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VCSEL photonics —advances and new challenges—

Fumio Koyama[a)]
Microsystem Research Center, Tokyo Institute of Technology,
4259–R2–22 Nagatsuda, Midori-ku, Yokohama 226–8503, Japan
a) *koyama@pi.titech.ac.jp*

Abstract: We had the 30-year anniversary since a VCSEL was invented by Kenichi Iga, Tokyo Institute of Technology. We have seen various applications including datacom, sensors, optical interconnects, spectroscopy, optical storages, printers, laser displays, laser radar, atomic clock, optical signal processing and so on. A lot of unique features have been proven, low power consumption, a wafer level testing and so on. In this paper, the brief history and our recent research activities on VCSEL photonics will be reviewed. We present the wavelength engineering of VCSEL arrays for use in high speed short-reach systems, which includes the wavelength integration and wavelength control. The joint research project on ultra-parallel optical links based on VCSEL technologies will be introduced for high speed LANs of 100 Gbps or higher. The small footprint of VCSELs allows us to form a densely packed VCSEL array both in space and in wavelength. The wavelength engineering of VCSELs may open up ultra-high capacity networking. Highly controlled multi-wavelength VCSEL array and novel multi-wavelength combiners are developed toward Terabit/s-class ultrahigh capacity parallel optical links. In addition, the MEMS-based VCSEL technology enables widely tunable operations. We demonstrated an “athermal VCSEL” with avoiding temperature controllers for uncooled WDM applications. In addition, new functions on VCSELs for optical signal processing are addressed. We present an optical nonlinear phase shifter based on a VCSEL saturable absorber and the tunable optical equalization function.

Also, highly reflective periodic mirrors commonly used in VCSELs enables us to manipulate the speed of light. This new scheme provides us ultra-compact intensity modulators, optical switches and so on for VCSEL-based photonic integration. Also, this paper explores plasmonic VCSELs.

Keywords: surface emitting laser, long wavelength laser, laser array, WDM, local area network
Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

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1 Introduction

A vertical cavity surface emitting laser (VCSEL) was invented by Kenichi Iga of Tokyo Institute of Technology in 1977 [1]. We have seen various applications including datacom, sensors, optical interconnects, spectroscopy, optical storages, printers, laser displays, laser radar, atomic clock, optical signal processing and so on. A lot of unique features have been shown, low power consumption, a wafer level testing and so on. The market of VCSELs has been

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growing up rapidly and they are now key devices in local area networks based on multi-mode optical fibers. Also, long wavelength VCSELs are currently attracting much interest for use in single-mode fiber metropolitan area and wide area networks [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19].

In this paper, our recent research activities on VCSEL photonics will be reviewed. We present the wavelength engineering of VCSEL arrays for use in high speed short-reach systems, which includes the wavelength integration and wavelength control. The joint research project on ultra-parallel optical links based on VCSEL technologies will be introduced for high speed LANs of 100 Gbps or higher. The small footprint of VCSELs allows us to form a densely packed VCSEL array both in space and in wavelength. The wavelength engineering of VCSELs may open up ultra-high capacity networking. Highly controlled multi-wavelength VCSEL array and novel multi-wavelength combiners are developed toward Tera-bit/s-class ultrahigh capacity parallel optical links.

In addition, the MEMS-based VCSEL technology enables widely tunable operations [20]. The recent activity with nano-mechanical tuning scheme with high contrast grating results in the increase of tuning speed [21]. Also we proposed and demonstrated a "athermal VCSEL" with avoiding temperature controllers for uncooled WDM applications [22, 23]. The temperature dependence of long-wavelength VCSELs could be reduced by a factor of 50 with a novel thermally-actuated membrane mirror.

New functions on VCSELs for optical signal processing [24, 25, 26, 27, 28, 29, 30] are addressed. We present an optical nonlinear phase shifter based on a VCSEL saturable absorber [31, 32]. A large nonlinear phase shift could be observed in both modeling and experiments. The proposed device would be useful for mitigating fiber nonlinearities in optical domain and for optically manipulating the phase of light. In addition, we demonstrate the tunable optical equalization function using a 1.55 μm VCSEL biased below threshold. Bandwidth enhancement can be tuned by bias current. A modulation bandwidth beyond 70 GHz was obtained on $LiNbO_3$ modulators.

Also, highly reflective periodic mirrors commonly used in VCSELs enables us to manipulate the speed of light. This new scheme provides us ultra-compact intensity modulators, optical switches and so on for VCSEL-based photonic integration. We present our results on the modeling and experiments of VCSEL-based slow light devices and plasmonic VCSELs.

2 Wavelength engineering and integration

The schematic structure of a 1.2 μm GaInAs/GaAs VCSEL is shown in Fig. 1. We realized the wavelength extension of GaInAs/GaAs strained quantum wells to open up a new wavelength band of 1.0-1.2 μm [13, 14]. We achieved a low threshold current of below 1 mA, high-temperature operation of up to 450 K, uncooled 10 Gbps operations and high reliability of $>$ 2000 hours [2]. The room temperature L/I characteristic of 1.2 μm VCSEL is shown in Fig. 2 [4], exhibiting a single-mode output power of over 2 mW.

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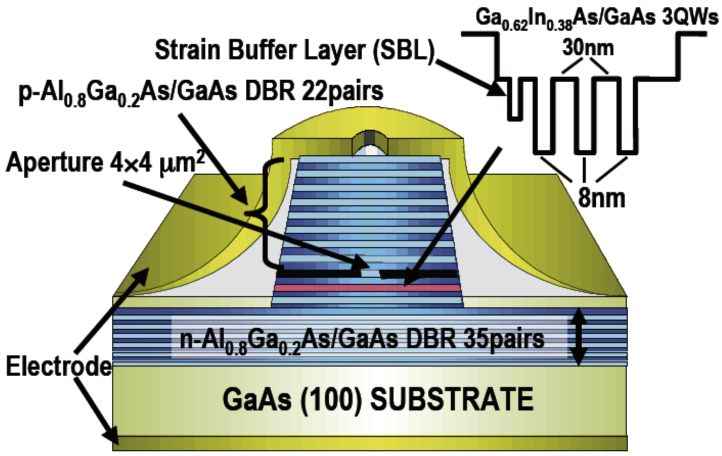

Fig. 1. Schematic structure of GaInAs/GaAs VCSEL [4].

