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Jørgensen, Carsten; Durhuus, T.; Braagaard, C.; Mikkelsen, Benny; Stubkjær, Kristian

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4 Gb/s Optical Wavelength Conversion Using Semiconductor Optical Amplifiers

C. Joergensen, T. Durhuus, C. Braagaard, B. Mikkelsen, and K. E. Stubkjaer

Abstract—**Semiconductor optical amplifiers are used for efficient wavelength conversion up to 4 Gb / s. The rise and fall time as well as extinction ratio are experimentally analyzed. System performance at 4 Gb / s is evaluated showing a penalty of only 1.5 dB for the converted signal for conversion over 17 nm.**

INTRODUCTION

WAVELENGTH converters are expected to be important in future high capacity optical communication systems. As examples, they make WDM networks flexible [1] and are key elements in wavelength routed networks [2].

Several conversion techniques have been proposed in the literature, e.g., gain saturation in DBR lasers [3], injection locking in Y-lasers [4] as well as four-wave-mixing [5] and gain saturation in semiconductor optical amplifiers (SOA's) [6], [7]. The advantages of using SOA's are that they can be polarization independent [8] and that variations in the operating conditions (e.g., signal input power and signal wavelength) are less critical compared to other types of converters.

Here we investigate important properties for the SOA converter (SOA-C) such as the dependency of bit-rate capability on bias current and facet reflectivity. Also the extinction ratio dependency on input power and wavelength is considered. Finally, the SOA-C is assessed by a system experiment demonstrating conversion over 17 nm at 4 Gb/s.

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The authors are with the Center for Broadband Telecommunications, Electromagnetics Institute, Technical University of Denmark, DK-2800 Lyngby, Denmark.

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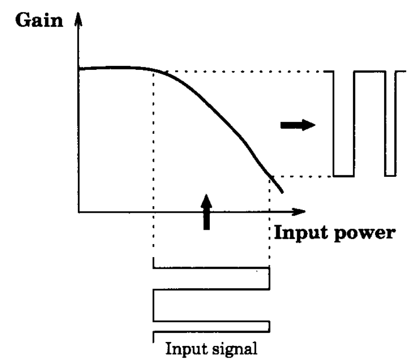

Fig. 1. Schematic of the principle of optical gain modulation that is used in SOA wavelength converters.

EXPERIMENTAL

The operation principle is simple and relies on gain saturation in the SOA [6]. An injected CW channel is modulated according to the bit pattern of the input signal channel due to gain saturation in the SOA as depicted in Fig. 1.

Fig. 2 shows the experimental arrangement for measurements of the extinction ratio, rise/fall time and bit-error-rate (BER). The CW channel and the signal channel are coupled into the SOA-C by a 3 dB coupler. At the output the converted signal is selected by a 20 GHz Fabry–Perot filter and detected by a 15 GHz front-end followed by a sampling oscilloscope or a BER counter. The SOA's have a M-DCPBH structure with an active region grown by GSMBE [8]. They exhibit a typical fiber to fiber gain of 18 dB for a bias current of 80 mA.

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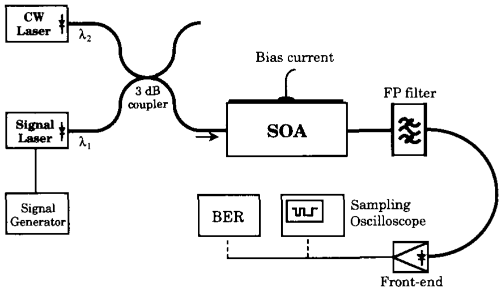

Fig. 2. Experimental setup.

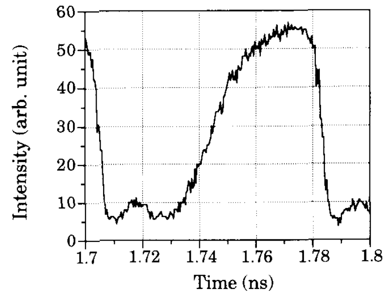

Fig. 3. Example of a converted signal waveform (at 1543 nm). Input wavelength and power is 1553 nm and −10 dBm, respectively. CW channel input power is −16 dBm.

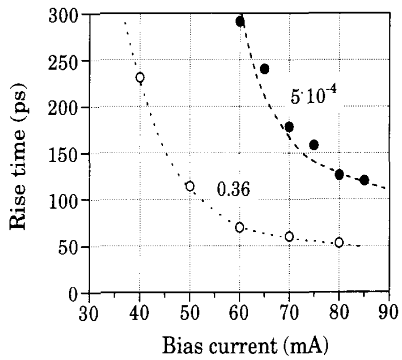

Fig. 4. Rise time versus bias current for the wavelength converters with an output facet reflectivity of $5 \cdot 10^{-4}$ (●) and 0.36 (○). Fall time are below 70 ps at 80 mA for both devices.

