Eight-Channel Simultaneous Wavelength Conversion From Equal to Unequal Channel Spacing

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***Abstract*—Eight-channel simultaneous wavelength conversion from equal to unequal wavelength-division-multiplexing (WDM) channel spacing is successfully demonstrated using two arrayed-waveguide-gratings (AWGs) and cross-gain modulation (XGM) in a spot-size converter-integrated semiconductor optical amplifier array on a planar-lightwave-circuit platform. The input AWG concurrently demultiplexed both the equal-spaced WDM signal and unequal-spaced pump lights to couple a pair comprising a signal and a pump for the XGM. Only a small power penalty of less than 0.5 dB was observed for all eight channels. The receiver sensitivity at 2.5 Gb/s was −33 dBm for all eight channels.**

***Index Terms*—Frequency conversion, nonlinear optics, semiconductor optical amplifiers, wavelength-division multiplexing.**

I. Introduction

THE EXPLOSIVE demand for large data traffic has resulted in the progress of various types of wavelength-division-mulitplexing (WDM) systems; the S-band (1460–1530 nm) [1], [2], C-band (1530–1565 nm) [1], [2], and L-band (1565–1625 nm) [3] have all been used. Several networks use equal channel spacing with conventional single-mode fibers [1], [2], while others have adopted unequal channel spacing to avoid four-wave mixing (FWM) impairment over dispersion-shifted fiber (DSF) [1], [4]. Channel spacing of 25, 50, and 100 GHz [1] have been utilized individually.

Simultaneous wavelength conversion of multi-WDM channels is expected to be a key technique for connecting networks with different bands or channel spacings. So far, ten-channel wavelength conversion with 9-GHz channel spacing and a 140-Mb/s modulation rate has been achieved by using FWM in a semiconductor optical amplifier (SOA) [5]. Watanabe *et al.* demonstrated five-channel wavelength conversion using FWM with a highly nonlinear fiber [6]. In these techniques, however, the signal-to-noise ratio (SNR) drops rapidly with increasing channel number [7] and the power level fluctuates due to the saturation output power of the single converter, especially when the number of the WDM channels vary because of the network reconfiguration or network failure.

To solve the SNR and the level fluctuation problems, we have introduced C-band to L-band four-channel simultaneous wavelength conversion using a hybrid wavelength selector module [8], which consists of spot-size converter-integrated (SS)-SOA gate arrays and two arrayed waveguide gratings (AWGs). Because the wavelength selector has an individual SS-SOA for the FWM of each WDM channel, there is negligible interference between channels. It should be noted that our aim is not random wavelength switching, but fixed wavelength conversion to connect different networks. This aim allowed very easy operation and control, which is necessary for practical use. The optical power level of the converted signals can be controlled individually. With this FWM technique, however, it is hard to change the WDM channel spacing, for example from 100- to 50-GHz spacing, or from equal to unequal spacing, because of the complicated wavelength arrangement of WDM input signals, pumps, and converted signals.

Here, we present the first eight-channel simultaneous wavelength conversion from equal to unequal WDM channel spacing using input and output AWGs and a hybrid integrated SS-SOA array. The key technique is the input AWG, which concurrently demultiplexes both the equal-spaced WDM signal and unequal-spaced pump lights to couple a pair comprising a signal and a pump. In the experiment, eight signal-and-pump pairs were launched into each SS-SOA, which operated as a cross-gain modulation (XGM) device. The output AWG multiplexed only the converted unequal-spaced conjugated signal. Only a small power penalty of less than 0.5 dB was observed for all eight channels. The receiver sensitivity for 2.5-Gb/s signals was -33 dBm at a bit-error rate (BER) of 10^{-9}.

II. Experimental Setup

To evaluate the feasibility of the simultaneous wavelength conversion, we demonstrate a system using eight WDM channels.