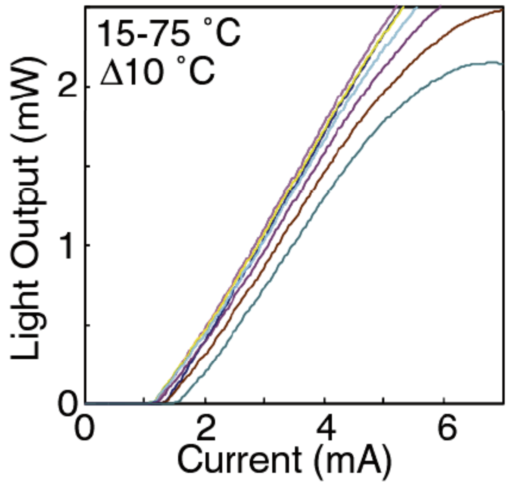

Fig. 2. Temperature dependences of L/I characteristic of 1.2 μm GaInAs VCSELs [4].

A characteristic temperature T0 is over 200 K, which is much higher than 1.3 μm InP based lasers. The excellent temperature characteristic is due to the deep potential well of this material system. The extension of the emission wavelength up to 1.2 μm enables high speed data transmission in single mode fibers. The optical feedback sensitivity is an important issue for low cost single-mode LD module. Figure 3 shows the result on isolator-free single-mode fiber transmission [15].

For upgrading bit rates beyond several tens Gbps, we may expect the use of WDM links even for short reach systems. For this purpose, a multiple-wavelength VCSEL array will be a key device. We have spent much effort for realizing multiple-wavelength VCSEL array on patterned substrates [16]. We demonstrated a single-mode multiple-wavelength VCSEL array on a patterned GaAs substrate as shown in Fig. 4. By optimizing a pattern shape, we achieved multiple-wavelength operation with widely and precisely controlled lasing wavelengths. The maximum lasing span reaches 190 nm [17]. We also demonstrated a densely integrated multi-wavelength VCSEL array

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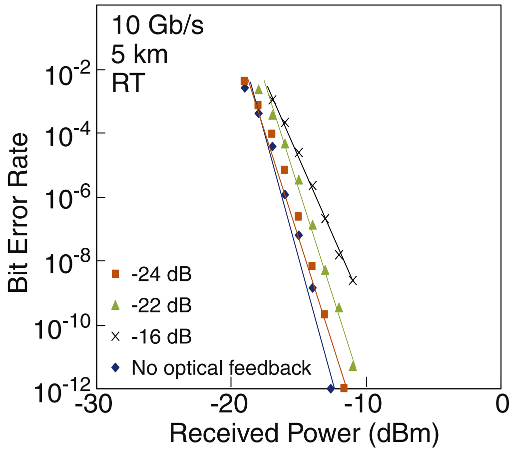

Fig. 3. 10 Gb/t data transmission using 1.2 μm VCSEL [15].

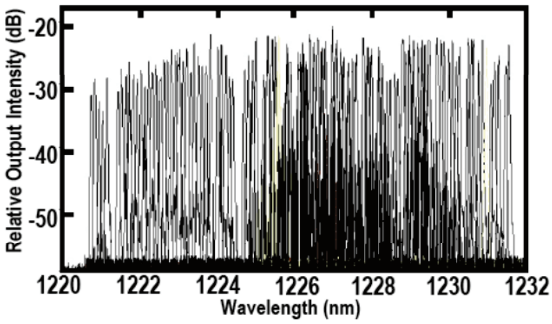

Fig. 4. Lasing spectra of 110 channel VCSEL array [18].

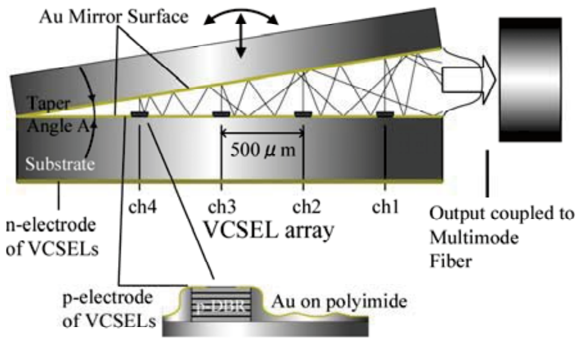

Fig. 5. Schematic structure of a tapered hollow waveguide multiplexer for multi-wavelength VCSEL array [19].

with a spacing of 50 μm. We also achieved 110 channel VCSEL array with separation of 0.1 nm as shown in Fig. 4 [18].

In order to realize WDM transceivers based on multi-wavelength VCSEL arrays, however, a low-cost and compact multiplexer of each VCSEL output is necessary. We proposed a tapered hollow waveguide multiplexer for coupling multi-wavelength VCSEL array output into a multi-mode fiber as shown in Fig. 5 [19]. The structure consists of two high-reflectivity mirror.

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The core is air and a VCSEL array is integrated on the bottom mirror in the figure. Each output from VCSEL is radiated vertically from the bottom mirror side. An upper mirror and bottom mirror are placed with a taper angle. After multiple reflections, the reflection angle of the output is simply changed. Therefore the propagation direction of the output from each VCSEL is converted to a horizontal direction. The output from the tapered hollow waveguide multiplexer can be coupled to a multimode fiber and simple and low-cost multiplexer can be realized without losing the advantages of small footprint of VCSEL arrays. We demonstrated multiplexing of 4-channel output of a VCSEL array formed on a patterned substrate for coupling into a multi-mode fiber. The proposed hollow waveguide multiplexer is helpful for realizing compact, simple and low-cost WDM transceiver for short reach applications.

3 Athermal operations of VCSELs

The temperature dependence of semiconductor lasers, which is typically 0.1 nm/K even for single-mode semiconductor lasers, is a remaining problem to be solved. The elimination of costly thermoelectric controllers is desirable for use in low cost WDM networks. If it is realized, we expect low power consumption as well as small packaging. We proposed an athermal VCSEL with a fixed wavelength even under temperature changes using the self-compensation based on a thermally actuated cantilever structure [22]. We have demonstrated small temperature dependence in micromachined vertical cavity optical filters and light emitters of GaAs/GaAlAs materials. It is a challenge to realize an athermal VCSEL based on the proposed concept.

