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Control Scheme for Optimizing the Interferometer Phase Bias in the Symmetric-Mach-Zehnder All-Optical Switch

Yoshiyasu UENO[†,††a)], ***Nonmember***, **Morio TAKAHASHI**[†], ***Regular Member***, **Shigeru NAKAMURA**[†], ***Nonmember***, **Kouichi SUZUKI**[†], **Takanori SHIMIZU**[†], ***Regular Members***, **Akio FURUKAWA**[†], **Takemasa TAMANUKI**[†*], **Kazuo MORI**[†††], **Satoshi AE**[†††], ***Nonmembers***, **Tatsuya SASAKI**[†††], ***Regular Member***, ***and*** **Kazuhito TAJIMA**[†], ***Nonmember***

SUMMARY Control scheme for accurately optimizing (and also automatically stabilizing) the interferometer phase bias of Symmetric-Mach-Zehnder (SMZ)-type ultrafast all-optical switches is proposed. In this control scheme, a weak cw light is used as a supervisory input light and its spectral power ratio at the switch output is used as a bipolar error signal. Our experimental result at 168-Gb/s 16:1 demultiplexing with a hybrid-integrated SMZ switch indicates the feasibility and the sensitivity of this control scheme.

key words: *all-optical, control scheme, demultiplexing, interferometer, phase bias*

1. Introduction

Ultrafast all-optical demultiplexing has successfully been demonstrated at 168–336 Gb/s with Symmetric-Mach-Zehnder (SMZ) -type semiconductor switches [1]–[5]. The response times of these switches are not limited by the semiconductor's carrier relaxation times [6], [7]. It has also been demonstrated that the SMZ-type all-optical-switch structure is applicable to ultrafast wavelength conversion [8]–[11] and 3R regeneration [12]–[14] as well as the all-optical demultiplexing.

The principle of the original SMZ switch is schematically illustrated in Fig. 1. The SMZ switch consists of two identical semiconductor optical amplifiers (SOA's) and a symmetrical Mach-Zehnder interferometer. Without the optical control pulses, all the optical data pulses go through the interferometer and reach the first output port. Each time we input a pair of control pulses, this switch is all-optically opened for a specific time Δt, as follows. When the switch-on control pulse is amplified by SOA1, the refractive index of SOA1 quickly jumps up and slowly recovers due to the band-filling effect. The optical phase of the co-

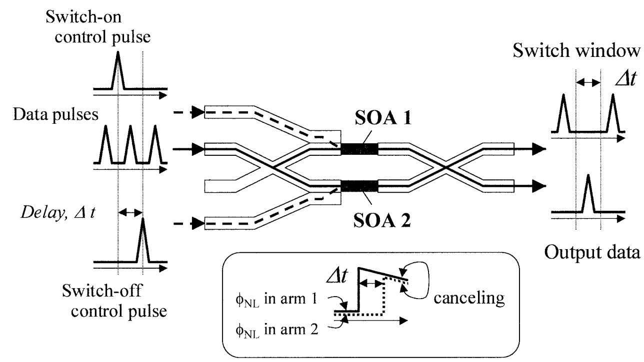

Fig. 1 Principle of operation of the Symmetric-Mach-Zehnder (SMZ) all-optical switch [6].

propagating data pulses in arm1 quickly jumps up (i.e. nonlinear phase shift), and then slowly recovers as is schematically illustrated in the inset. The switch-off control pulse is amplified by SOA2 at a time Δt later, so that the optical phase of the data pulses in arm2 jumps up and recovers at a time Δt later. As a result, the data pulse inside the Δt switch window is switched to the second output. The rise and fall times of the switch window are determined by the width of the control pulses. Those times can be ultrafast because the slow recovery components in the two arms are cancelled with each other at the interference.

Figure 2 shows our hybrid-integrated SMZ switch [15]. As schematically shown in Fig. 2(a), an SOA array chip having spot-size converters [16]–[18] is precisely mounted on a deep groove of a silica-based planar-lightwave-circuit (PLC) platform with self-aligned assembly technique [19], [20]. Four MZ interferometers are integrated in one PLC platform, as are seen in the top view (Fig. 2(b)). Figure 2(c) shows a detailed view at around the SOA-array chip.

One of the important operating conditions of the SMZ switch is the optical phase bias between the two arms. For specific applications that require a large switch-extinction ratio, the interferometer's phase bias has to be accurately optimized and also automatically stabilized for guaranteeing long-term operation. One example of such applications is N:1 demultiplex-

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[†]The authors are with Networking Research Laboratories, NEC Corporation, Tsukuba-shi, 305-8501 Japan.

[††]The author is with the Department of Electronic Engineering, University of Electro-Communications, Chofu-shi, 182-8585 Japan.

[†††]The authors are with Photonic and Wireless Devices Research Laboratories, NEC Corporation, Otsu-shi, 520-0833 Japan.