Fig. 1 shows the experimental setup. Eight equally spaced WDM signal lights were modulated at 2.5 Gb/s. Another eight lights with unequal spacing were used as pump lights. A fiber amplifier was used to compensate for the optical loss. The averaged input power of the equally spaced signal was from 0 to $+2$dBm at the output of the fiber amplifier. Note that a single input AWG demultiplexed both the signals and pumps, and each signal-and-pump pair was launched into each SS-SOA. It is true that the input AWG should be specially designed considering the wavelength of WDM signals and pumps [9], but here we used a conventional 50-GHz spacing AWG, because our proposal is simply to confirm the feasibility. The wavelength arrangement for the input AWG is shown in Table I.

Two four-channel SS-SOA gate arrays were hybrid integrated on a planar-lightwave-circuit (PLC) platform. The SS-SOA

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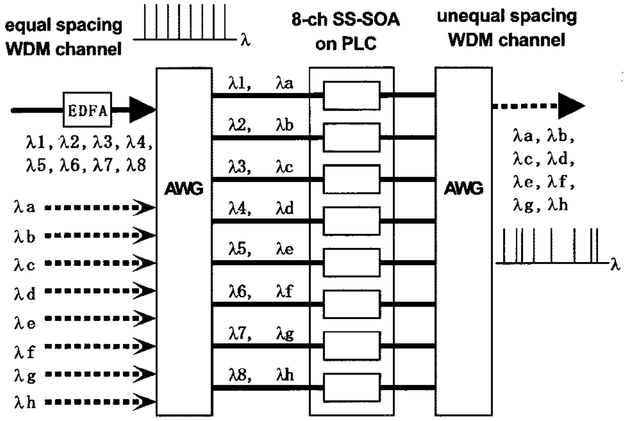

Fig. 1. Configuration for simultaneous wavelength conversion.

TABLE I
WAVELENGTH ARRANGEMENT OF THE INPUT AWG

(nm)

in \ out	1	2	3	4	5	6	7	8
1	1545.8	-	-	-	-	-	-	-
2	-	1546.5	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-
6	-	-	1548.1	-	-	-	-	-
7	-	-	-	-	-	-	-	-
8	-	-	-	1549.3	-	-	-	-
9	-	-	-	-	1550.1	-	-	-
10	-	-	-	-	-	-	-	-
11	-	-	-	-	-	-	-	-
12	-	-	-	-	-	1550.7	-	-
13	-	-	-	-	-	-	-	-
14	-	-	-	-	-	-	1552.9	-
15	-	-	-	-	-	-	-	1553.7
16	1551.3	1551.7	1552.1	1552.5	1552.9	1553.3	1553.7	1554.1

unequal spacing WDM channel (in 1–15)

input equal spacing WDM channel (in 16)

gate consists of a 600-μm bulk active region (gain-peak wavelength $= 1.55$ μm) and two 300-μm SS tapered bulk passive regions (bandgap wavelength $= 1.3$ μm at the facet). The tapered waveguide was selectively grown and butt-jointed to the active layer. The waveguide is 0.4-μm thick at the butt-joint portion and 0.2-μm thick at the facet. A 0.5-μm stripe was formed throughout the active and SS regions using CH_4–H_2 dry-etching.

Each SS-SOA operates as a wavelength converter using XGM. The injection currents of the SS-SOA range from 70 to 100 mA according to the wavelength dependence of XGM. The converted lights were multiplexed at the second output AWG. The spectrum and BER were evaluated for the converted lights.

III. RESULTS

Fig. 2 shows the XGM characteristics of an SS-SOA. The horizontal axis is the signal power before the first AWG, and the vertical axis is the converted power after the second AWG. The optical loss was 15 dB, which is due to the loss of AWGs. The extinction ratio was 10 dB.