Figure 6 shows the principle of athermal operations and the schematic structure of a micromachined VCSEL. The base structure of the devices was grown in Corning Incorporated, which is similar to that of InP-based VCSELs with tunnel junction [12]. Because GaInAsP has a larger thermal expansion coefficient than InP, we are able to obtain the thermal actuation of the cantilever for compensating the temperature dependence of wavelength.

The SEM view of a micromachined InP-based VCSEL is shown in Fig. 7 [23]. The cantilever length is varied from 65 μm to 95 μm, which give us different temperature dependences. The threshold is 1.3 mA and the maximum power is 0.3 mW under room temperature cw operation. The device was operated at a constant current of 4 mA to avoid the effect of self-heating. The measured lasing spectra of VCSELs are shown in Fig. 8 for cantilever length of 95 μm.

Figure 9 shows the temperature dependence of lasing wavelengths. The solid and dashed lines show theoretical calculation and experimental data fitting, respectively. Experimental data are in agreement with the calculations. For increasing thermal actuations, the top InP layer with a thickness of d on the cantilever was etched by using focused ion beam (FIB). The circles and squares of Fig. 9 show the data of etched samples with d = 0 nm. The lasing wavelength could be locked within 0.03 nm for temperature changes of 19 K

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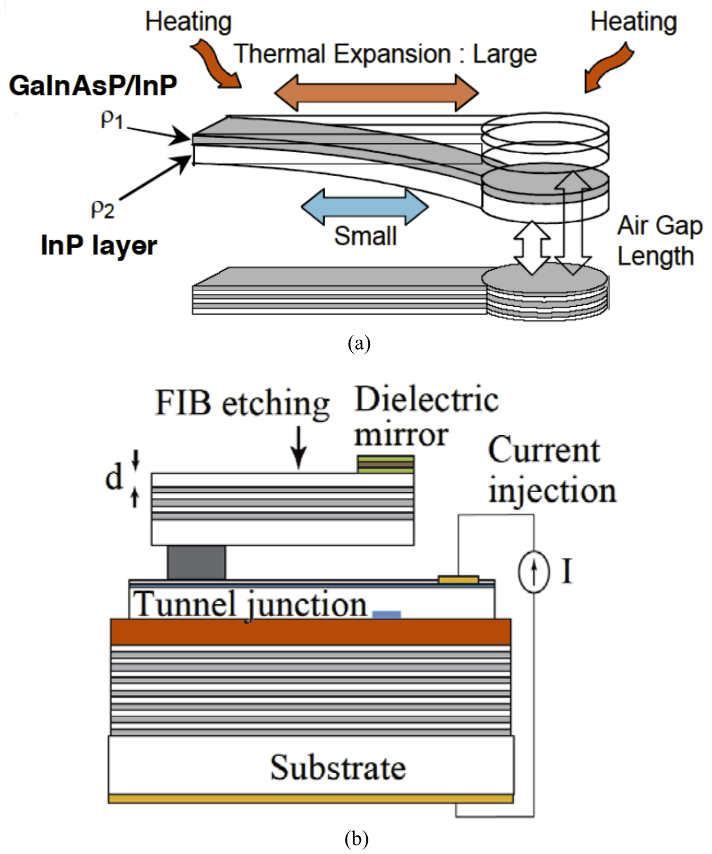

Fig. 6. (a) Principle and (b) schematic structure of athermal VCSEL with a micromachined cantilever structure [23].

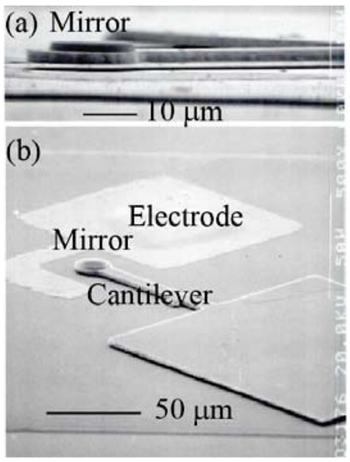

Fig. 7. SEM image of athermal InP-based VCSEL with a thermally-actuated cantilever structure [23].

with a cantilever length of 95 μm and the lowest temperature dependence we achieved is as low as 0.0016 nm/K [23].

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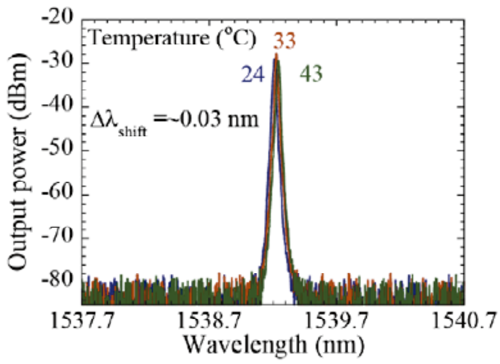

Fig. 8. Temperature dependences of lasing spectra for L = 95 μm with a fixed bias current of 4 mA [23].

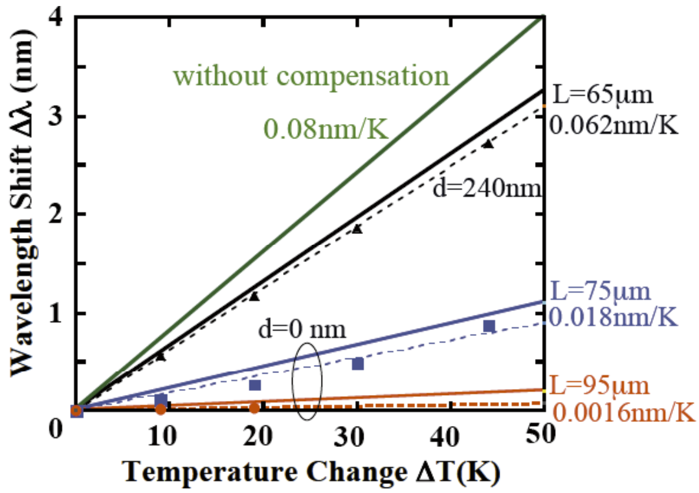

Fig. 9. Wavelength shift versus temperature changes. Solid lines show the calculation. Closed circles, squares and triangles show experiments. The thickness d of the top InP strain control layer is changed with FIB etching [23].