[*]Presently, with Interintelligence, Inc., USA.

a) E-mail: y.ueno@ieee.org

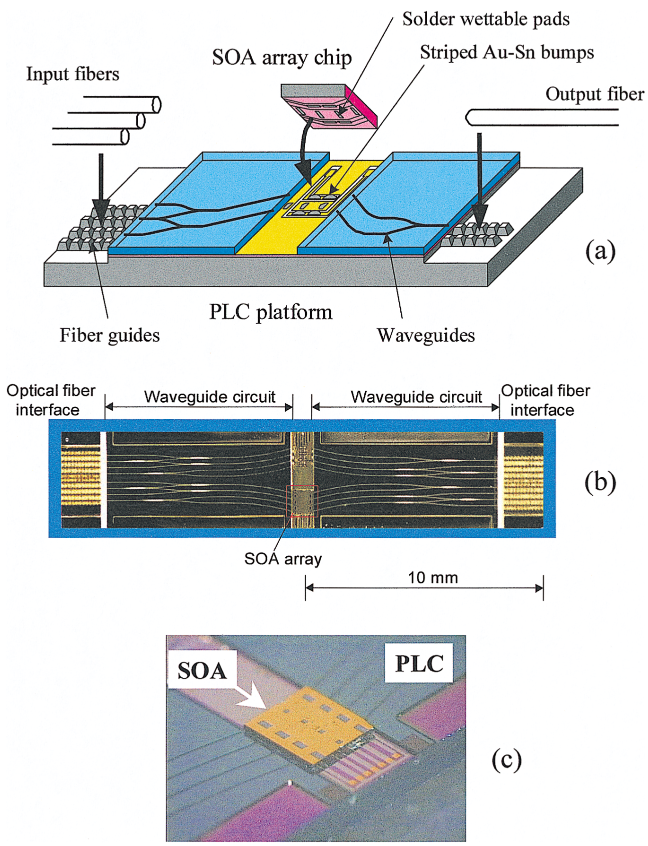

Fig. 2 Hybrid-integrated SMZ switch [15], [19].

ing where N is relatively large. Recently, we proposed a control scheme for such purposes [21], [22]. In this paper, we report our research results in more details, including some of the latest results.

2. Principle of the Phase-Bias Control Scheme

In our control scheme, we input a weak cw light to the SMZ switch as a supervisory light. The modulated cw light at the switch output is then used as a bipolar error signal in optimizing the phase bias (Fig. 3). The cw wavelength is chosen to be sufficiently longer than the gain peak wavelength so that the cw-light-induced carrier recombination inside the SOA's is negligibly small as compared with that induced by the control pulses.

In principle, the cw supervisory light reaches the switch output only when the switch is all-optically opened by each control pulse. Consequently, the switch generates short pulses from the cw light in a manner similar to a SMZ-type wavelength convertor [9], [23]. As a result, the spectrum of the cw light at the switch output is broadened as is schematically shown in Fig. 4. The spectrum is composed of equally-spaced discrete components, where the spectral envelope has a width of the order of $(\Delta t)^{-1}$ (Δt: the width of the switch window). The spacing of the spectral components exactly matches the switch repetition frequency.

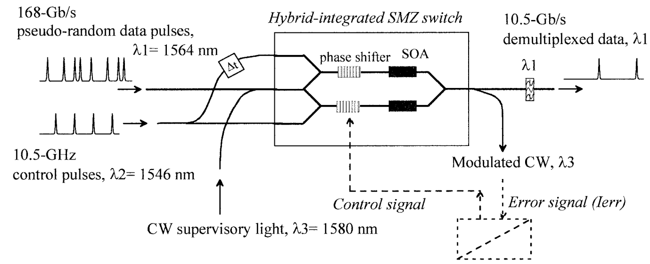

Fig. 3 Experimental setup for demonstrating the phase-bias control scheme that we proposed in Ref. [22]. The feed back system drawn with dashed lines is proposed only in this work.

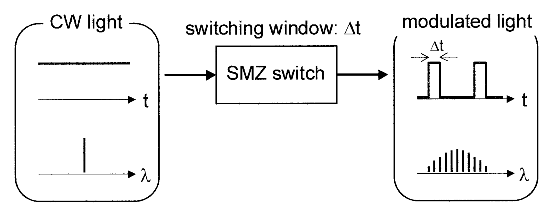

Fig. 4 Schematic view of the role that the cw supervisory light plays in the control scheme.

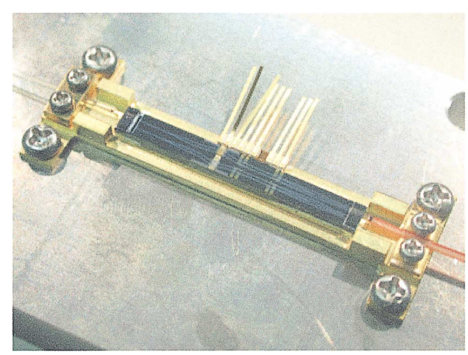

Fig. 6 The hybrid-integrated SMZ switch module with thermo-optic phase shifters [25] used in this work. The length of the PLC platform was 36 mm. The injection currents to the two SOA's were set to 70–90 mA. The ribbon cable at the right end includes the three input fibers to the respective input ports. The clear cable at the left end is the output fiber. (In this device sample, only one of the four SMZ switches on the PLC platform was both optically and electrically wired.)