Fig. 3 shows the spectrum of the input and output WDM signals. Simultaneous wavelength conversion from equal to unequal spacing is successfully demonstrated. The polarization dependence of the conversion was less than 0.5 dB. This small

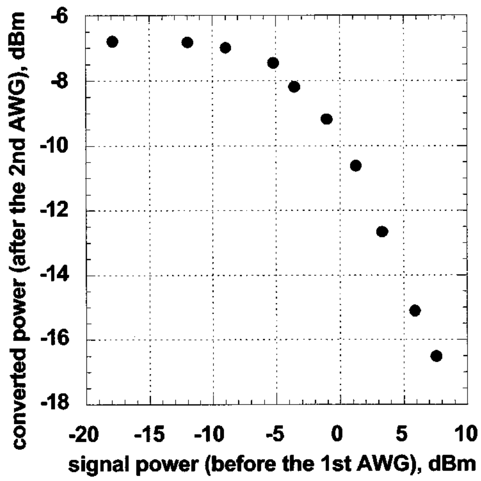

Fig. 2. Wavelength conversion using XGM.

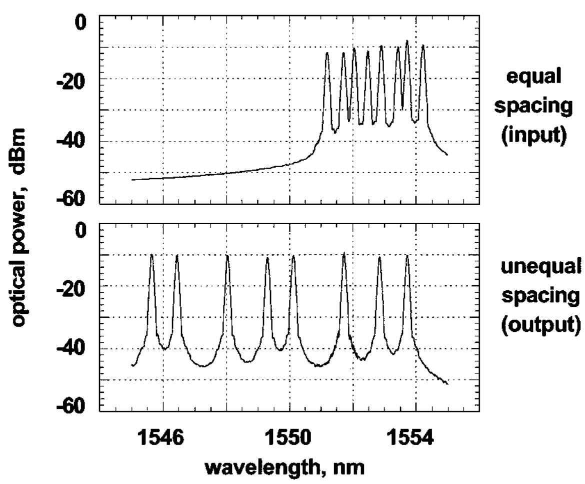

Fig. 3. Input and output spectra.

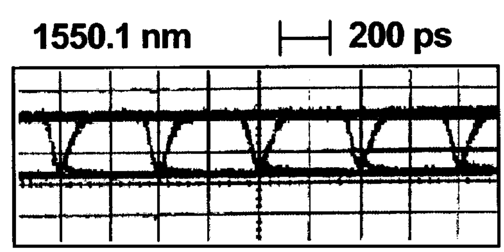

Fig. 4. Eye pattern.

dependence results from the low polarization sensitivity of SS-SOA and AWGs.

Dynamic performance was measured at 2.5 Gb/s. Fig. 4 shows the eye patterns of the converted light at the wavelength of 1550.1 nm. The eye openings are clear. Fig. 5 shows the BER characteristics for eight converted signals. Only a small power penalty of less than 0.5 dB was observed. The receiver sensitivity was -33 dBm at a BER of 10^{-9}. These results indicate that this simultaneous wavelength conversion is a useful technique for the channel space shifting of WDM networks. It could also be used with much larger scale systems that have more (i.e., 16 or 32) WDM channels.

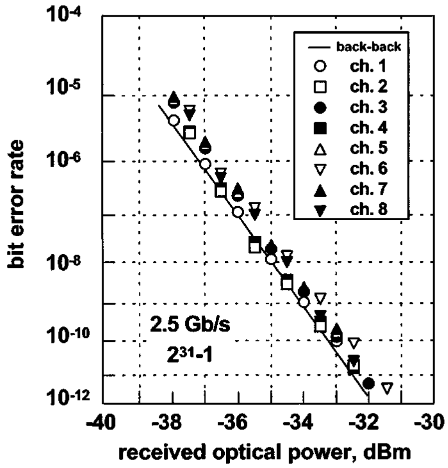

Fig. 5. BER.