4 Optical signal processing

In contrast to the optoelectronic regenerators, all-optical regenerators have a potential for low power consumption, as well as simple and cost-effective configuration. All-optical signal processing using VCSELs has recently been investigated for future photonic networks. The optical injection locking is very useful for reducing chirp and for extending the modulation bandwidth [24]. We are also able to obtain a nonlinear transfer function which can be used for all-optical signal processing. The injection locking of VCSELs has been examined theoretically and experimentally [25, 26, 27]. It was shown that a variety of interesting nonlinear behaviors were observed, which was dependent on injection power and frequency detuning. All-optical format conversion was demonstrated using a polarization switching in a VCSEL [28]. All-optical inverter based on transverse mode switching in a two-mode VCSEL was proposed, which has attractive features of low power consumption, dense

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packaging and polarization insensitivity [29]. The transverse mode switching is induced when a first-high-order mode was injection-locked by a signal light. The dominant lasing mode switches from a fundamental mode to the high-order mode due to injection locking. If we look at the output power of the fundamental mode as a function of the input power, an optical inverter function with abrupt switching is obtained. The VCSEL structure may provide us possibilities of low power consumption and polarization insensitive operations for all-optical signal processing. We demonstrated all optical regeneration and optical polarization control based on the injection-locking scheme [30].

Fiber nonlinearities are dominant limiting factors for high-speed transmission systems of 40 Gb/s or beyond. Waveform distortion is induced by various fiber nonlinear effects such as SPM (self-phase modulation), XPM (cross-phase modulation) and FWM (four-wave mixing). The fiber nonlinear effects cannot be compensated by linear optical circuits in optical domain. If we realize a nonlinear optical compensator, which gives us a negative phase-shift in an opposite sign of optical Kerr effect in fibers, we are able to compensate fiber nonlinealities by inserting the device. An optical nonlinear phase-shifter based on a VCSEL structure with a saturable absorber was demonstrated [31, 32].

Figure 10 shows the schematic structure and the operating principle of the optical phase shifter based on 1.55 μm VCSEL structure [31]. An intensity dependent negative refractive index change appears with an opposite sign of optical Kerr effect in the saturable absorber, which is enhanced by a resonant vertical-cavity. The modeling result shows that either positive or negative phase-shifts of reflected light can be obtained with 1.55 μm-VCSEL, depending on the cavity Q-value [31]. Both positive and negative phase shifts are useful for the compensation of laser chirp and fiber nonlinearities in optical domain, respectively.

There is the trade-off between the phase-shift and optical bandwidth. Therefore, we have to choose suitable design of mirrors for optimizing bandwidth and phase-shift. An InGaAlAs saturable absorber is sandwiched by the two mirrors. If the input light power coupled to this device increases, the

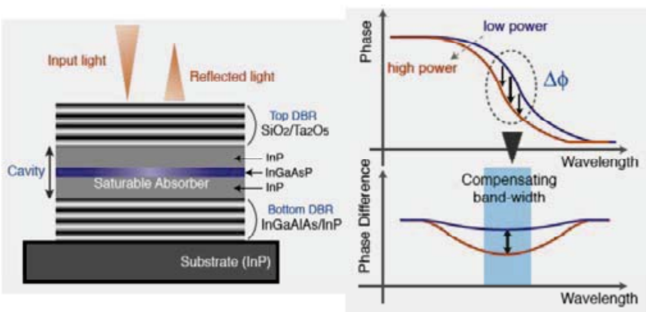

Fig. 10. Schematic structure and operating principle of nonlinear-effect optical compensator using InGaAlAs vertical cavity saturable absorber [31].

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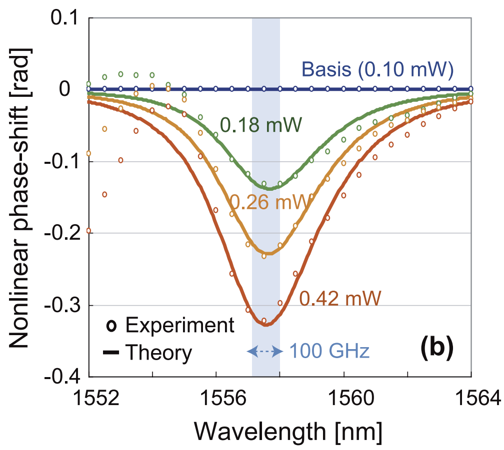

Fig. 11. Measured wavelength dependence of nonlinear phase shift for different input power [32].

phase difference is induced by the refractive index change in the saturable absorber. No reverse bias gives slow recovery time of 1 nsec range. The reflectivity and the group delay dependence on input power was measured by using an optical component analyzer (Advantest Q7761) with a tunable laser source. The phase shift was estimated from performing spectral domain integration of the measured group delay. Figure 11 shows the nonlinear phase-shift from the data of 0.10 mW input power. The solid lines show the calculation [32]. Here, we assume that saturation coefficient is 2 kW/cm2, which corresponds to the case of $\tau = 1$ ns recovery time for a saturable absorber without reverse bias. A positive group delay and negative phase-shifts were observed as predicted in theory. We obtained a large negative phase-shift of a -0.4 radian for input power of 0.42 mW, which is large enough for compensating 100 km long fiber nonlinearities. The reduction of absorption recovery time below 10 ps with reverse bias enables us to use the compensator for high bit-rate signals. The addition of 1.2 V reverse-bias showed the transient response of nonlinear phase shifts even for 7 psec input pulses.

We carried out the optical compensation of self-phase modulation for high-speed signals by using our VCSEL-based compensator as shown in Fig. 12 (a) [32]. As can be seen in Fig. 12 (b), the transient phase change induced by self-phase modulation with an input peak power of 8 mW can be optically compensated by using our VCSEL-based compensator. The tail of residual phase-shift (imperfect compensation) would be due to the insuffícnt recovery time of photo-carries in the sarurable absorver. The novel nonlinear-effect compensator shows a large nonlinear negative phase-shift depending on input power levels. The proposed concept may open up a novel technology for compensating fiber nonlinearities in optical domain.

