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

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***Abstract*—A 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 continuous-wave 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.**

***Index Terms*—All-optical, control scheme, demultiplexing, interferometer, Mach–Zehnder, phase bias, semiconductor, supervisory light.**

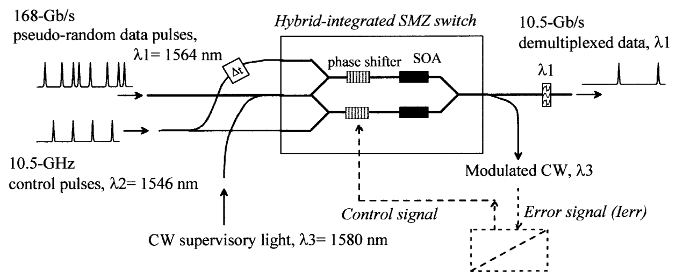

Fig. 1. Experimental setup for demonstrating the phase-bias control scheme. The feedback system drawn with dashed lines is proposed only in this work.

I. Introduction

ULTRAFAST all-optical demultiplexing has successfully been demonstrated at 168–252 Gb/s with hybrid-integrated symmetric-Mach–Zehnder (SMZ)-type semiconductor switches [1]–[3]. The response times of these switches are not limited by the semiconductor's carrier relaxation times [4]. It has also been demonstrated that the SMZ-type all-optical-switch structure is applicable for ultrafast wavelength conversion [5], [6] and 3R regeneration [7], [8], as well as all-optical demultiplexing.

For specific applications that require a large switch-extinction ratio, the interferometer phase bias inside the SMZ-type switch has to be accurately optimized and also automatically stabilized for long-term operation. One example of such applications is $N:1$ demultiplexing, where N is relatively large. In this work, we propose a control scheme for optimizing (and also automatically stabilizing) the interferometer's phase bias.

II. Principle of the Control Scheme

We propose the input of a weak continuous-wave (CW) light to the SMZ switch as a supervisory light. A specific signal extracted from the CW light at the switch output is then used as a bipolar error signal in optimizing the phase bias (Fig. 1). The CW wavelength is chosen to be sufficiently longer than the gain peak wavelength so that the CW-light-induced carrier recombination inside the semiconductor optical amplifiers (SOAs) is negligibly small as compared with that induced by the control pulses.

In principle, the CW 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], [10]. As a result, the spectrum of the CW light at the switch output is broadened. As was reported in an earlier work [10], 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. Based on this phenomenon, we propose the use of the power ratio between two specific components of the output spectrum as an error signal for adjusting the phase bias to its optimum value [11].

III. 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. 1). Thermooptic optical phase shifters were incorporated into the silica-based planar-lightwave-circuit (PLC) part of the SMZ switch. 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 16× fiber multiplexer. The 10.5-GHz 1.5-ps 1546-nm control pulses were generated with a synchronized mode-locked fiber ring laser.

Manuscript received February 19, 2002; revised July 11, 2002. This work was supported in part by the New Energy and Industrial Technology Development Organization (NEDO) under the Femtosecond Technology Research Association (FESTA).

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Digital Object Identifier 10.1109/LPT.2002.804643

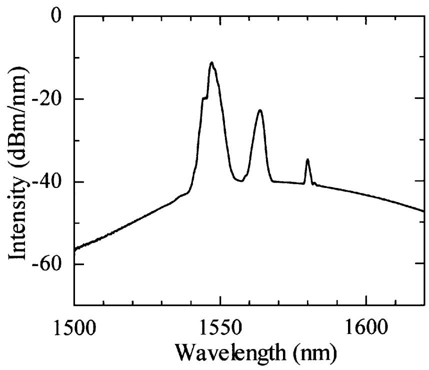

Fig. 2. Spectrum at the SMZ output.

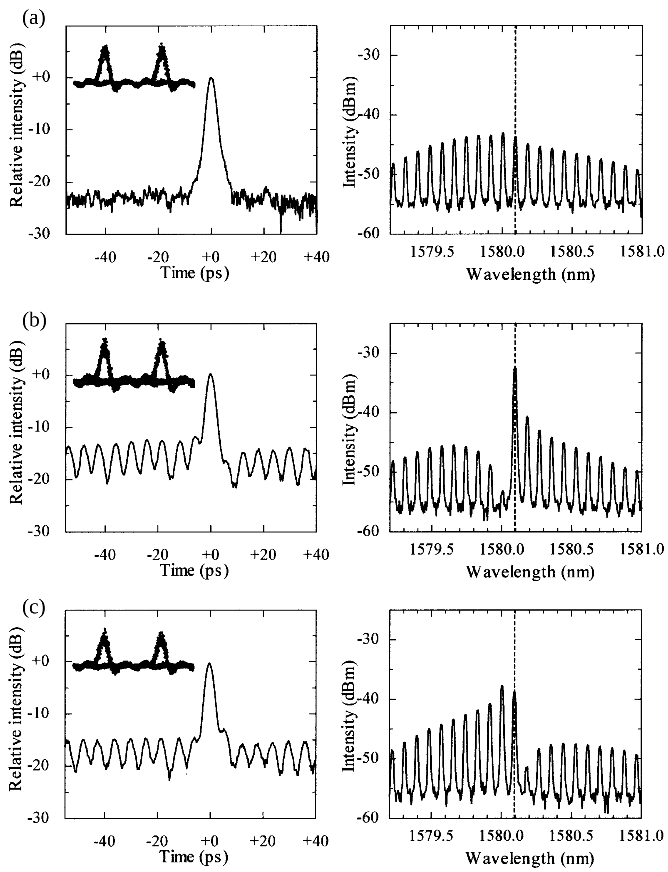

Fig. 3. Demultiplexed data-pulse waveforms (averaged) and the corresponding supervisory-light spectra at the SMZ output. The relative phase bias determined with one of the phase shifters was: (a) 1.37π (the optimum value for this particular device); (b) 1.58π; and (c) 1.24π. Insets show the eye diagrams of the demultiplexed random data pulses.