The shape of this spectrum in the region around the original cw wavelength changes dramatically when the interferometer's phase bias wanders slightly away from its optimum value, as was experimentally observed and understood in an earlier work [23]. We explain the origin of this dramatic change with referring to Fig. 5. The difference between the optical phases of the two-split interference components as a function of time, $\Delta\Phi(t) \equiv \Delta\Phi_2(t) - \Delta\Phi_1(t)$, is shown in the left column of Fig. 5. Each pair of the ultrafast phase shifts forms an ultrafast rectangular switching window with a width of Δt [6], [14], [15], [21], [24]. In Fig. 5, the width of the control pulses (and therefore the rise and fall times of each switching window) was assumed to be negligibly

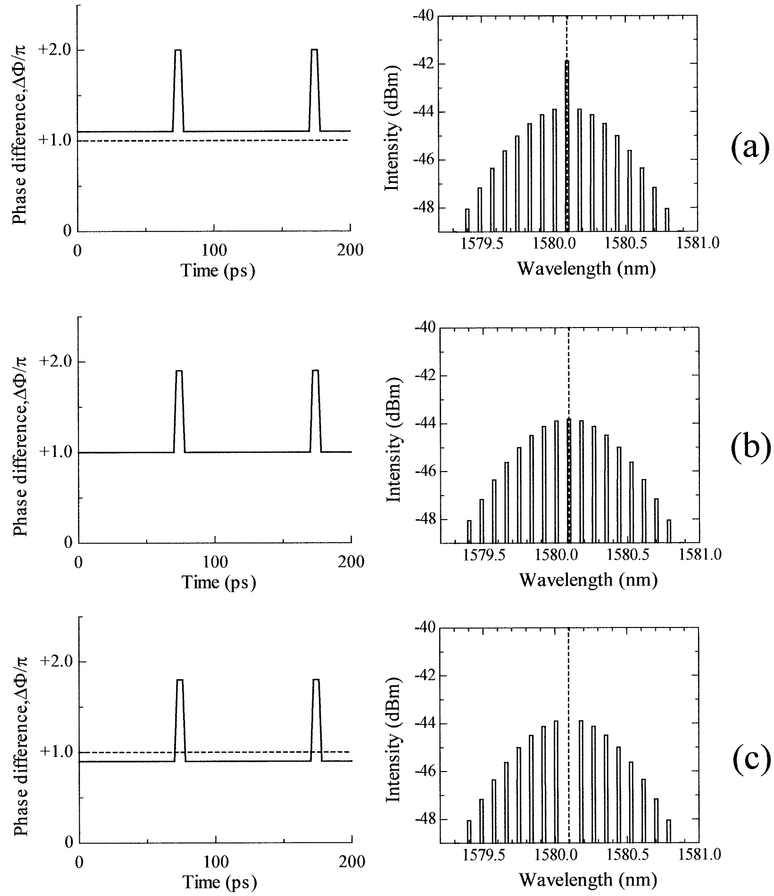

Fig. 5 Schematic view of the correlation between the interferometer phase bias and the supervisory light spectrum at the switch output. The phase bias is assumed to be (a) over-biased, (b) optimized, and (c) under-biased.

small. When the interferometer's phase bias is optimized (Fig. 5(b)), the phase difference at outside the switching windows remains $+\pi$ and consequently the two split components of the cw supervisory light are destructively interfered at outside the windows. When the phase bias wanders from its optimum value, the center component of the respective spectra hops up or drops down as are schematically shown in the right column of Fig. 5. The center component hops up when the phase bias is over-biased, because a weak cw component leaks out the switch (Fig. 5(a)). The center component drops down or even disappears, when the phase bias is slightly under-biased [23]. This is because a weak cw component leaks at outside the switch window and also it interferes *destructively* with that spectral component of the rectangular-shaped pulses (Fig. 5(c)). Based on this phenomenon, we have proposed the use of the power ratio between two specific spectral components as an error signal, for adjusting the phase bias to its optimum value [21], [22].

3. Experimental Results

We have tested the feasibility and the sensitivity of this control scheme by applying it to the all-optical demultiplexing of 168-Gb/s pseudorandom data pulses to 10.5 Gb/s (16:1) with our hybrid-integrated SMZ switch (Fig. 3). Thermo-optic optical phase shifters were incorporated into the silica-based planar-lightwave-circuit (PLC) part of the SMZ switch [25]. Figure 6 shows a photo of the hybrid-integrated SMZ switch module that was used in this work. The length of this PLC platform on which the SMZ switch was integrated was 36 mm. The maximum power required for operating one of the two phase shifters was 300–400 mW. The injection currents to the two SOAs were set to 70–90 mA.

The 168-Gb/s 1.5-ps 1564-nm pseudorandom data pulses were generated with a 10.496-GHz actively-mode-locked fiber ring laser (Pritel, Inc.), a 10-GHz $LiNbO_3$ modulator, and a 16x fiber multiplexer (Pritel, Inc.). The 10.496-GHz 1.5-ps 1546-nm control pulses were generated with a synchronized actively-mode-locked fiber ring laser.