High-speed modulation beyond several tens Gbps are becoming important for both long-haul and short-reach broadband access networks. The modulation bandwidth of light sources has been limited by their device parasitic and intrinsic limitations such as the relaxation oscillation and heating effect seen in directly modulated semiconductor lasers. Recently, bandwidth

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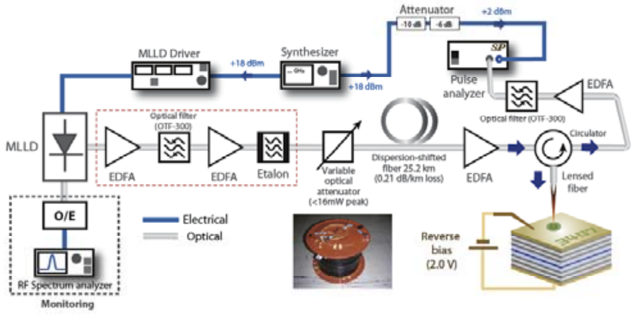
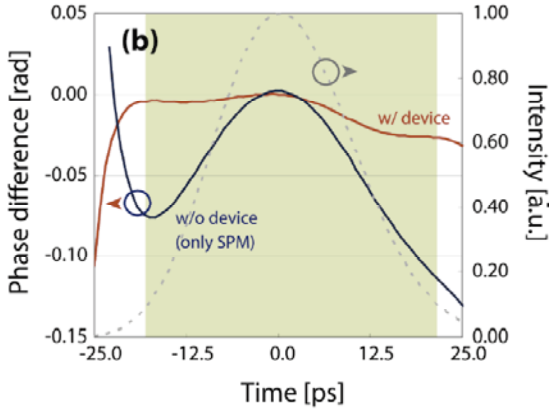


(a)



(b)

Fig. 12. (a) Measurement setup for all optical compensation of fiber nonlinearity and (b) measured nonlinear-phase shift [32].

enhancement beyond several tens GHz was demonstrated in optical injection-locked lasers [33, 34]. Alternatively, optical [35] or electrical [36] equalization techniques have been demonstrated, showing an increase of the modulation bandwidth of low speed light sources. We have also previously reported a diffraction-grating optical equalizer for bandwidth enhancement [37]. Here, we present a compact VCSEL-based tunable optical equalizer, which can help enhance the modulation bandwidth of a $LiNbO_3$ modulator beyond 70 GHz.

Figure 13 shows the operating principle of our tunable optical equalizer based on a 1.55 μm VCSEL [38]. The InP-based VCSEL used in this experiment was fabricated by Corning Incorporated, which has a 7 μm-φ tunnel junction aperture [12]. The bias current for operating the VCSEL as an equalizer is below its lasing threshold of 0.6 mA, thus very low power consumption is expected for the proposed optical equalization function. Biasing the VCSEL below threshold enables us to obtain a dip-shaped response on the reflection spectra. The bandwidth, the center-dip and the center wavelength can all be tunable, depending on the bias. Figure 14 shows the measured reflection spectra of the VCSEL tunable equalizer with various bias currents. The center dip varies between -3 dB and -13 dB. By suppressing the carrier of the modulated light, which is intentionally placed at the center-dip, modulation sidebands are comparatively increased, thus resulting in bandwidth enhancement.

We carried out the characterization of bandwidth enhancement of $LiNbO_3$

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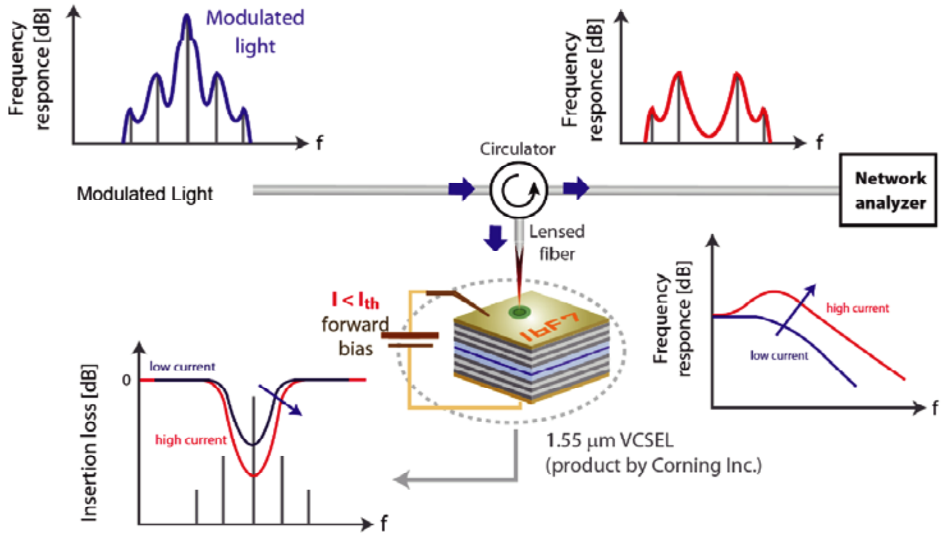

Fig. 13. Operating principle of a VCSEL optical equalizer biased below threshold.

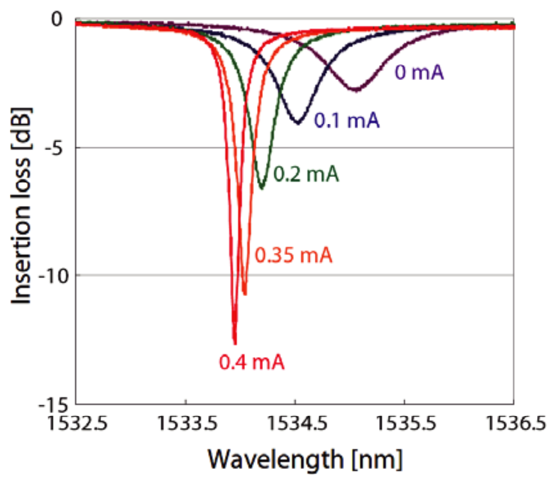

Fig. 14. Measured reflection spectra of a 1.55 μm InP-based VCSEL at different bias currents [38].

