface relief grating and liquid crystal alignment on azobenzene functionalized polymers, Opt. Mater, **21**, 627-631

T. Kobayashi, J-B. Savaitier, G. Jordan, W.J. Blau, Y. Suzuki, T. Kaino, (2004) Near-infrared laser emission from luminescent plastic waveguides, Appl. Phys. Lett., **85**, 185-187

M.A. Reilly, C. Marinelli, C.N. Morgan, R.V.P ently, I.H. White, R. Roman, M. Ariu, R. Xia, D.D.C. Bradley, (2004) Rib waveguide dye-doped polymer amplifier with up to 26 dB optical gain at 625 nm, Appl. Phys. Lett., **85**, 5137-5139

T, Hirose, T, Omatsu, R, Kato, K. Hoshino, K. Harada, T. Watanabe, M. Fujii, (2003) Azo-benzene polymer thin film laser amplifier with grating couplers based on light-induced relief hologram, Opt. Commun., **228**, 279-283

W.H. Wong, E.Y.B. Pun, K.S. Chgan, (2004) Er^{3+}-Tb^{3+} co-doped polymer optical waveguide amplifier, Appl. Phys. Lett., **82**, 176-178

J. Thompson, M. Anni, S. Lattante, D. Pisignano, R.I. Blyth, G. Gigli, R. Cingolani, (2004) Amplified spontaneous emission in the near infrared from a dye-doped polymer thin film, Synth. Metals, **143**, 305-307

M. Karimi, N. Granpayeh, M.K.M. Farshi, (2004) Analysis and design of a dye-doped polymer optical fibre amplifier, Appl. Phys. B., **78**, 387-396

D10. Photonic Crystals

Susumu Noda
Kyoto University

Photonic crystals, in which the refractive index changes periodically, provide an exciting new tool for the manipulation of photons and have received a keen interest from a variety of fields.

In these five years, manipulation of photons by using 2D photonic crystals has been extensively studied, and remarkable progresses have been made in waveguides, bends, cavities, and their combination, as well as the connection to the outer space. For example, although the waveguide loss was very high (70dB/mm) five years ago, it is now reduced down to 0.7dB/mm. On another hand, in waveguide bends, topology optimization methods enable us to achieve even a 120 degree bend, which is beyond the initial prediction. The nanocavity *Q* factor has been drastically increased owing to the invention of a general design rule: a Gaussian-like confinement suppresses the out-of-slab leakage of light significantly. Ultrahigh-*Q* nanocavities with *Q* factor of the order of 10^5～10^6 has been recently achieved. Encouraged by the success of ultrahigh *Q* nanocavities, tuning or nonlinear switching operation of photonic-nano devices has started. The new concept of "In-Plane Hetero" structure has been applied to the defect engineering, and photonic-nanostructure devices with high functionality has been realized.

Progresses in 3D photonic crystals have been also remarkable. The demonstration of spontaneous emission control by 3D photonic crystals has been long-waited after the photonic crystal concept appeared. The recent success in the introduction of light-emitters and artificial point defects into 3D photonic crystals with full bandgap has enabled to demonstrate it. It has been successfully shown that the spontaneous emission is suppressed by 100 times at the complete bandgap while a strong emission is observed at the artificial defect.

Progresses in band edge and/or band engineering have been also made. When the operation wavelength approaches the band edge and/or the mode edge of a waveguide, the group velocity of light can be slowed down. Such kind of velocity control of light is very important and it has been recently demonstrated. On another hand, when the band edge itself is utilized, a large area laser cavity can be constructed. Novel 2D lasers based on 2D band edge effect have been developed.

In conclusion, the recent progresses of photonic crystals are really remarkable, and the initially promised features have been well demonstrated. In the following 10 years, higher quality and more reliable devices will be developed with the aid of the progress of nanotechnology. In the case of the 2D photonic crystal slab, the combination with Si LSI technology will proceed with an all-optical main part, but with the control driven by the electronics. Sensing applications, memory, single photon emitters, in summary all new application areas will be also developed since extremely high *Q* nanocavities has already been achieved. In the case of 3D photonic crystals, the fabrication technology will develop continuously and an ultimate control of photons will be demonstrated. Materials will be expanded from semiconductors, to organic, magnetic, etc.

References:

M. Fujita, T. Ueno, K Ishihara, T. Asano, S. Noda, H. Ohata, T. Tsuji, H. Nakada, and N. Shimoji [2004], "Reduction of operating voltage in organic light-emitting diode by corrugated photonic crystal structure," Applied Physics Letters, vol.85, no.23, pp.5769-5771.

Y. Tanaka, T. Asano, R. Hatsuta, and S. Noda [2004], "Analysis of a line-defect waveguide on a silicon-on-insulator two-dimensional photonic-crystal slab," IEEE/OSA Journal of Lightwave Technology, vol.22, no.12, pp.2787-2792.

B. S. Song, T. Asano, Y. Akahane, Y. Tanaka, and S. Noda [2004], "Transmission and reflection characteristics of in-plane hetero-photonic crystals," Applied Physics Letters, vol.85, no.20, pp.4591-4593.

M. Fujita, A. Sugitatsu, T. Uesugi, and S. Noda [2004], "Fabrication of Indium Phosphide compound photonic crystal by Hydrogen Iodide/Xenon inductively coupled plasma etching," Japanese Journal of Applied Physics, vol.43, no.11, pp.L1400-L1402.

M. Okano and S. Noda [2004], “Analysis of multimode point-defect cavities in three-dimensional photonic crystals using group theory in frequency and time domains,” Physical Review B, vol.70, no.12, pp.125105-1-125105-15.

A. Sugitatsu, T. Asano, and S. Noda, “Characterization of line-defect-waveguide lasers in two-dimensional photonic-crystal slabs,” Applied Physics Letters, vol.84, no.26, pp.5395-5397 (2004).

T. Asano, K. Kiyota, D. Kumamoto, B. S. Song, and S. Noda [2004], “Time-domain measurement of picosecond light-pulse propagation in a two-dimensional photonic crystal-slab waveguide,” Applied Physics Letters, vol.84, no.23, pp.4690-4692.

S. Ogawa, M. Imada, S. Yoshimoto, M. Okano, and S. Noda [2004], “Control of light emission by 3D photonic crystals,” Science, vol.305, no.5681, pp.227-229. (published online 3 June 2004 (10.1126/science.1097968))

T. Asano and S. Noda [2004], “Tuning holes in photonic-crystal nanocavities,” Nature, vol.429, doi:10.1038, no.6988.

D. Ohnishi, T. Okano, M. Imada, and S. Noda [2004], “Room temperature continuous wave operation of a surface-emitting two-dimensional photonic crystal diode laser,” Optics Express, vol.12, no.8, pp.1562-1568.

H. Takano, Y. Akahane, T. Asano, and S. Noda [2004], “In-plane-type channel drop filter in a two-dimensional photonic crystal slab,” Applied Physics Letters, vol.84, no.13, pp.2226-2228.