The wavelength of the cw supervisory light was set to 1580.09 nm with a single-mode external-cavity tunable laser. The input power of the cw light was sufficiently suppressed so that the cw power at the SMZ output under the demultiplexing operation was less than −20 dB of the control pulse power (Fig. 7). This cw power suppression assures that the cw-light-induced carrier recombination inside the SOA's is sufficiently reduced.

Figure 8 is a set of examples that show the correlation between the (averaged) demultiplexed data-pulse waveform and the spectrum of the cw supervisory light at the switch output. The waveforms of the demultiplexed data were measured with a 82-MHz synchronized streak camera that has a time resolution of less than 1 ps (Hamamatsu Photonics, C6860). The spectra were measured with an optical spectrum analyzer that has a spectral resolution of 10 pm= 1.3 GHz (Advantest, Q8384). The dashed lines in the spectra indicate the original cw wavelength. The injection currents to the two SOA's were optimized to 77 mA (SOA1) and 94 mA (SOA2) for effectively balancing their gains,

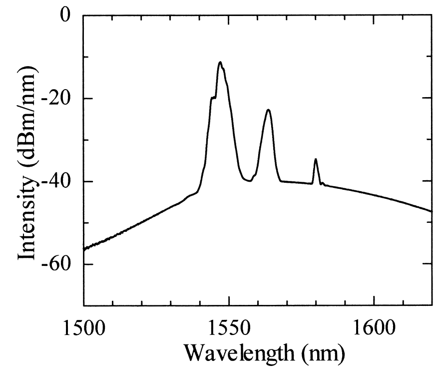

Fig. 7 Spectrum observed at the SMZ output. The peaks at 1546, 1564, and 1580 nm indicate the 10.5-GHz control pulses, the 168-GHz input signal pulses, and the supervisory light, respectively.

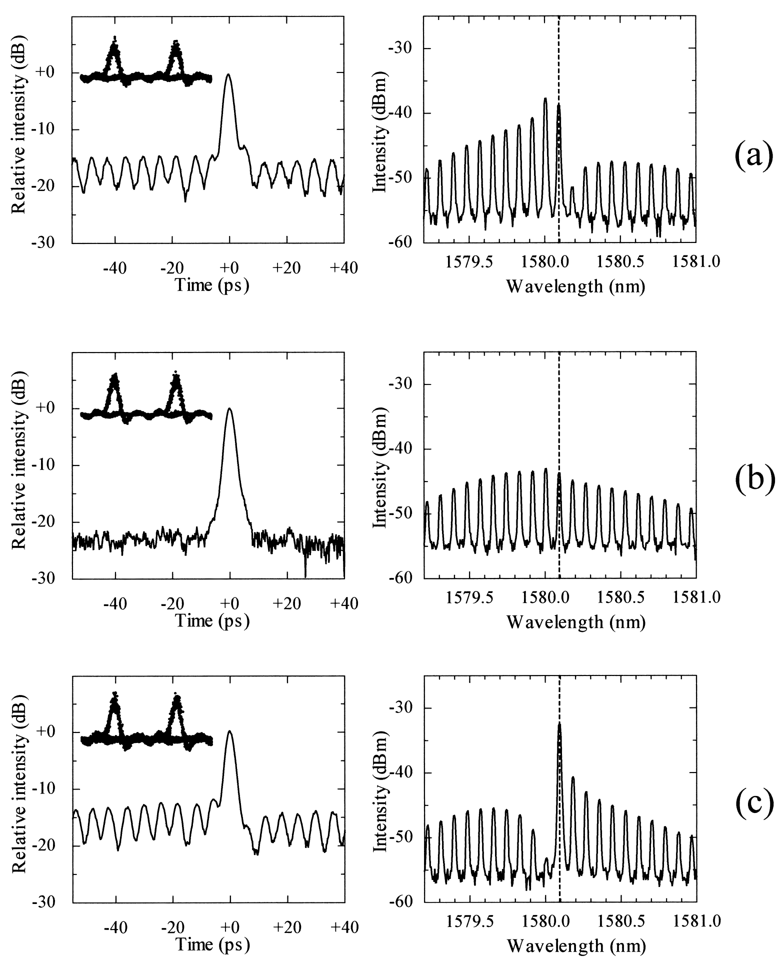

Fig. 8 Demultiplexed data-pulse waveforms (averaged) and the corresponding supervisory-light spectra at the SMZ output. The relative phase bias determined with one of the phase shifters was (a) 1.24π (under-biased by -0.13π), (b) 1.37π (the optimum value for this particular device), and (c) 1.58π (over-biased by $+0.21\pi$). The insets show the eye diagrams of the demultiplexed random data pulses.