modulators using the VCSEL equalizer. We tested 10-GHz and 25-GHz $LiNbO_3$ modulators. The modulated light was coupled into the VCSEL equalizer through an optical circulator and a lensed fiber. The coupling loss is 3 dB. We used a 70 GHz-bandwidth network analyzer for measuring small signal modulation responses. An EDFA was used to compensate for the insertion loss, but it might be unnecessary if the output power of the light sources are chosen higher. The input power into the equalizer was −4 dBm. Figures 15 show the measured small signal frequency response with the optical equalizer at various bias currents for 25-GHz $LiNbO_3$ modulators [38]. The 3 dB bandwidth could be increased from 10 GHz to 45 GHz for the 10-GHz modulator. Also, the bandwidth enhancement beyond the measurement limit (70 GHz) can be seen for a 25-GHz $LiNbO_3$ modulator. Note that the notch and the noisy response at frequencies > 55 GHz are due to the device parasitics. Basically, the results shown here are similar as demonstrated pre-

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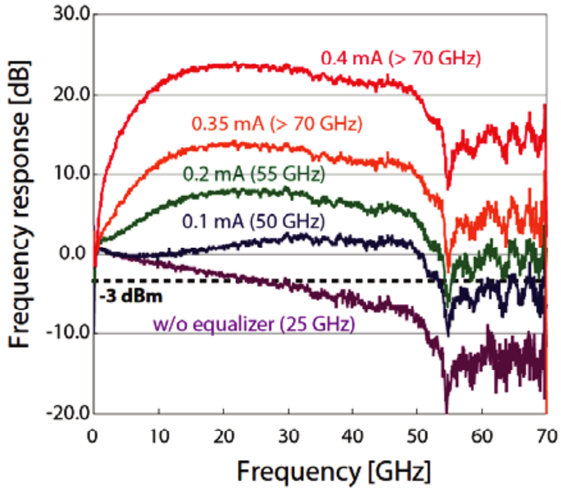

Fig. 15. Small signal response of 25-GHz $LiNbO_3$ modulators with the VCSEL equalizer operating at different bias currents [38].

viously using a grating-type equalizer [37]. However, the VCSEL equalizer is much more compact and integratable.

5 Slow light optical devices

The manipulation of the speed of light has been attracting much interest in recent years. In particular, slow light appearing in photonic crystals, semiconductor amplifiers and micro-resonators has been studied for optical buffer memories, optical delay lines and so on [39, 40, 41]. Also, the slow group velocity of light dramatically reduces the size of various optical devices such as optical amplifiers, optical switches, nonlinear optical devices and so on [42, 43]. We have also observed large waveguide dispersion and slow light [44] in Bragg waveguides where light is confined with highly reflective Bragg reflectors [45]. We proposed a slow light modulator with a Bragg waveguide [46, 47]. We expect high speed modulation of such an ultra-compact waveguide modulator, which enables us to avoid velocity-matching traveling-wave schemes. An important issue is the coupling between free-space propagation light and slow light.

The group velocity decreases with increasing the waveguide dispersion when the wavelength approaches to the cut-off wavelength. The slow-down factor, which is defined as the ratio of the group velocity of slow light versus that in conventional semiconductor waveguides, is over 10 in the wavelength range of 1550-1560 nm. Thus, the electro-absorption effect is enhanced by a factor of more than 10 in this wavelength range and we are able to reduce the size. Even for an ultra-compact modulator, we expect an extinction ratio of 7 dB over 1550 nm, which will be large enough for short-reach optical links. We also expect low polarization dependence, which is very difficult for that of photonic crystal slab waveguides.

An important issue is how to couple with slow light in a Bragg waveguide. We proposed a simple and practical method of a tilt-coupling scheme

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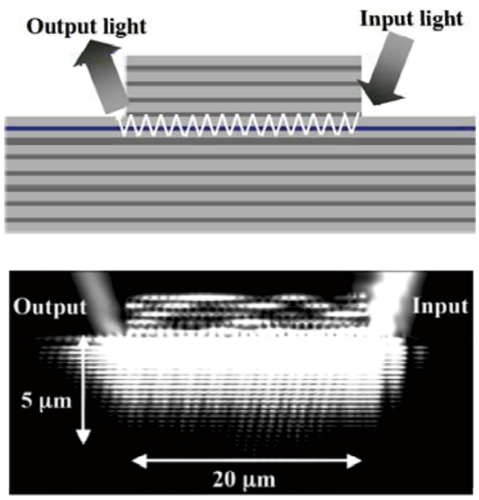

Fig. 16. Calculation model and calculated intensity distribution with tilt light input for efficient excitation of slow light [47].

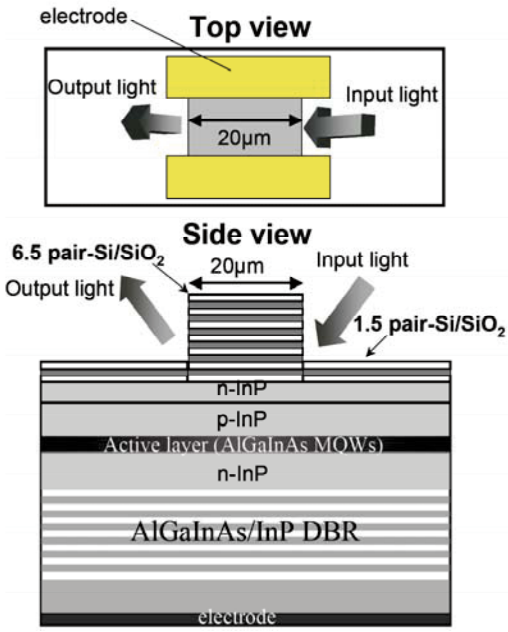

Fig. 17. Schematic structure of a slow light AlGaInAs MQW electro-absorption modulator [47].

as shown in Fig. 16 [47]. The input beam is off from the vertical axis and the tilt angle is typically 30 degrees. We carried out the full-vectorial numerical simulation using the film-mode-matching method (FIMMWAVE, Photon Design Co.). Figure 16 shows the model and the calculated field distribution [47]. The coupling loss is less than 1.5 dB for TE and TM modes with a 4 μm-spot-size Gaussian beam input. This coupling scheme enables us to excite slow light propagating in a Bragg waveguide where light is confined by Bragg mirrors.