M. Yokoyama and S. Noda [2004], “Finite-difference time-domain simulation of two-dimensional photonic crystal surface-emitting laser having a square-lattice slab structure,” IEICE Transactions, Special Issue on Photonic Crystals and Their Device Applications, vol.E87C, no.3, pp.386-392.

S. Noda and T. Baba [2004], “Special issue on photonic crystals and their device applications,” IEICE Transactions on Electronics, vol.E87C, no.3, pp.257.

E. Miyai and S. Noda [2004], “Structural dependence of coupling between a two-dimensional photonic crystal waveguide and a wire waveguide,” Journal of the Optical Society of America B, vol.21, no.1, pp.67-72.

M. Okano, S. Kako, and S. Noda [2003], “Coupling between a point-defect cavity and a line-defect waveguide in three-dimensional photonic crystal," Physical Review B, vol.68, no.23, pp.235110-1-235110-10.

M. Fujita, T. Ueno, T. Asano, S. Noda, H. Ohhata, T. Tsuji, H. Nakada, and N. Shimoji [2003], "Organic light-emitting diode with ITO/organic photonic crystal," Electronics Letters, vol.39, no.24, pp.1750-1752.

Y. Akahane, T. Asano, B. S. Song, and S. Noda [2003], "High-Q photonic nanocavity in a two-dimensional photonic crystal," Nature, vol.425, no.6961, pp.944-947.

M. Yokoyama and S. Noda [2003], "Polarization mode control of two-dimensional photonic crystal laser having a square lattice structure," IEEE Journal of Quantum Electronics, vol.39, no.9, pp.1074-1080.

Y. Akahane, T. Asano, B. S. Song, and S. Noda [2003], "Investigation of high- Q channel drop filters using donor-type defects in two-dimensional photonic crystal slabs," Applied Physics Letters, vol.83, no.8, pp.1512-1514.

T. Asano, B. S. Song, Y. Tanaka, and S. Noda [2003], "Investigation of a channel-add/drop-filtering device using acceptor type point defects in a two-dimensional photonic crystal slab," Applied Physics Letters, vol.83, no.3, pp.407-409.

B. S. Song, S. Noda, and T. Asano [2003], "Photonic devices based on in-plane hetero photonic crystals," Science, vol.300, no.5625, pp.1537.

S. Ogawa, M. Imada, and S. Noda [2003], "Analysis of thermal stress on wafer bonding of dissimilar materials for the introduction of InP-based light-emitter into GaAs-based three dimensional photonic crystals," Applied Physics Letters, vol.82, no.20, pp.3406-3408.

T. Asano, M. Mochizuki, S. Noda, M. Okano, and M. Imada (2003), "A channel drop-filter using a single defect in a 2D photonic crystal slab - Defect engineering with respect to polarization mode and ratio of emissions from upper and lower sides -," IEEE/OSA Journal of Lightwave Technology, vol.21, no.5, pp.1370-1376.

D. Ohnishi, K. Sakai, M. Imada, and S. Noda (2003), "Continuous wave operation of surface emitting two-dimensional photonic crystal laser," Electronics Letters, vol.39, no.7, pp.612-614.

Y. Tanaka, T. Asano, Y. Akahane, B. S. Song, and S. Noda (2003), "Theoretical investigation of propagation loss of a line defect waveguide in a two-dimensional photonic crystal slab with tapered air holes," Applied

Physics Letters, vol.82, no.11, pp.1661-1663.

Y. Akahane, M. Mochizuki, T. Asano, Y. Tanaka, and S. Noda (2003), "Design of a channel drop filter by using a donor-type cavity with high-quality factor in a two-dimensional photonic crystal slab," Applied Physics Letters, vol.82, no.9, pp.1341-1343.

A. Sugitatsu and S. Noda (2003), "Room temperature operation of a two dimensional photonic crystal slab defect-waveguide-laser with optical pump," Electronics Letters, vol.39, pp.123-125.

E. Miyai, M. Okano, M. Mochizuki, and S. Noda (2002), "Analysis on coupling between 2D photonic crystal slab and external waveguide," Applied Physics Letters, vol.81, no.20, pp.3729-3731.

M. Okano, A. Chutinan, and S. Noda (2002), "Analysis and design of single-defect cavities in a three-dimensional photonic crystal," Virtual Journal of Nanoscale Science & Technology, vol.6, no.18.

M. Okano, A. Chutinan, and S. Noda (2002), "Analysis and design of single-defect cavities in a three-dimensional photonic crystal," Physical Review B, vol.66, no.16, pp.165211-1-6.

N. Yamamoto and S. Noda (2002), "Accurate identification of the band gap of photonic crystals from transmission spectra," Journal of Applied Physics, vol.92, no.5, pp.2256-2259.

S. Noda, M. Imada, A. Chutinan, and N. Yamamoto (2002), "III-V based-semiconductor photonic crystals," Optical and Quantum Electronics, vol.34, no.8, pp.723-736.

S. Noda, M. Imada, M. Okano, S. Ogawa, M. Mochizuki, and A. Chutinan (2002), "Semiconductor three-dimensional and two-dimensional photonic crystals and devices," IEEE Journal of Quantum Electronics, vol.38, no.7, pp.726-735.

T. Asano, S. Noda, K. Kiyota, Y. Tanaka, Y. Akahane, B. S. Song, M. Mochizuki, and M. Imada (2002), "Channel-add operation of a device using defects in a two-dimensional photonic crystal slab," Materials Research Society Symposium Proceedings "Materials and devices for optoelectronics and microphotonics", vol.722, pp.363-367.

M. Imada, A. Chutinan, S. Noda, and M. Mochizuki (2002), "Multidirectionally distributed feedback photonic crystal lasers," Virtual Journal of Nanoscale Science & Technology, vol.5, no.18.

M. Imada, S. Noda, A. Chutinan, M. Mochizuki, and T. Tanaka (2002), "Channel drop filter using a single defect in a 2-D photonic crystal slab waveguide," IEEE/OSA Journal of Lightwave Technology, vol.20, no.5, pp.845-850.

M. Imada, A. Chutinan, S. Noda, and M. Mochizuki (2002), "Multidirectionally distributed feedback photonic crystal lasers," Physical Review B, vol.65, no.19, pp.195306-1-195306-8.

A. Chutinan, M. Okano, and S. Noda (2002), "Wider bandwidth with high transmission through waveguide bends in two-dimensional photonic crystal slabs," Applied Physics Letters, vol.80, no.10, pp.1698-1700.

S. Noda and M. Imada (2002), "2D photonic crystal surface-emitting laser using triangular-lattice structure," IEICE Transactions on Electronics, vol.E85C, no.1, pp.45-51.

S. Ogawa, K. Tomoda, and S. Noda (2002), "Effects of structural fluctuations on three-dimensional photonic crystals operating at near-infrared wavelengths," Journal of Applied Physics, vol.91, no.1, pp.513-515.