while the control pulse energies to the two SOA's were optimized to approximately 250 fJ (SOA1) and 160 fJ (SOA2) for balancing their nonlinear refractive-index changes. When the interferometer phase bias was optimized, we achieved the maximum output extinction ratio (22 dB) and the spectrum formed a smooth envelope (Fig. 8(b)). At this point, we obtained a bit error rate of less than 1×10^{-9}. The effect of the input of the cw supervisory light on the bit error rate was not detectable. Its effect on the received-power penalty was not detectable, either. When we increased the phase bias by $0.21\,\pi$, we paid attention to the ratio between the intensities of the +10-GHz sideband ($I_{+10\,\mathrm{GHz}}$) and the −10-GHz sideband ($I_{-10\,\mathrm{GHz}}$). The ratio, $I_{+10\,\mathrm{GHz}}/I_{-10\,\mathrm{GHz}}$, rapidly decreased while the level of the output extinction was significantly degraded (Fig. 8(c)). On the other hand, the value of $I_{+10\,\mathrm{GHz}}/I_{-10\,\mathrm{GHz}}$ rapidly increased when the phase bias was decreased by 0.13π from its optimum value (Fig. 8(a)). The insets in Fig. 8 show the respective eye diagrams of the demultiplexed random data pulses observed with a 30-GHz optical sampling scope. The decrease in the extinction ratio as measured with the streak camera in Figs. 8(a) and (c) was not so visible in the respective eye diagram. In these eye diagrams, only slight increases in the zero-level noise in average were observed because of the limited bandwidth of the scope.

Figure 9(a) shows the optical spectrum of the supervisory output light obtained with the optimum phase bias in a wider spectral range. The dashed curve in Fig. 9(a) shows a calculated spectrum of a 6-ps-wide rectangular pulse, for comparison. Figure 9(b) show calculated spectra of a hyperbolic secant pulse (dashed curve) and a Gaussian pulse (dotted curve) for comparison with that of the rectangular pulse (solid curve), where all of the pulses were assumed to have the same full width at the half maximum (6 ps). As seen in Fig. 9(b), the spectral width of a rectangular pulse is 2.8 times broader than that of a hyperbolic-secant pulse as are tabulated in Table 1. With these results in Figs. 9(a) and (b), we have confirmed that the spectral behavior in Fig. 8 was originated from the supervisory-light component that was sliced by 6-ps-wide rectangular-shaped all-optical switching windows.

The experimentally observed spectral behavior in Fig. 8 was, however, obviously different from the original idea that was schematically illustrated earlier in Fig. 5. So, we numerically calculated the spectral behavior with our all-optical switch simulator that has successfully reproduced or predicted our experimental results [23], [26]–[28]. The simulator that we have developed is based on the simplest assumptions (Appendix), i.e., the dependency of the refractive index change on the carrier density due to the semiconductor's bandfilling effect was assumed to be linear. The rate equation for the carrier density consists of only the lowest-order

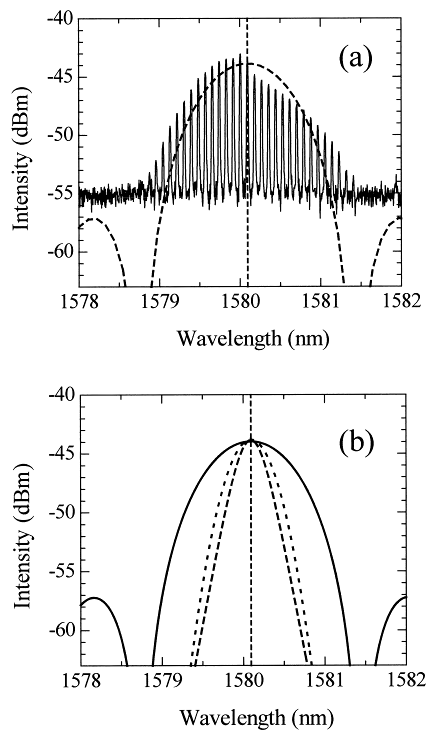

Fig. 9 Comparisons between measured spectrum of the supervisory light at the switch output and calculated spectra of rectangular [dashed curve in (a) and solid curve in (b)], hyperbolic secant [dashed curve in (b)], and Gaussian [dotted curve in (b)] pulses having the same full width at the half maximum (6 ps).

Table 1 Theoretical spectral full-widths at the half maximum.

	Spectral width, Δf	Spectral width of 6-ps 1.5-μm pulses, Δλ (nm)	Ratio
Rectangular pulse	$\Delta f = \dfrac{0.883}{\Delta t}$	1.18	2.8
Hyperbolic secant pulse	$\Delta f = \dfrac{0.315}{\Delta t}$	0.421	1.0
Gaussian pulse	$\Delta f = \dfrac{0.441}{\Delta t}$	0.590	1.4