IV. Conclusion

We proposed simultaneous wavelength conversion with an individual wavelength converter for each WDM channel. Eight-channel simultaneous wavelength conversion from equal to unequal WDM channel spacing is successfully demonstrated using XGM in spot-size converter-integrated SOA arrays on a PLC platform. The input AWG concurrently demultiplexed both the equal-spaced WDM signal and unequal-spaced pump lights to couple a pair comprising a signal and a pump. Eight signal-and-pump pairs were launched into each SS-SOA, which operated as a XGM device. The output AWG multiplexed only the unequal-spaced conjugated signal. The receiver sensitivity at 2.5 Gb/s was less than -33 dBm at a BER of 10^{-9}.

References

[1] J. Kani, T. Sakamoto, M. Jinno, K. Hattori, M. Yamada, T. Kanamori, and K. Oguchi, “Novel 1470-nm-band WDM transmission and its application to ultra-wide-band WDM transmission,” *IEICE Trans. Commun.*, vol. E82-B, pp. 1131–1139, Aug. 1999.

[2] A. K. Srivastava, D. L. Tzeng, A. J. Strentz, J. E. Johnson, M. L. Pearsall, O. Mizuhara, T. A. Strasser, K. F. Dreyer, J. W. Sulhoff, L. Zhang, P. D. Yeates, J. R. Pedrazzani, A. M. Sergent, R. E. Tench, J. M. Freund, T. V. Nguyen, H. Manar, Y. Sun, C. Wolf, M. M. Choy, R. M. Kummer, D. Kalish, and A. R. Chrapilyvy, “High-speed WDM transmission in allwave™ fiber in both the 1.4-μm and 1.55-υm bands,” in *Proc. 9th Opt. Amp. Applicat. (OAA)*, Vail, CO, 1998, Postdeadline Paper 2.

[3] T. Sakamoto, K. Hattori, M. Fukutoku, M. Fukui, M. Jinno, and K. Oguchi, “Properties of gain-shifted EDFA (1580 nm-band EDFA) cascades in WDM transmission systems,” in *Proc. 9th Opt. Amp. Applicat.*, Vail, CO, 1998, pp. 88–91.

[4] F. Forghieri, R. W. Tkach, A. R. Chraplyvy, and D. Marcue, “Reduction of four-wave mixing crosstalk in WDM systems using unequally spaced channels,” *IEEE Photon. Technol. Lett.*, vol. 6, pp. 754–756, June 1994.

[5] R. Schnabel, U. Hilbk, T. Hermes, P. Meiβner, C. Helmolt, K. Magari, F. Raub, W. Piepper, F. J. Westphal, R. Ludwig, L. Kuller, and H. G. Weber, “Polarization insensitive frequency conversion of a 10-channel OFDM signal using four-wave-mixing in a semiconductor laser amplifier,” *IEEE Photon. Technol. Lett.*, vol. 6, pp. 56–58, Jan. 1994.

[6] S. Watanabe, S. Takeda, G. Ishikawa, H. Ooi, J. G. Nielsen, and C. Somme, “Simultaneous wavelength conversion and optical phase conjugation of 200 Gb/s (5 × 40 Gb/s) WDM signal using a highly nonlinear fiber four wave mixer,” in *Proc. 11th Int. Conf. Integrated Opt. Opt. Fiber Commun. and 12th Eur. Conf. Optical Communications*, vol. 5, Edinburgh, U.K., Sept. 1997, pp. 1–4.

[7] A. Mecozzi, S. Scotti, A. D’Ottavi, E. Iannone, and P. Spano, “Four-wave mixing in traveling-wave semiconductor amplifiers,” *J. Quantum Electron.*, vol. 31, pp. 689–699, Apr. 1995.

[8] T. Ito, I. Ogawa, Y. Suzaki, K. Magari, and Y. Kawaguchi, “Simultaneous 4-channel wavelength conversion using four-wave mixing in a PLC-SOA hybrid wavelength selector,” in *Proc. 10th Opt. Amp. Applicat.*, Nara, Japan, June 1999, pp. 251–254.

[9] *Optical Interfaces for Multichannel Systems with Optical Amplifiers*, Standard ITU-T Recommendation G.692, Oct. 1998.