T. Tanaka, S. Noda, A. Chutinan, T. Asano, and N. Yamamoto (2002), "Ultra-short pulse propagation in 3D GaAs photonic crystals," Optical and Quantum Electronics, vol.34, no.1-3, pp.37-43.

T. Asano, S. Yoshizawa, and S. Noda (2001), "Carrier relaxation dynamics in an ultrafast all-optical modulator using an intersubband transition," Applied Physics Letters, vol.79, no.27, pp.4509-4511.

A. Chutinan, M. Mochizuki, M. Imada, and S. Noda (2001), "Surface-emitting channel drop filters using single defects in two-dimensional photonic crystal slabs," Applied Physics Letters, vol.79, no.17, pp.2690-2692.

S. Noda (2001), "Teaching light new tricks," SPIE OE Magazine, vol.1, no.10, pp.28-31.

M. Yokoyama, K. Akimoto, M. Imada, and S. Noda (2001), "Wafer fusion condition for GaAs/AlGaAs system and its application to laser diode," Japanese Journal of Applied Physics, vol.40, no.8A, pp.L847-L849.

S. Noda, M. Yokoyama, M. Imada, A. Chutinan, and M. Mochizuki (2001), "Polarization mode control of two-dimensional photonic crystal laser by unit cell structure design," Science, vol.293, no.5532, pp.1123-1125.

S. Noda (2001), “Two- and three-dimensional photonic crystals in III-V semiconductors,” MRS Bulletin, vol.26, no.8, pp.618-621.

K. Sakoda, N. Kawai, T. Ito, A. Chutinan, S. Noda, T. Mitsuyu, and K. Hirao (2001), “Photonic bands of metallic systems. I. Principle of calculation and accuracy,” Physical Review B, vol.64, no.4, pp.45116-1-45116-8.

D11 Silicon Photonics

Tadamasa Kimura
Electro-Communication Technology

1. Introduction

The recent demonstration of a Raman optical amplifier and a Raman laser in silicon by UCLA researchers in 2004 [1] and by Intel [2,3] aroused people who were engaged not only in the silicon photonics but also in the silicon electronics to become aware of the possibility of silicon photonics. Though various types of silicon photonic devices have been studied and some passive devices have been developed in the progress of silicon optoelectronics and photonics, the lack of an efficient light emitter (silicon laser and light emitting diode) and an optical amplifier has been a major roadblock. Ozdal Boyraz and Bahram Jalali of UCLA have described pulsed Raman laser emission at 1675 nm with a 25-MHz repetition rate, using a silicon waveguide as the gain medium. The laser has a clear threshold at 9 W of peak pump pulse power and a slope efficiency of 8.5 percent in 2004[1], and the Intel group achieved a continuous-wave Raman silicon laser in 2005[3].

Many researchers have attempted to create an efficient silicon LED or a silicon laser. A relatively strong visible light emission from porous silicon reported by Canham in 1990 was one of the major breakthroughs to the silicon photonics. This led to the development of the luminescence of nanocrystalline silicon embedded in silicon dioxide. Another approach was to incorporate exotic impurities such as erbium or thulium in silicon. The first Er-doped silicon LED was reported by H. Ennen et al. in 1985 [5] and an efficient LED (external efficiency of 10% at 300K) was reported by SI microelectronics in 2003[6]. Er-doped fiber amplifier (EDFA) contributed greatly to the development of the long distance optical fiber communication system However, in the development of WDM (wavelength division multiplexing) system, its 15-30nm bandwidth cannot cover the broadening of the wavelength, and the Raman fiber amplifier and laser have been developed for light amplification and generation [7]. Semiconductor Raman lasers and amplifiers were studied in some semiconducting materials such as GaP [8, 9].

The silicon Raman laser has some favourable features compared with other efforts such as defect or impurity incorporation in Si. . Firstly, it uses a pure crystalline silicon and is compatible with standard silicon manufacturing technology. Secondly, the lasing and amplification is not in principle restricted to fixed wavelength ranges. However, the Raman laser requires a strong light for excitation and this should be solved in use for optoelectronic systems.

The luminescence of nc-Si in SiO_2 at visible wavelengths has also attracted a great attention from the point of view of both physics and practical application. The materials are, however, high resistive and it needs optical excitation.

In contrast, Er-doped silicon has a possibility of realising electrically excitable LEDs or LDs. Though a high external efficiency (10%) was reported for a Si LED at 1.54 μm Si by ST microelectronics[6], the LED was composed of a thin Er-doped SiO_2 sandwiched with p- and n-silicon and it was high resistive and was still far from a laser diode due to current injection. Strong enhancement in the 1.54μm luminescence from Er and nc-Si codoped SiO_2 reported by M. Fujii et al. had also attracted a great attention [10] and have been followed by lots of studies for the energy transfer mechanisms, efficiency, excitation cross section, optical gains etc. The excitation cross section of Er (2 x 10^{-17} cm^2 was increased by 4-5 orders compared with that of Er doped SiO_2 (8 x $10^{-21}cm^2$ where the Er ions are excited by direct absorption of photons [11]. However, this material is also high resistive and needs optical excitation. One of the problems of Er-doped silicon to be solved is the limitation of the Er concentration at around 10^{19} - $10^{20}/cm^3$. Too high Er concentration resulted in concentration quenching due to strong interaction among Er ions at high Er concentrations. Recently, an Er-Si-O new crystal which shows a superlattice structure has been reported by H.Isshiki et al. [12]. This material contains Er not as an impurity element but as a constituent atom at around 20at%. It shows a semiconducting property and at the same time, a strong photoluminescence with a fine-structured luminescence at 1.54μm at room temperature. Efforts are now made to make optical waveguide amplifiers, LEDs or LDs using this material. In the following, activities of Japanese researchers in the field of silicon photonics in these five years are reviewed.

2. Optical waveguides

PLC (planar lightwave circuit) technology which is now deployed in fiber-optic telecommunications systems has been practiced since the late 1980's and is based on silica waveguide technology. Light-guiding channels are defined on a silicon platform. The core layer with an elevated refractive index is patterned using photolithography and dry etching. This technology is well suited to the fabrication of passive devices. PLC established its fame due to compactness, commercial productivity, reliability etc. and is widely used in the photonic technology combined with the fiber optics technology. Various passive photonic devices have been developed such as AWG (arrayed waveguide grating), optical switch, dispersion compensation devices, and filter. Japan is one of the leading countries in the PLC technology and lots of efforts have been and still are made to develop this technology both in the research as well as in the production fields. Though PLCs is one of the vicious technologies in the silicon photonics, the review of the PLC technology will appear somewhere from the general photonic technology point of view.