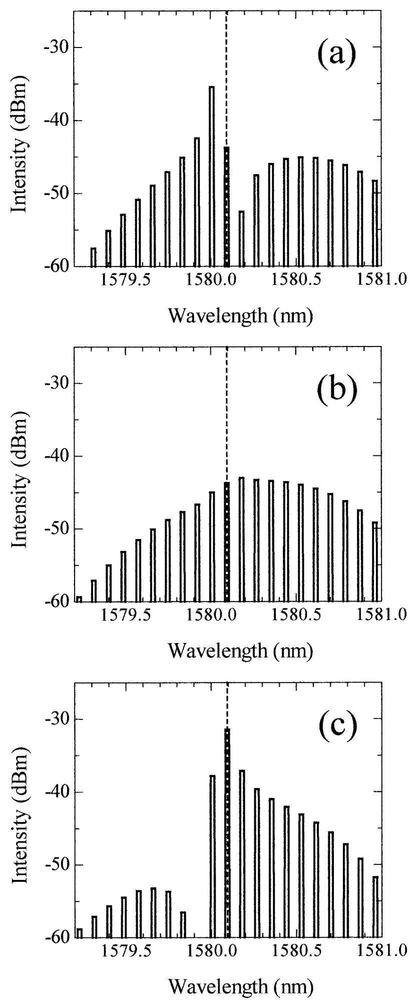

Fig. 10 Calculated behavior of the supervisory-light spectrum at the SMZ output. The interferometer phase bias was assumed to be (a) 0.935π (under-biased by -0.13π), (b) 1.065π (optimum), (c) 1.275π (over-biased by $+0.21\pi$). This calculation, done with our all-optical switch simulator [23], [26], has successfully predicted the asymmetric behavior of the observed spectrum (Fig. 8).

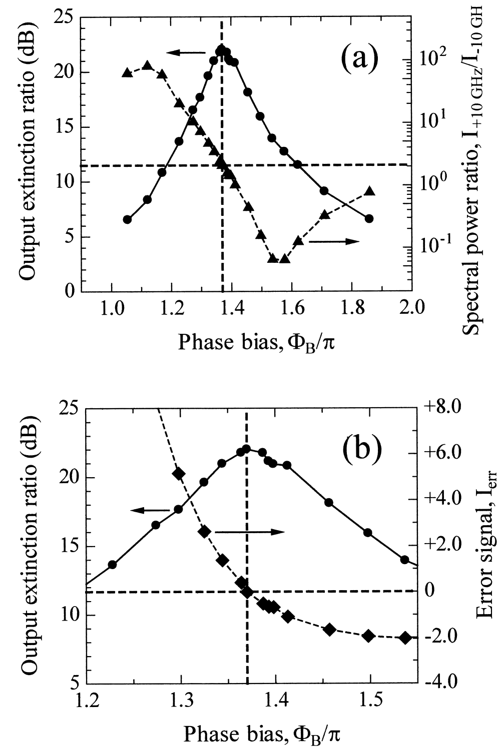

Fig. 11 The correlation between the switch extinction ratio and the spectral power ratio of the supervisory light at the switch output. The error signal (I_{err}) obtained from the spectral power ratio is sensitive to the phase bias and crosses zero when the phase bias drifts across its optimum value. The definition of I_{err} is described in the text.

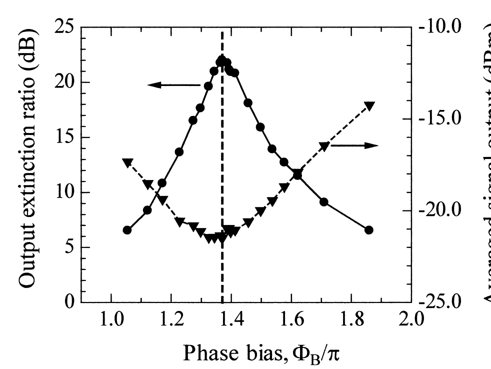

Fig. 12 The correlation between the switch extinction ratio and the average demultiplexed-signal power at the switch output, for comparison. The average output power is also effective as an error signal. It is, however, unipolar and less sensitive to the phase bias.

terms. Figure 10 shows the numerically predicted behavior of the spectrum, where the asymmetric behavior of the spectrum in Fig. 8 was successfully reproduced. Detailed studies are going on, for clearly understanding the origin of the asymmetric behavior. It should be noted here that no fitting parameter was used in the above calculation. The experimentally obtained parameters in Refs. [23] and [26] were used in the calculation.

4. Bipolar Error Signal

Observing the asymmetric spectral behavior in Fig. 8, we have chosen the spectral intensity ratio $I_{+10\,\mathrm{GHz}}/I_{-10\,\mathrm{GHz}}$ for monitoring the interferometer's phase bias. The correlation between the output pulses' extinction ratio and the spectral intensity ratio $I_{+10\,\mathrm{GHz}}/I_{-10\,\mathrm{GHz}}$ is summarized in Fig. 11(a). These results indicate that $I_{err} \equiv I_{+10\,\mathrm{GHz}}/I_{-10\,\mathrm{GHz}} - \gamma$ ($\gamma \equiv 2.1$ in the present example) is effective as a bipolar error signal. The value of I_{err} is sensitive to the phase bias and crosses zero when the phase bias drifts across its optimum value, as indicated in Fig. 11(b). The advantage of such a bipolar error signal is that the feedback control system can track the optimum conditions without introducing any intentional error. (In contrast, feedback systems with using unipolar error signals have to introduce intentional errors, that causes noise to the optical output signals.)

For comparison, the average power of the demultiplexed output signal is also effective as an error signal as is indicated in Fig. 12. It is, however, unipolar and is less sensitive in terms of optimizing the phase bias.