We fabricated an electroabsorption modulator consisting of Bragg waveguides with slow light enhancement as shown in Fig. 17 [47]. The base struc-

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ture is similar to that of a conventional InP-based VCSEL without tunnel junction [12]. The bottom mirror is AlGaInAs quarter-wavelength stack mirror. At first, 1.5-pairs Si/SiO_2 dielectric mirror was deposited over the entire surface except top electrodes and then a 5-pair Si/SiO2 dielectric mirror was partly deposited to form a 20 μm long Bragg waveguides. The role of 1.5-pair Si/SiO_2 dielectric mirror is the efficient excitation of slow light in a Bragg waveguide. The absorption layer consists of AlGaInAs MQWs in a 1.5 μm wavelength band. With applying reverse bias voltages in its p-n junction, an electro-absorption takes place.

We measured the zero-biased insertion loss from the measured near-field intensity. We could achieve a minimum coupling loss of 1 dB, indicating the low coupling loss of the proposed coupling scheme. We achieved an extinction ratio of 6 dB and an insertion loss of 2 dB for a 20 μm long compact waveguide modulator. The proposed structure can be monolithically integrated with VCSELs. The proposed modulator would be useful for ultrahigh speed short reach optical links. We also proposed an ultra-compact slow light optical switch with giant refractive index changes as shown in Fig. 18 [48, 49]. In addition, simple coupling scheme with slow light in Bragg waveguides would also be useful for various slow light photonic circuits involving optical switches, amplifiers, lasers and so on.

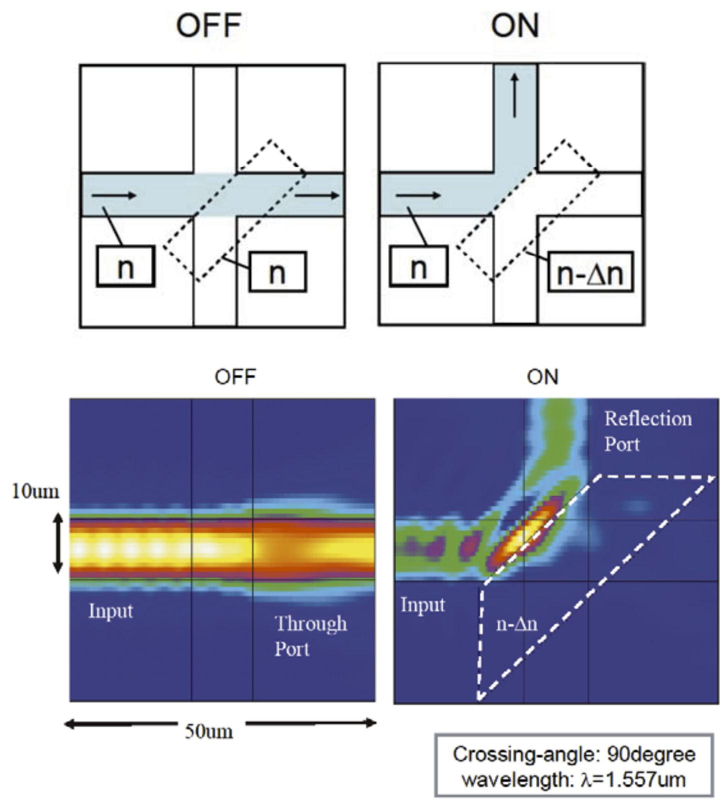

Fig. 18. Modeling slow light waveguide switch [49].

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6 Plasmonic VCSELs

High-density optical data storages with Tera-bytes capacity have been attracting much interest. An optical near-field technology is one of candidates to make a breakthrough for future optical storages [50, 51] surface emitting laser (VCSEL) array was proposed and a metal nano-aperture VCSEL was demonstrated for producing optical near-field localized at the metal nano-aperture [52]. The voltage change induced by scattering in a nano-aperture enables us to use the same nano-aperture VCSEL chip for optical near-field probing [53].

We have developed metal nano-sperture VCSELs for producing localized optical near-fields [52]. The spot-size of the optical-near-field through a metal aperture is determined by the aperture size. Increase in the optical power through the nano-aperture is an important issue for practical applications. An interesting approach for enhancing optical near-fields is to use surface plasmon in metallic nano-structures [54, 55, 56, 57]. We demonstrated the surface plasmonic enhancement by using the metal nano structure. However, the plasmonic-enhancement is strongly dependent on the polarization, which should be controlled.

We demonstrated the generation of sun-100 nm optical near-field from metal nano-aperture VCSELs by loading a metal nano-aperture array which enables polarization control. In addition, the increase of the size of a rectangular aperture array allows us to realize polarization controlled top emitting VCSELs. Figure 19 shows the schematic structure of a metal nano-aperture array VCSEL [57]. The number of the p-type top DBR pair was designed to be about a half of a standard design for increasing the near-field intensity through the nano-aperture. The surface Au film functions as a part of the mirror. We inserted a SiO_2 layer underneath the aperture in order to enhance the plasmonic resonance. The thickness of SiO_2 and Au layer is

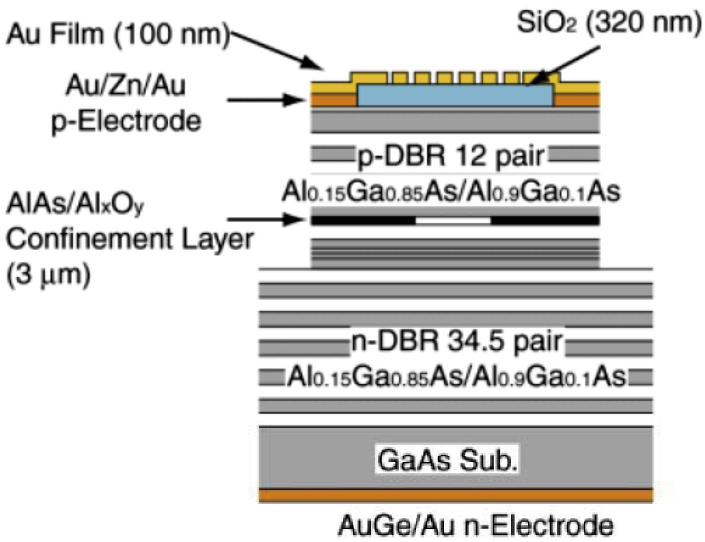

Fig. 19. Schematic structure of metal nano-aperture array VCSEL. The oxide aperture size is $3\,\mu$m [57].