(1) Silicon-wire waveguides:

In the PLC waveguides, the difference in the refractive index between the core- and clad-layers is from 0.3 % to 2 %, which leads to the bending radius from 25 mm to 2 mm and limits the size reduction. Reduction in the bending radius requires a lager refractive index difference. Recently, silicon wire waveguide has been attracted lots of attention. Submicron size silicon wires are used as cores and the air or SiO_2 are used as clad. The high refractive index of silicon (n_r~3.5) compared to the air (n_r=1) or SiO_2 (n_r=1.4) can reduce the bending radius down to several microns. Moreover, a use of the silicon semiconductor as a clad may open the way to the development of active waveguide devices. The key problems are the propagation loss due to scattering at the core/clad boundary and the coupling loss to optical fibers Even a tiny roughness at the core/clad boundary may cause a large scattering of light at the boundary due to the large refractive index difference between core and clad causes

S. Itabashi and co-workers with NTT Microsystem Integration laboratories fabricated a Si channel waveguide on an SOI substrate; that is, Si core of a size of e.g. 0.3 x 0.3 μm^2 with SiO_2 clad [13]. With improved fabrication methods, the propagation loss down to less than 3dB/cm and the bending radius of < 5 μm with almost negligible bending loss were attained. Coupling loss to optical fiber was reduced using a spot-size converter and the loss of <3dB/point was obtained for a normal single mode fiber. They also fabricated various passive functional devices; multimode interference branch, directional coupler, star coupler, microspectrometer, lattice filter, ring resonator, 1D photonic crystal filter etc. They also fabricated some active functional devices; wavelength converter and all-optical modulator, where the semiconducting properties of Si, two photon absorption and four wave mixing, were used. Their work was well reviewed by themselves in [14].

T. Baba and his coworkers attempted to fabricate a silicon wire waveguide on SOI [15]. They reported a propagation loss coefficient of 10 cm-1 which was caused by the light scattering at the rough interfaces. They also showed a bend loss of less than 1 dB at a 0.5 μm radius. They also reported an AWG demultiplexer using Si photonic wire waveguides [16]. An AWG of 110 × 93 μm^2 size on SOI was fabricated on SOI. The demultiplexing function was observed in the wavelength range of 1.50-1.57 μm with a channel spacing of < 6 nm and a free spectral range of > 90 nm.

They studied on the suppression of the polarization crosstalk [17]. The crosstalk from TE-like to TM-like polarization was evaluated experimentally to be -13 dB to -10 dB at a wavelength of 1.55 μm, which was compared with -25 dB obtained by 3-D finite-difference time-domain (FDTD) simulation for a 90º bend with a radius of 0.35-1.75 μm is less than. The large experimental value was explained by a small tilt of waveguide side-walls, which seriously increased the crosstalk. They proposed that a U-shape bend could be the most effective for the suppression of the crosstalk. They also achieved the insertion loss of less than 0.1dB for the elliptical intersection [18]. H. Yamada et al. reported an optical add-drop multiplexers based on Si-wire waveguides [19].

(2) Porous silicon waveguides:

Waveguides using porous silicon have been also studied extensively. Koshida et al. reported three-dimensionally buried porous silicon optical waveguides with an extremely high refractive index contrast in 1999 [20]. They achieved a buried bent PS waveguide with a curvature of 250μm. One of the features of the porous silicon waveguide is that the refractive index of PS is easily controlled both by the pore size and the incorporation of impurity atoms into pores. PS optical microcavities are fabricated using porosity-multilayer PS [21]. Nagata et al. [22] formed silica waveguides by oxidation of selectively anodized porous silicon. They incorporated titanium into core to obtain a desired large refractive index difference and obtained the optical loss of 0.3dB/cm at 632.8nm in the slab-waveguides.

(3) Photonic crystal waveguides:

Photonic crystal (PC) structures which show well-defined photonic bandgap have been extensively studied. Especially, Si photonics crystals fabricated on SOI substrates have been developed due to its matured fabrication processes. Various photonic devices have been demonstrated using 1D, 2D or 3D photonic crystals by Japanese researchers; filters [23, 24], waveguides [25-31], resonators [32, 33] etc. Si nanopillars fabricated on SiO_2 using SOI are extensively studied [34-36]. Optical waveguides of a submicron bent radius with almost complete optical confinement has been reported using e.g. a simple pillar missing line defect structure of 2D Si pillars [26, 29]. Optical delay lines are also designed and fabricated using impurity band-based photonic crystal waveguides which are composed of one-dimensional cylindrical air holes formed in Si on SiO_2 ridge waveguides [38], suppression of off-plane diffractive leakage has been a serious problem in SOI-PC line-defect waveguides, but it is overcome by adopting a narrow line-defect and phase-shifted-hole line-defect waveguide structures [25]. Two-dimensional ordered arrays of submicron-size dielectric microspheres such as silica [39] or Si_3N_4 [40] are found to show the photonic band structure and promising photonic crystals. 3D photonic crystals which show full bandgaps have also fabricated and propagation of light beams along line defects formed in a-Si/SiO_2 3D photonic crystals were observed [41-43]. Reduction of a coupling loss between photonic crystal-based optical devices and optical fibers may be one of the key technologies for the industrialization. Heterostructured photonic crystals fabricated by the autocloning technology solved this problem and achieved the coupling loss 0.43dB with a net propagation loss of 0.1dB/mm [44]. There are lots of studies and reports on the developments of photonic crystal optical devices other than waveguides, but they are not described in this report.

(4) Surface Plasmon Waveguides:

Surface plasmon propagation along metal nanoparticle chains can be used to form subwavelength-scale optical waveguides. By converting the optical mode into nonradiative surface plasmons, electromagnetic energy can be guided in structures with lateral dimensions of less than 10% of the free-space wavelength [45]. Several studies have also been reported by Japanese researchers. Nanodot couples were fabricated using a linear array of closely spaced metallic nanoparticles [46].

Other surface plasmon waveguide structures were also studied; a nanometer-sized oxide core with a metal clad [47] or two parallel metallic plates (surface plasmon polariton gap waveguide) [48]. In the former, the propagation length of the surface plasma polariton extended from 2μm to 6μm corresponding to the wavelength of 532nm to 830nm, respectively.

3. Silicon-based luminescence materials and devices

(1) Nanocrystalline Si (n-Si) and porous Si:

The difficulties of making Si LDs, LEDs or optical amplifier for practical use have been the main obstacle for the development of the Si photonic technology. Due to the indirect gap band structure of Si, the radiative recombination rate is too low to surpass other nonradiative recombinations at defects or at surfaces. Observation of strong luminescence from porous silicon by Canham was an indication of the enhanced radiative recombination in nanosize semiconductor particles.