5. Conclusion

We have proposed a new control scheme for accurately optimizing the interferometer phase bias of an ultrafast SMZ-type all-optical switch. A cw supervisory light is input to the switch and generates a bipolar error signal at the output. This control scheme does not require any high-speed opto-electronics. The error signal derived as a result of this work, $I_{err} \equiv I_{+10\,\mathrm{GHz}}/I_{-10\,\mathrm{GHz}} - \gamma$, appeared to provide a feasibile and sensitive means for the phase-bias control. We confirmed that the input of the weak supervisory cw light does not affect the received power penalty at a bit-error-rate level of 1×10^{-9}. This scheme will be useful for building a feedback circuit that automatically optimizes and stabilizes the interference phase bias in the SMZ-type all-optical switches. We believe that this scheme will also be effective for other functions with these all-optical switches, such as wavelength conversion and optical 3R regeneration.

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Appendix: Rate Equation and Other Basic Equations for Our Numerical Simulation

The generation of the supervisory light output from a SMZ switch was modeled in exactly the same manner as that of an output signal from a delayed-interference signal-wavelength converter (DISC) [23], [26], as follows. The carrier density was assumed to obey a rate equation,

$$\frac{d}{dt}\overline{n_c(t)} = \frac{I_{op}}{qV} - \frac{\overline{n_c(t)}}{\tau_c} - \frac{1}{V}\cdot\left(G\left\{\overline{n_c(t)}\right\} - 1\right) \cdot \frac{|E_{control}(t)|^2 + |E_{cw}|^2}{\hbar\omega}, \quad (\mathrm{A}\cdot 1)$$

where $\overline{n_c(t)}$ is the excess carrier density averaged over the SOA length,

$$\overline{n_c(t)} \equiv \frac{1}{L}\int_{z=0}^{L} n_c(z,t)dz, \quad (\mathrm{A}\cdot 2)$$

and

$$n_c(z,t) \equiv n(z,t) - n_{tr}. \quad (\mathrm{A}\cdot 3)$$

L is the SOA length, $n(z,t)$ is the carrier density, n_{tr} is the transparency carrier density, I_{op} is the operating current, q is the elementary charge, V is the volume of the SOA's active layer, τ_c is the carrier lifetime, and G is the temporal chip gain. $E_{control}(t)$ and $E_{cw}(\mathrm{t})$ are the electric fields of the input control pulses and the input supervisory cw light, respectively. The temporal chip gain, G, was modeled with assuming a linear material gain as,

$$G(t) \equiv \exp\left[dg/dn_c \cdot \overline{n_c(t)} \cdot \Gamma L\right], \quad (\mathrm{A}\cdot 4)$$

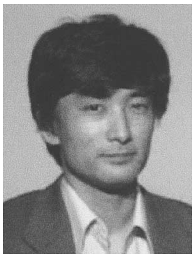
where dg/dn_c is the differential gain and Γ is the optical confinement factor. The nonlinear optical phase shift $\Phi(t)$ that the supervisor cw light receives after propagating through the SOA was assumed to be proportional to the carrier density change,

$$\Phi(t) = k_0 \cdot dn_r/dn_c \cdot \left\{n_c^0 - \overline{n_c(t)}\right\} \cdot \Gamma L, \quad (\mathrm{A}\cdot 5)$$

where k_0 is the wave vector in vacuum and dn_r/dn_c is the nonlinear coefficient in refractive index. The equilibrium excess carrier density, n_c^0, is defined as the excess carrier density of the SOA when it does not receive any input lights. Finally, the electric field of the supervisory light at the SMZ switch output is obtained as,

$$\begin{aligned} &E^{out}_{\sup ervisory}(t) \\ &\quad = \frac{1}{2}\Big(\sqrt{G(t)}\exp[i\Phi(t) + \Delta\Phi_b]E_{cw}(t) \\ &\qquad + \sqrt{G(t-\Delta t)}\exp[i\Phi(t-\Delta t)]E_{cw}(t)\Big), \end{aligned} \quad (\mathrm{A}\cdot 6)$$

where $\Delta\Phi_b$ is the optical phase bias between the two-split interference components.

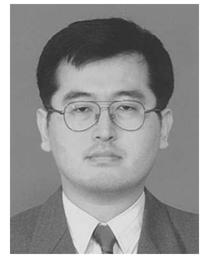


Yoshiyasu Ueno received his M.S. and Ph.D. degrees in physics in 1987 and in applied physics in 1998, respectively, from the Univ. of Tokyo. After he joined NEC Corporation, he was engaged in R&D of high-power 680-nm AlGaInP lasers from 1987 through 1994. From 1995 through 1996, he studied on the nonlinear chi(2) processes in ordered GaInP crystals at CREOL, Univ. of Central Florida. Since April 1996, he has been working on the ultrafast ultrahigh-frequency all-optical switchings. Since March 2002, he has moved from NEC Corporation to the Univ. of Electro-Communications, Tokyo and started building a new laboratory. He is a member of the Institute of Electrical and Electronics Engineers, the Optical Society of America, and the Japan Society of Applied Physics.