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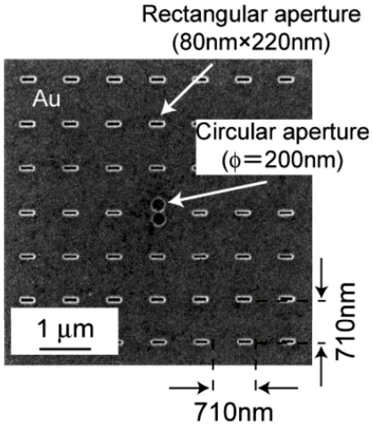

Fig. 20. SEM image of fabricated metal nano-aperture array [57].

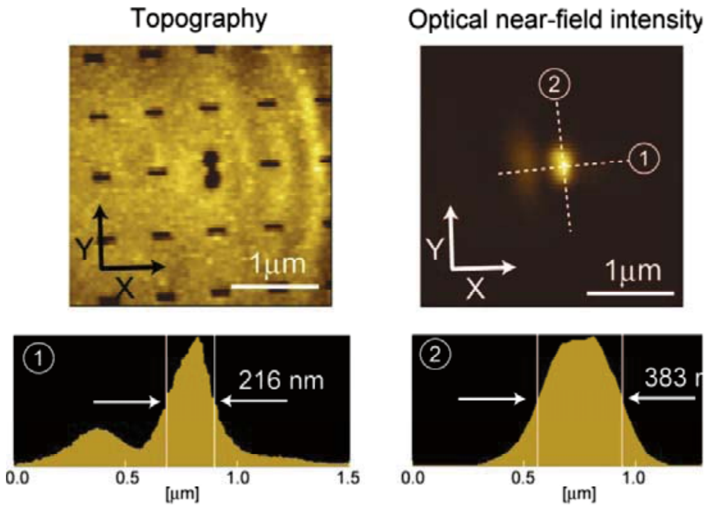

Fig. 21. SNOM measurement of optical near-field distribution. The spatial resolution of the SNOM is 150 nm [57].

320 nm and 100 nm, respectively. To reduce the optical spot size, we formed the double aperture structure at the center of rectangular aperture array. The fabricated metal nano-structure is shown in Fig. 20. The diameter and spacing of the double-apertures are 200 nm and 40 nm, respectively, which were formed using a FIB (focused ion beam) etching system. The lasing wavelength is 850 nm. The structure except the top mirror design and the metal nano-aperture is the same as conventional GaAs oxidized VCSELs.

We measured the optical near-field distribution using a SNOM setup with a fiber probe. Figure 21 shows the topography image and optical near-field intensity distribution image [57]. Clear localization of an optical near-field between the double circular apertures can be seen. The net FWHM of optical near-field is estimated to be 70 nm $\times$ 240 nm with taking the SNOM resolution of 150 nm into account. We estimate the far field power from the center double-apertures by subtracting the output power before making the center double-apertures. From this far filed power measurement we derive

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the optical near-field power density to be 0.8 MW/cm^2. The power density is much larger than that of conventional VCSELs. We also found that the polarization direction is locked with single transverse mode operation.

7 Conclusion

It has already been 30 years since a VCSEL was invented. The emission wavelength is from ultra-violet to infrared spectral regions. We have seen various potential applications including datacom, sensors, optical interconnects, spectroscopy, optical storages, printers, laser displays, laser radar, atomic clock, optical signal processing and so on. On the other hand, VCSELs with external cavities, so-called VECSELs, allow a large emitting area of the device with a single-transverse mode and thus much high power of over 1 W can be obtained. The external cavity configuration also allows intracavity frequency doubling, which are currently attracting much interest for green light emitters of laser display applications. These high power applications are also challenging for future optoelectronics. Another interesting application is the spontaneous emission in microcavities. Microcavity VCSELs with quantum dots would be one of good candidates for single-photon emitters.

In this paper, recent advances on VCSEL photonics were reviewed, including the wavelength engineering and new functions of VCSELs. The small footprint of VCSELs allowed us to form a densely packed VCSEL array both in space and in wavelength. The wavelength engineering of VCSELs may open up ultra-high capacity networking. In addition, new functions of VCSEL structures for optical signal processing were addressed, which include the manipulation of optical phase, slow light optical devices and plasmonic VCSELs. These new functionalities may give us new opportunities of VCSEL photonics for new era of optoelectronics.

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Fumio Koyama
received the B.S., M.S., and Ph.D. degrees in physical electronics from the Tokyo Institute of Technology, Tokyo, Japan, in 1980, 1982 and 1985, respectively. He is a Professor of Microsystem Research Center, P&I Lab., Tokyo Institute of Technology. Currently, he is doing research on VCSELs, photonic integrated WDM devices, optical MEMS devices, and related semiconductor microfabrication technologies. From 1992 to 1993 he was with AT&T Bell Labs. Crawford Hill as a visiting researcher. In 1985, he joined the research team of Prof. Emeritus Kenichi Iga of Tokyo Institute of Technology, who is the inventor of VCSELs. He realized the first room temperature CW operations of VCSELs in 1988. He and his co-workers have spent much effort and did contributions for the progress of VCSEL photonics. He also contributed to the suggestion and understanding for frequency chirping in external modulators. This concept is important for long-haul and broadband optical communication networks with avoiding frequency chirping. He has authored or co-authored more than 370 journal papers and 400 conference papers, including 40 invited papers. He is one of ISI's highly cited researchers. Dr. Koyama received the IEEE Student Paper Award in 1985, the IEE Electronics Letters Premium in 1985 and in 1988, the Paper Awards from the IEICE of Japan in 1990, 2002, 2004 and 2007, the excellent review paper award from the Japan Society of Applied Physics in 2000, Marubun Scientific Award from Marubun Research Promotion Foundation in 1998, the Ichimura Award from the New Technology Development Foundation in 2004, the Electronics Society Award from the IEICE of Japan in 2006, the Prize for Science and Technology from the Minister of Education, Culture, Sports, Science and Technology in 2007 and IEEE/LEOS William Streifer Scientific Achievement Award in 2008. He is Fellow of IEEE and the Japan Society of Applied Physics.

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