Photoluminescence and electroluminescence of nc-Si have been studied worldwide. Various processes for the formation of nanocrystalline Si (quantum wells, wires and dots) were devised. Efficient photoluminescence at controlled wavelengths .in the visible region was obtained by changing the size of nanocrystalline Si spheres embedded in SiO_2. Electroluminescence of nc-Si in SiO_2 was also achieved by applying direct current in the visible region from red to blue. Excitation was carried out by impact excitation and the external quantum efficiency is lower than 1% [49-51] which is compared with a recent report of 2% from nc-Si embedded in Si_3N_4 [52]. Visible electroluminescence of nc-Si from CaF_2/nc-Si embedded in CaF_2 multilayers formed on a p-Si substrate was also reported, where the luminescence was obtained by recombination of electrons and holes injected by tunneling into nc-Si from ITO and p-Si, respectively [53, 54].

(2) Er-doped Si:

Luminescence of rare-earth doped semiconductors, especially electroluminescence of Er-doped Si has been attracted much attention since H. Ennen reported the electroluminescence from Er-implanted Si at 1.54 μm [5]. This emission was due to the 4f-4f transition of Er^{3+} and the wavelength coincides with that of optical communication. Lots of efforts have been done to find the way to realizing laser diodes and amplifier, but there are still problems which should be overcome. To realize a sufficient gain for lasing in the device size of mm or less, the Er concentration of the order of 10^{21}-$10^{22}/cm^3$ is necessary, but the solution limit of Er in crystalline Si is around 1019/cm3. Temperature quenching: due to energy back transfer from excited Er^{3+} to host Si at room temperature and concentration quenching due to energy exchange among Er^{3+} ions at high Er concentrations (above ~$10^{20}/cm^3$) should also be suppressed.

Oxygen co-incorporation or use of silicon-rich SiO_2, amorphous Si, porous Si [55] as hosts could increase the solution limit of Er at $10^{20}/cm^3$ and suppress the temperature quenching extensively and the increased photoluminescence or electroluminescence were obtained. .However, the Er concentration is still insufficient for LD or amplifier.

(3) Er and nc-Si codoped SiO_2:

Another attractive approach to the efficient Er luminescence is the co-doping of nc-Si and Er into SiO_2 which were demonstrated for the first time by Japanese researchers [10] and lots of studies on the energy transfer mechanisms, efficiency, luminescence characteristics etc have been carried out world-wide. . The main features of the materials are increased photoluminescence excitation cross section (10-16cm2) by about 4-5 orders compared with that of Er doped SiO_2, ($10^{-21}cm^2$) [11]. In Er-doped SiO_2, excitation of Er^{3+} ions is due to direct absorption of photons by 4f-electrons of Er^{3+} ions. However, in Er and nc-Si codoped SiO_2, nc-Si is first excited by irradiation of the above band gap light of nc-Si and then the e-h recombination energy is effectively resonant-transferred to Er^{3+} ions [56]. The advantage of these materials in comparison with Er-doped SiO_2 is that a simple lamp is used for the excitation. However, the materials are in principle high resistive and EL may be possible only by impact excitation.

(4) ErSiO superlattice crystals:

Recently, superlattice structured ErSiO was synthesized by H. Isshiki et al, a group of Japan and the Netherlands [12]. This ErSiO is a crystal which contain Er at ~$10^{22}/cm^3$ as a constituent atom, and shows a fine structure in the Er-related 1.54μm photoluminescence at room temperature. It also shows a semiconducting nature and is excited by the recombination of e-h pairs. Even at such a high Er concentration, defects are not caused in contrary to the case of Er doping and therefore the concentration quenching does not occur. . The superlattice structure is composed of Er_2O3 and Si layers with a period of 0.9nm, and it is speculated that the energy back transfer is suppressed due to the separation of Er^{3+} and host Si from its superlattice structure. Due to its semiconducting nature, studies on ErSiO LDs, LEDs and electrically excited waveguides with gain at 1.54μm are now in progress [57, 58].

(5) β-$FeSi_2$ on Si:

Heteroepitaxial growth of $SiFe_2$ by molecular epitaxy and its photoluminescence properties were studied [59, 61]. Room temperature electroluminescence from β-$FeSi_2$ on Si [62], p-Si/β-$FeSi_2$ particles/n-Si [63] and from a Si-based p-i-n diodes with β-$FeSi_2$ particles embedded in the intrinsic Si at 1.55 μm [64] have been reported.

(6) III-V compounds on Si:

Heteroepitaxial growth of luminescent III-V compound semiconductors on Si substrates has also been also studied extensively to utilize high their luminescence efficiency. .Following the success of epitaxial growth of GaP on Si/Si [65], lattice matched $GaP_{1-x}N_x$ (x = 2.9 %) -was successfully grown epitaxially on Si with no threading and misfit dislocations [66,-68], GaAsP LED diode was fabricated and showed infrared and visible luminescence at room temperature [69]. Polycrystalline GaN films were obtained by reactive rf-magnetron sputter-deposition on Si (110) and photoluminescence was observed at 100K [70, 71] and a possibility of epitaxial growth of crystalline GaN films was expected. LEDs using strained GaSb quantum dots (QDs) embedded in Si within the active region was fabricated and showed an external quantum efficiency of 0.3% was obtained for near band edge luminescence at 11 K [72].

4 Switches and modulators

Various types of optical switches or modulators using Si have been proposed and studied. MEMS switch/modulator has been developed extensively but it is beyond the scope of this review. Free-carrier absorption of infrared signal light due to the optically excited carriers in Si was studied for optical switch [73]. The response was limited by the slow free carrier lifetime. Nondegenerate two photon absorption processes inside silicon wire waveguides was also successfully applied for ultra fast switch, modulation and wavelength conversion [74]. Optical pulses of 1.6 ps at 1 GHz repetition rate have been successfully converted from 1552 nm to 1536 nm. TPA process is expected for high speed photonic signal processing in the Si photonic device system.

5. Concluding Remarks

Si laser has been our long-cherished dream and its realization using Raman amplification by UCLA and Intel attracted lots of attention and the research of Si photonic systems including both active and passive devices will be accelerated. There are still lots of important studies concerning Si photonics; which are not mentioned in this review; Si/Ge and Ge dots for infrared detectors, microcavity, and optical MEMs devices and so on. Research on silicon photonics in Japan has been mainly carried out at university laboratories and institutes and is material or physics-oriented rather than device fabrication. For example, study on the Raman amplification gain of Si was already measured by *Japan and Semiconductor Research Institute.* It is expected that Japanese government and companies become aware of the importance of Si photonics and promote cooperative developments of Si photonics technology with universities and institutes.