The wavelength of the CW supervisory light was set to 1580.09 nm with a single-mode external-cavity tunable laser. Furthermore, 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. 2). This CW power suppression assures that the CW-light-induced carrier recombination inside the SOAs is sufficiently reduced.

Fig. 3 is a set of examples that show the correlation between the (averaged) demultiplexed data-pulse waveform and the shape of the spectrum produced by the CW supervisory light at the switch output. The waveforms of the demultiplexed data were measured with a high-speed streak camera (Hamamatsu Photonics, C6860). The dashed lines in the spectra indicate the original CW wavelength. Once the phase bias had been optimized to achieve the maximum output extinction ratio (22 dB), the spectrum formed a smooth envelope [Fig. 3(a)], as was theoretically predicted [10]. At this point, the ratio between the intensities of the +10-GHz sideband ($I_{+10\ \mathrm{GHz}}$) and the -10-GHz sideband ($I_{-10\ \mathrm{GHz}}$) was 2.1 (3.2 dB) and the bit-error rate was less than 1×10^{-9}. The effect of the input of the CW supervisory light on the bit error rate was not detectable. When the phase bias was increased by 0.21 π, the intensity ratio $I_{+10\ \mathrm{GHz}}/I_{-10\ \mathrm{GHz}}$ rapidly decreased, and the level of the output extinction was significantly degraded [Fig. 3(b)]. On the other hand, the value of $I_{+10\ \mathrm{GHz}}/I_{-10\ \mathrm{GHz}}$ rapidly increased when the phase bias was decreased by 0.13 π from its optimum value [Fig. 3(c)]. The insets in Fig. 3 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 Fig. 3(b) and (c) was not so visible in the respective eye diagram. In the eye diagram, only an increase in

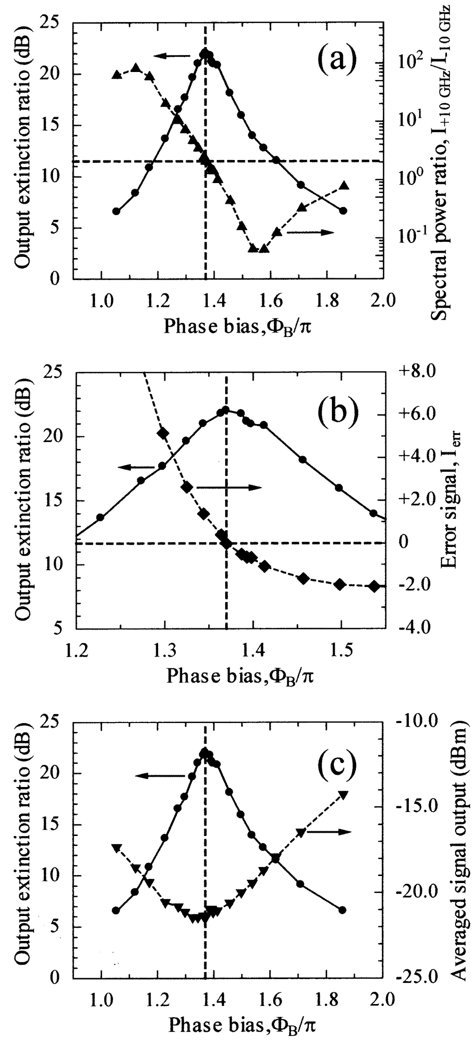

Fig. 4. Extinction ratio after demultiplexing as a function of the relative phase bias (solid curves).

the zero-level noise in average was observed (because of the limited bandwidth).

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. 4(a). These results indicate that $Ierr\ \equiv\ I_{+10\ \mathrm{GHz}}I_{-10\ \mathrm{GHz}} - \gamma$ ($\gamma\ \equiv 2.1$ in the present example) is effective as a bipolar error signal. The value of $Ierr$ is sensitive to phase and crosses zero when the phase bias drifts across its optimum value [Fig. 4(b)]. For comparison, the average power of the demultiplexed signal is also effective as an error signal [Fig. 4(c)]. It is, however, unipolar and is less sensitive in terms of optimizing the phase bias.

IV. Conclusion

We proposed a new control scheme for accurately optimizing the interferometer phase bias of a SMZ-type ultrafast 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 optoelectronics. The error signal derived as a result of this work, $Ierr \equiv I_{+10\ \mathrm{GHz}}/I_{-10\ \mathrm{GHz}} - \gamma$, appears to provide a feasible and sensitive means for the phase-bias control. This scheme will be useful for building a feedback circuit that automatically optimizes and stabilizes the interference phase bias in SMZ-type all-optical switches.

Acknowledgment

One of the authors, Y. Ueno, acknowledges I. Ogura for discussion on feedback systems.

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