Morio Takahashi received the B.S., M.S., and Ph.D. degrees in physics from Tokyo University of A&T in 1996, 1998, and 2001, respectively. In 2001, he joined NEC Corporation and has been engaged in the research and development of the hybrid integrated photonic devices for ultrafast all-optical switching, and the planar lightwave circuits for optical communication network systems. Dr. Takahashi is a member of the Japan Society of Applied Physics.

Shigeru Nakamura received the B.S. and M.S. degrees in physics from the University of Tokyo in 1988 and 1990, respectively. In 1990, he joined NEC Corporation and has been engaged in the research and development of ultrafast all-optical devices. He is a member of the Japan Society of Applied Physics, the Physical Society of Japan, and the Optical Society of America.

Kouichi Suzuki received B.S., M.E., and Ph.D. degrees in electrical engineering from the Tokyo Institute of Technology in 1995, 1997 and 2000, respectively. After, he joined NEC Corporation and has been engaged in the research and development of the Planar Lightwave Circuit devices.

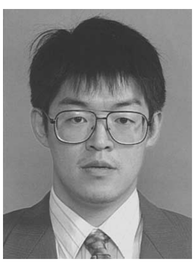


Takanori Shimizu was born in Tokyo, Japan, in 1965. He received the B.S. and M.S. degrees in electrical engineering from Waseda University, Tokyo, Japan in 1989 and 1991, respectively. In 1991, he joined Opto-Electronics Research Laboratories, NEC Corporation, Tsukuba, Japan, where he was engaged in research and development on ultrafast optical pulse generation and device fabrication of modelocked semiconductor lasers for ultrafast communication and measurement systems. Since 1999, he has been engaged in research and development on hybrid integrated photonic devices and packaging the planar lightwave circuits for optical communication network systems. He is a member of the Japan Society of Applied Physics.

Akio Furukawa received the B.S., M.S., and Ph.D. degrees in physics from University of Tokyo in 1979, 1981, and 1984, respectively. He joined NEC Corporation in 1985 where he was engaged in the research of MBE growth, HBT and FET of compound semiconductor and CMOS. Presently, he is engaged in research of Planar Lightwave Circuit. Dr. Furukawa is a member of the Japan Society of Applied Physics.

Takemasa Tamanuki was born in Kanagawa prefecture, Japan, on November 2, 1964. He received his B.S. degree in applied physics from the Science University of Tokyo in 1988 and M.E. and Ph.D. degrees in information processing from the Tokyo Institute of Technology in 1990 and 1993, respectively. He was with the Opto-Electronics Research Laboratories, NEC Corporation, Japan from 1993 to 2002, where he has been engaged in research on semiconductor lasers and optical semiconductor amplifiers for optical fiber communication systems. In 2003, he joined InterIntelligence, Inc., USA, where he has been researching and developing optical parallel interconnect modules and planer lightwave circuits. Dr. Tamanuki is a member of the Japan Society of Applied Physics.

Kazuo Mori was born in Chiba, Japan, in 1961. He received the B.E. degree in electrical and electronic engineering and the M.E. degree in information processing from Tokyo Institute of Technology in 1983 and 1985, respectively. In 1985, he joined NEC Corporation, Kawasaki, Japan, where he was engaged in research on metalorganic atomic layer epitaxy, highly mismatched epitaxy by gas source molecular beam epitaxy and wafer bonding. He is currently engaged in research and development of selective epitaxy by atmospheric pressure metalorganic vapor phase epitaxy and optical semiconductor devices for optical communications. Mr. Mori is a member of the Japan Society of Applied Physics.



Satoshi Ae was born in Hyogo, Japan, in 1965. He received the B.E. degree in material engineering and M.E. degree in electrical engineering from Osaka University, Osaka, Japan, in 1989 and 1991, respectively. In 1991, he joined NEC Corporation, Kawasaki, Japan. He has been engaged in research and development of crystal growth by metalorganic vapor phase epitaxy and optical semiconductor devices for optical communications. Mr. Ae is a member of the Japan Society of Applied Physics (JSAP).

Tatsuya Sasaki was born in Tokyo, Japan, in 1961. He received his B.S. and M.S. degrees in electrical engineering from Keio University, Japan, in 1983 and 1985, respectively. In 1985, he joined the Opto-Electronics Research Laboratories, NEC Corporation, Japan. Since then, he has been engaged in research and development related to laser diodes and photonic integrated devices for optical fiber transmission systems. He received the 13th Kenjiro Sakurai Memorial Prize from the Optoelectronic Industry and Technology Development Association, Japan in 1997, and the 10th Anniversary Paper Award from the International Conference on Indium Phosphide and Related Materials in 1998. Mr. Sasaki is a member of the Japan Society of Applied Physics.

Kazuhito Tajima received his B.S. degree from Keio University in 1774, M.S. and Ph.D. degrees from The Ohio State University in 1979 and 1984, respectively. He was with the Fujisawa Development Lab., IBM Japan from 1974 to 1980. In 1984, he joined NEC Corporation where he has been researching nonlinear propagation problems of optical fibers and ultrafast all-optical devices based on optical nonlinearities of semiconductors. He is a member of the Japan Society of Applied Physics and the Optical Society of America.