References

[1] Ozdal Boyraz and Bahram Jalali, Demonstration of a silicon Raman laser, Optics Express, **12**, 5269 – 5273 (2004)

[2] Haisheng Rong, Ansheng Liu, Richard Jones, Oded Cohen, Dani Hak, Remus Nicolaescu, Alexander Fang, Mario Paniccia, An all-silicon Raman laser, Nature **433**, 292-294 (2005)

[3] Haisheng Rong1, Richard Jones1, Ansheng Liu1, Oded Cohen2, Dani Hak2,Alexander Fang1 & Mario Paniccia1, A continuous-wave Raman silicon laser,Nature **433**, 725-728 (2005)

[4] L.T. Canham, Silicon quantum wire array fabrication by electrochemical and chemical dissolution of wafers, *Appl. Phys. Lett.* **57** 1046-1048(1990)

[5] H. Ennen, G. Pomrenke, A. Axmann, K. Eisele, W. Haydl, and J. Schneider, 1.54-µm electroluminescence of erbium-doped silicon grown by molecular beam epitaxy**,** Appl. Phys. Lett. **46**, 381-383(1985)

[6] Castagna ME, Coffa S, Monaco M, Muscara A, Caristia L, Lorenti S, Messina A, High efficiency light emitting devices in silicon, MATERIALS SCIENCE AND ENGINEERING B-SOLID STATE MATERIALS FOR ADVANCED TECHNOLOGY 105 (1-3): 83-90 (2003)

[7] S. V. Chernikov Y. Zhu R. Kashyap J. R. Taylor, High-gain, monolithic, cascaded fibre Raman amplifier operating at 1.3 µm, Electronics Letters, **31**, 472-473 (1995)

[8] K. Suto, T. Kimura, J. Nishizawa, Semiconductor Raman laser with pump light wavelength in the 800nm region, JOURNAL OF THE ELECTROCHEMICAL SOCIETY **140** (6): 1805-1808 (1993)

[9] Takao Saito, Ken Suto, Tomoyuki Kimura, Akiyoshi Watanabe and J. Nishizawa**,** Backward and forward Raman scattering in highly efficient GaP Raman amplifier waveguides, *Journal of Luminescence,* **87-89**, 883-885 (2000)

[10] Minoru Fujii, Masato Yoshida, Yoshihiko Kanzawa, Shinji Hayashi and Keiichi Yamamoto, 1.54 mu m photoluminescence of Er^{3+} doped into SiO_2 films containing Si nanocrystals: Evidence for energy transfer from Si nanocrystals to Er^{3+}, Appl. Phys. Lett. **71,** 1198-1200(1997)

[11] Franzo G, Vinciguerra V, Priolo F, The excitation mechanism of rare-earth ions in silicon nanocrystals, APPLIED PHYSICS A-MATERIALS SCIENCE & PROCESSING **69,** 3-12 (1999)

[12] Isshiki H, de Dood MJA, Polman A, and Kimura T. Self-assembled infrared-luminescent **Er**-**Si**-O

crystallites on silicon, Appl. Phys. Lett.. **85,** 4343-4345 (2004)

[13] S. Itabashi, H. Fukuda, T. Tuchizawa, T. Watanabe, T. Shoji and K. Yamada, Silicon wire waveguide and silicon microphotonis devices, Proceedings of Technical Meeting on Silicon photonics, IEICE, pp.61-68 (July, 2005)

[14] Tsuchizawa, T.; Yamada, K.; Fukuda, H.; Watanabe, T.; Jun-ichi Takahashi; Takahashi, M.; Shoji, T.; Tamechika, E.; Itabashi, S.; Morita, H, Microphotonics devices based on silicon microfabrication technology,.;Selected Topics in Quantum Electronics, IEEE Journal of, **11**, I232-240(2005)

[15] Atsushi Sakai, Go Hara and Toshihiko, Baba, Propagation Characteristics of Ultrahigh-Δ Optical Waveguide on Silicon-on-Insulator Substrate, J. Appl. Phys. **40** L383-L385(2001)

[16] Tatsuhiko Fukazawa, Fumiaki Ohno, and Toshihiko Baba**,** Very Compact Arrayed-Waveguide-Grating Demultiplexer Using Si Photonic Wire Waveguides, J.pn J. Appl. Phys. **43,** L1673-L1675 (2004)

[17] Sakai A, Fukazawa T, Baba T, Estimation of polarization crosstalk at a micro-bend in Si-photonic wire waveguide, JOURNAL OF LIGHTWAVE TECHNOLOGY **22** 520-525 (2004)

[18] Tatsuhiko Fukazawa, Tomohisa Hirano, Fumiaki Ohno and Toshihiko Baba, Low Loss Intersection of Si Photonic Wire Waveguides, Jpn. J. Appl. Phy. **43,** 646-647(2004)

[19] Hirohito Yamada, Tao Chu, Satomi Ishida, and Yasuhiko Arakawa, Optical add-drop multiplexers based on Si-wire waveguides**,** Appl. Phys. Lett. **86,** 191107 (2005)

[20] Takahashi M, Koshida N, Fabrication and characteristics of three-dimensionally buried porous silicon optical waveguides, J. APPL. PHYS.86, 5274-5278 (1999)

[21] Koshida N, Kojima A, Migita T, Nakajima Y, Multifunctional properties of nanocrystalline porous silicon as a quantum-confined material, MATERIALS SCIENCE & ENGINEERING C-BIOMIMETIC AND SUPRAMOLECULAR SYSTEMS **19**, 285-289 (2002)

[22] Seiichi Nagata, Shinobu Matsushita, Kazuya Saito, Yoshio Ohshita, Yoshinobu Maeda, Masafumi Yamaguchi, and Akira J. Ikushima, Silica waveguides fabricated by oxidization of selectively anodized porous silicon, Appl. Phys. Lett. **82**, 2559-2561 (2003)

[23] Hyun-Yong Lee, Hisao Makino, Takafumi Yao, and Akinori Tanaka, Si-based omnidirectional reflector and transmission filter optimized at a wavelength of 1.55μm, Appl. Phys. Lett. **81**, 4502 (2002)

[24] Hyun-Yong Lee, Sung-June Cho, Gi-Yeon Nam, Wook-Hyun Lee, Takeshi Baba, Hisao Makino, Meoung-Whan Cho, and Takafumi Yao, Multiple-wavelength-transmission filters based on Si-SiO2 one-dimensional photonic crystals, J. Appl. Phys. **97**, 103111 (2005)

[25] Koji Yamada, Masaya Notomi, Akihiko Shinya, Itaru Yokohama, Tetsufumi Shoji, Tai Tsuchizawa, Toshifumi Watanabe, Jun-Ichi Takahashi, Emi Tamechika, and Hirofumi Morita, SOI-based photonic crystal line-defect waveguides, Proc. SPIE Int. Soc. Opt. Eng. **4870**, 324 (2002)

[26] Masatoshi Tokushima, Hideo Kosaka, Akihisa Tomita, and Hirohito Yamada, Lightwave propagation through a 120[degree] sharply bent single-line-defect photonic crystal waveguide, Appl. Phys. Lett. **76**, 952 (2000)

[27] Yasuo Ohtera, Hiroyuki Ohkubo, Kenta Miura, Takashi Sato, Takayuki Kawashima, and Shirijo Kawakami, Waveguide and guided-wave devices consisting of heterostructured photonic crystals, Opt. Eng. **43**, 1022 (2004)

[28] Koji Yamada, Masaya Notomi, Akihiko Shinya, Itaru Yokohama, Tetsufumi Shoji, Tai Tsuchizawa, Toshifumi Watanabe, Jun-Ichi Takahashi, Emi Tamechika, and Hirofumi Morita, SOI-based photonic crystal line-defect waveguides, Proc. SPIE Int. Soc. Opt. Eng. **4870**, 324 (2002)

[29] Notomi M, Shinya A, Kuramochi E, Yokohama I, Takahashi C, Yamada K, Takahashi J, Kawashima T, Kawakami S, Si-based photonic crystals and photonic-bandgap waveguides, IEICE TRANSACTIONS ON ELECTRONICS E85C (4): 1025-1032 APR 2002

[30] Tsutomu Sato, Ichiro Mizushima, Shuichi Taniguchi, Keiichi Takenaka, Satoshi Shimonishi, Hisataka Hayashi, Masayuki Hatano, Kazuyoshi Sugihara, and Yoshitaka Tsunashima,, Fabrication of Silicon-on-Nothing Structure by Substrate Engineering Using the Empty-Space-in-Silicon Formation Technique, Jpn. J. Appl. Phys., **43,** 12 (2004)

[31] Y. Sugimoto, S. Lan, S. Nishikawa, N. Ikeda, H. Ishikawa, and K. Asakawa, Design and fabrication of impurity band-based photonic crystal waveguides for optical delay lines, Appl. Phys. Lett. **81**, 1946 (2002)

[32] Yukio Iida, Yasuhisa Omura, Yoshifumi Ogawa, Takeshi Kinoshita, and Masataka Tsuji, Ring resonator with sharp U-turns using a SOI-based photonic crystal waveguide with normal single-missing-hole-line defect, Proc. SPIE Int. Soc. Opt. Eng. **5277**, 206 (2004)

[33] Akihiko Shinya, Satoshi Mitsugi, Eiichi Kuramochi, Takasumi Tanabe, G. Kim Go Kira, Shingo Kondo, Kouji Yamada, Toshifumi Watanabe, Tai Tsuchizawa, and Masaya Notomi,Ultrasmall resonant tunneling/dropping devices in 2D photonic crystal slabs, Proceedings of SPIE -- Volume 5729, Optoelectronic Integrated Circuits VII, Louay A. Eldada, El-Hang Lee, Editors, March 2005, pp. 72-85

[34] Vladimir V. Poborchii, Tetsuya Tada, and Toshihiko Kanayama, A visible--near infrared range photonic crystal made up of Si nanopillars, Appl. Phys. Lett. **75**, 3276 (1999)

[35] Tetsuya Tada, Vladimir V. Poborchii, and Toshihiko Kanayama, Fabrication of photonic crystals consisting of Si nanopillars by plasma etching using self-formed masks, Jpn. J. Appl. Phys., Part 1 **38**, 7253 (1999)

[36] Vladimir V. Poborchii, Tetsuya Tada, and Toshihiko Kanayama, Photonic-band-gap properties of two-dimensional lattices of Si nanopillars, J. Appl. Phys. **91**, 3299 (2002)

[37] Y. Sugimoto, S. Lan, S. Nishikawa, N. Ikeda, H. Ishikawa, and K. Asakawa, Design and fabrication of impurity band-based photonic crystal waveguides for optical delay lines, Appl. Phys. Lett. **81**, 1946 (2002)

[38] Takashi Yamasaki and Tetsuo Tsutsui, Fabrication and optical properties of two-dimensional ordered arrays of silica microspheres, Jpn. J. Appl. Phys. **38**, 5916-5921(1999)

[39] T. Kondo, M. Hangyo, S. Yamaguchi, S. Yano, Y. Segawa, and K. Ohtaka, Transmission characteristics of a two-dimensional photonic crystal array of dielectric spheres using subterahertz time domain spectroscopy, Phys. Rev. **B 66**, 033111 (2002)

[40] Osamu Hanaizumi, Yasuo Ohtera, Takashi Sato, and Shojiro Kawakami, Propagation of light beams along line defects formed in a-Si/SiO_2 three-dimensional photonic crystals: Fabrication and observation, Appl. Phys. Lett. **74**, 777 (1999)

[41] Shojiro Kawakami, Takayuki Kawashima, and Takashi Sato,, Mechanism of shape formation of three-dimensional periodic nanostructures by bias sputtering, Appl. Phys. Lett. **74**, 463 (1999)

[42] Osamu Hanaizumi, Yasuo Ohtera, Takashi Sato, and Shojiro Kawakami, Optical waveguides in [small-caps A]-Si/SiO_2 submicrometer 3-D photonic crystals: Fabrication and observation, Opt. Photon. News **10**, 50 (1999)

[43] Yasuo Ohtera, Hiroyuki Ohkubo, Kenta Miura, Takashi Sato, Takayuki Kawashima, and Shirijo Kawakami, Waveguide and guided-wave devices consisting of heterostructured photonic crystals, Opt. Eng. **43**, 1022 (2004)

[44] Atwater H. A, Maier S, Polman A, Dionne JA, Sweatlock L, The new "p-n junction". Plasmonics enables photonic access to the nanoworld, MRS BULLETIN **30** (5): 385-389 (2005)

[45] Wataru Nomura and Motoichi Ohtsu, Takashi Yatsui, Nanodot coupler with a surface plasmon polariton condenser for optical far/near-field conversion, Appl. Phys. Lett. **86**, 181108 (2005)

[46] Onuki T, Watanabe Y, Nishio K, Tsuchiya T, Tani T, Tokizaki T, Propagation of surface plasmon polariton in nanometre-sized metal-clad optical waveguides, JOURNAL OF MICROSCOPY-OXFORD 210: 284-287 Part 3 (2003)

[47] Tanaka K, Tanaka M, Simulations of nanometric optical circuits based on surface plasmon polariton gap waveguide, Appl. Phys. Lett. **82** 1158-1160 (2003)

[48] Sato K, Hirakuri K, Izumi T, Significant improvement of luminance and stability of a red electroluminescent device using nanocrystalline silicon, JOURNAL OF NANOSCIENCE AND NANOTECHNOLOGY **5,** 738-741 (2005)

[49] Gelloz B, Kanda T, Uchida T, Niibe M, Kojima A, Koshida N, Electroluminescence enhancement assisted with ballistic electron excitation in nanocrystalline silicon diodes, Jpn. J. Appl. Phys.**44,** 2676-2679 (2005)

[50] Sato K, Hirakuri K, Iwase M, Izumi T, Fabrication of highly efficient full-color electroluminescent device composed of nanocrystalline silicon, JOURNAL OF NANOSCIENCE AND NANOTECHNOLOGY **5,** 271-276(2005)

[51] Gun Yong Sung, Kwan Sik Cho, Nae-Man Park, Tae-Youb Kim, Kyung-Hyun Kim, Silicon quantum dots LED with external quantum efficiency of 2%, 2005 APS March Meeting**,** March 21–25, 2005; Los Angeles, CA(2005)

[52] Maruyama T, Nakamura N, Watanabe M, Visible electroluminescence from nanocrystalline silicon embedded in single-crystalline CaF_2/Si(111) with rapid thermal anneal, Jpn. J. Appl. Phys. LETTERS **38,** L904-L906 (1999)

[53] Maruyama T, Nakamura N, Watanabe M, Improvement of the visible electroluminescence from nanocrystalline silicon embedded in CaF_2 on Si(111) substrate prepared by rapid thermal annealing, Jpn. J. Appl. Phys. LETTERS **39,**1996-2000 （2000）

[54] Kimura T, Yokoi A, Horiguchi H, Saito R, T, Ikoma, A, Sato, ELECTROCHEMICAL ER DOPING OF POROUS SILICON AND ITS ROOM-TEMPERATURE LUMINESCENCE AT SIMILAR-TO-1.54 MU-M, Appl. Phys. Lett. **65**, 983-985 (1994)

[55] Watanabe K, Fujii M, Hayashi S, Resonant excitation of Er^{3+} by the energy transfer from Si nanocrystals, J. Appl. Phys. **90,** 4761-4767(2001)

[56] Kimura T, Ueda K, Saito R, K. Masaki and H. Isshiki, Erbium-silicon-oxide nano-crystallite waveguide formation based on nano-porous silicon, OPTICAL MATERIALS **27,** 880-883 (2005)

[57] Masaki K, Isshiki H, Kimura T, Erbium-Silicon-Oxide crystalline films prepared by MOMBE, OPTICAL MATERIALS **27**, 876-879 (2005)

[58] Kenji Yamaguchi and Kazuki Mizushima, Luminescent FeSi[sub 2] Crystal Structures Induced by Heteroepitaxial Stress on Si(111), Phys. Rev. Lett. **86**, 6006 (2001)

[59] M. Takauji, N. Seki, T. Suemasu, F. Hasegawa, and M. Ichida, Growth of Si/beta-FeSi[sub 2]/Si double-heterostructures on Si(111) substrates by molecular-beam epitaxy and photoluminescence using time-resolved measurements, J. Appl. Phys. **96**, 2561 (2004)

[60] Y. Ozawa, T. Ohtsuka, Cheng Li, T. Suemasu, and F. Hasegawa. Influence of beta-$FeSi_2$ particle size and Si growth rate on 1.5 μm photoluminescence from Si/beta-$FeSi_2$-particles/Si structures grown by molecular-beam epitaxy, J. Appl. Phys. **95**, 5483 (2004)

[61] Takashi Suemasu, Yoichiro Negishi, Ken'ichiro Takakura, and Fumio Hasegawa, Room Temperature 1.6 μm Electroluminescence from a Si-Based Light Emitting Diode with beta-FeS_2 Active Region, Jpn. J. Appl. Phys., Part 2 **39**, L1013 (2000)

[62] T. Suemasu, Y. Negishi, K. Takakura, F. Hasegawa, and T. Chikyow, Influence of Si growth temperature for embedding beta-FeSi[sub 2] and resultant strain in beta-$FeSi_2$ on light emission from p-Si/beta-$FeSi_2$ particles/n-Si light-emitting diodes, Appl. Phys. Lett. **79**, 1804 (2001)

[63] Cheng Li, T. Suemasu, and F. Hasegawa, Room-temperature electroluminescence of a Si-based p-i-n diode with beta- $FeSi_2$ particles embedded in the intrinsic silicon, J. Appl. Phys. **97**, 043529 (2005)

[64] Takuto Tsuji, Hiroo Yonezu, Mikihiro Yokozeki, Yasufumi Takagi, Yasuhiro Fujimoto, and Naoki Ohshima, Defect-Controlled Selective Epitaxial Growth of GaP on Si by Migration-Enhanced Epitaxy under Atomic Hydrogen Irradiation, Jpn. J. Appl. Phys., Part 1 **36**, 5431 (1997)

[65] Yasuhiro Fujimoto, Hiroo Yonezu, Satoshi Irino, Katsuya Samonji, Kenji Momose, and Naoki Ohshima, High-quality $GaAs_xP_{1-x}/In_{0.13}Ga_{0.87}P$ quantum well structure grown on Si substrate with a very few threading dislocations, Jpn. J. Appl. Phys., Part 1 **38**, 6645 (1999)

[66] Kenji Momose, Hiroo Yonezu, Yasuhiro Fujimoto, Yuzo Furukawa, Yoshifumi Motomura, and Kunio Aiki, Dislocation-free and lattice-matched Si/GaP[sub 1 - x]N[sub x]/Si structure for photo-electronic integrated systems, Appl. Phys. Lett. **79**, 4151 (2001)

[67] Yuzo Furukawa, Hiroo Yonezu, Kaoru Ojima, Katsuya Samonji, Yasuhiro Fujimoto, Kenji Momose, and Kunio Aiki, Control of N Content of GaPN Grown by Molecular Beam Epitaxy and Growth of GaPN Lattice Matched to Si(100) Substrate, Jpn. J. Appl. Phys., Part 1 **41**, 528 (2002)

[68] Masahiro Yoshimoto, Mitsunari Itoh, Junji Saraie, Toshiyuki Yasui, Sanghoon Ha, Tatsuro Kurobe, and Hiroyuki Matsunami, GaAsP pn Diode on Si Substrate Grown by Metalorganic Molecular Beam Epitaxy for Visible Light-Emitting Devices, Jpn. J. Appl. Phys., Part 1 **40**, 3953 (2001)

[69] Takayuki Miyazaki, Tamotsu Fujimaki, Sadao Adachi, and Kohji Ohtsuka, Properties of GaN films

deposited on Si(111) by radio-frequency-magnetron sputtering, J. Appl. Phys. **89**, 8316 (2001)

[70] Takayuki Miyazaki, A. Kouhei Takada, and Sadao Adachi, and Kohji Ohtsuka, Properties of radio-frequency-sputter-deposited GaN films in a nitrogen/hydrogen mixed gas, J. Appl. Phys. **97**, 093516(2005)

[71] M. Jo, K. Ishida, N. Yasuhara, Y. Sugawara, K. Kawamoto, and S. Fukatsu, A Si-based quantum-dot light-emitting diode, Appl. Phys. Lett. **86**, Art.No. 103509 (2005)

[72] Mitsunori Saito and Takeshi Inoue, Infrared optical switch by the use of optically excited free carriers in semiconductors, Rev. Sci. Instrum. **71**, 2134 (2000)

[73] L. R. Nunes. T. K. Liang, D. Van Thourthout, P. Dumon, R. Baets, H. K. Tsang and M. Tsuchiya,, All-Optical Wavelength switching of 1.6ps pulses by cross-absorption modulation in silicon wire waveguides, Proceedings of Technical Meeting on Silicon photonics, IEICE, pp.51-54 (July, 2005)