Results and Discussion

The rise and fall time for the wavelength converter are of key importance since they determine the maximum allowable bit-rate. The dynamic properties are governed by the effective carrier lifetime, τ [9]:

$$\tau = \left[\tau_s^{-1} + \frac{\partial(g \cdot S)}{\partial N}\right]^{-1} \quad (1)$$

where τ_s is the differential carrier lifetime and g, S, and N are the material gain, the photon density, and the carrier density, respectively. The first and second term in the expression account for influence of the spontaneous and stimulated recombinations, respectively. As the SOA-C is controlled by the optical input signal τ will be strongly influenced by the input signal. The fall time for the converted signal is short since the photon density in the SOA-C is high because of the input signal. On the other hand, the rise time is relatively long due to the absence of the optical input signal at switch-on. In Fig. 3 this characteristic for the converted signal is shown with a rise time of approximately 200 ps and a fall time below 100 ps. Clearly the rise time is the limiting factor for the switching speed and therefore it will be investigated in the following.

One way to shorten the rise time is to increase S. This can be done simply by using a SOA with large facet reflectivities as shown in Fig. 4. Here the rise time (10–90%) is plotted versus the bias current for two SOA-C's with output facet reflectivities of $5 \cdot 10^{-4}$ and 0.36. Both devices have coated input facets giving a reflectivity of approximately $5 \cdot 10^{-4}$. The coupled input power for the signal and CW channel is −11 and −13 dBm, respectively, and the CW channel wavelength is 1531 nm. The extinction ratio for the input signal (at 1553 nm) is 10 dB while it is 7 dB for the converted signal (at high bias current). The fall time is below 70 ps for both devices. Shorter rise time at higher bias current level is due to the decrease in carrier lifetime with bias current [9]. The rise time is shortest for the SOA-C with the cleaved output facet (53 ps at 80 mA) due to the increased spontaneous photon density caused by the reflected light from the output facet. However, large facet reflectivities lead to higher gain ripples so the gain, extinction ratio and rise/fall times become critically dependent on the detuning of the signal and the CW channel wavelengths relative to Fabry–Perot resonances. Therefore in practical systems the reflectivity of the device should be low ($< 10^{-4}$).

A large extinction ratio for the converted signal is also important. Fig. 5 displays the extinction ratio dependency on CW channel power (CW channel wavelength: 1527 nm, signal wavelength/power: 1543 nm/−11 dBm). An increase in the power of the CW channel will increase its contribution to the gain saturation and thereby reduce the extinction ratio for the converted signal. Similarly, Fig. 6 shows the extinction ratio of the converted signal versus the average signal input power for two different wavelengths of the CW channel (1527 nm and 1543 nm). The coupled input power is −16.5 dBm, the input signal wavelength is 1553 nm and the gain peak wavelength of the amplifier is around 1545 nm. As seen from the figure, increasing the signal power leads to an increased extinction ratio for the converted signal. For example for the converted signal at 1527 nm the extinction ratio increases from 2.5 to 11.1 dB when the signal power increases from −21.4 to −11.7 dBm. This is due to the stronger gain suppression at high input powers.

Besides a higher signal input power a better extinction ratio can also be obtained by a shorter wavelength for the CW channel. As seen from Fig. 6 the extinction ratio

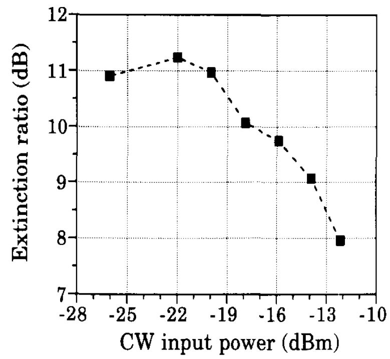

Fig. 5. Extinction ratio for the converted signal versus coupled CW signal power. Signal wavelength and power are 1543 nm and −11 dBm. CW channel wavelength: 1527 nm.

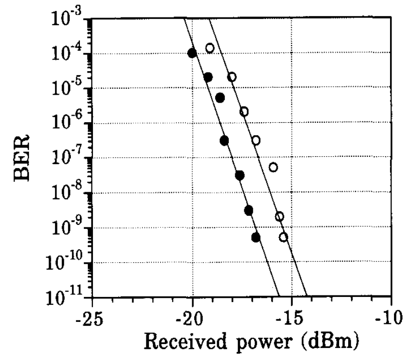

Fig. 7. BER versus received power for input signal at 1560 nm (●) and for converted signal at 1543 nm (○). Bit-rate: 4 Gb/s. Both facets for the SOA-C are AR-coated to reflectivities of approximately 5.10^{-4}.

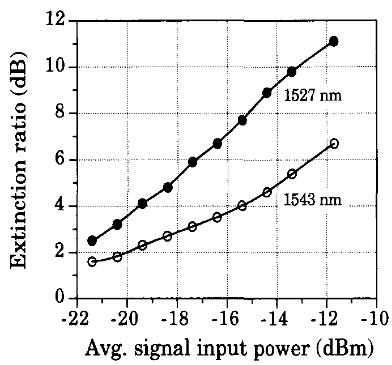

Fig. 6. Extinction ratio for the converted signal versus the average coupled input signal power. Wavelength for the converted signals are 1543 nm (○) and 1527 nm (●) while the input signal wavelength is 1553 nm.

increases from 6.7 to 11.1 dB as the wavelength decreases from 1543 to 1527 nm. The explanation is that the gain peak of the amplifier shifts towards longer wavelengths when the gain is saturated. Therefore, CW channels at shorter wavelengths will experience larger gain variations. Naturally, the wavelength of the input signal should at the same time be close to the gain peak to obtain a high gain and thereby a strong saturation.

According to the minimum rise time of 120 ps in Fig. 4, operation at 4 Gb/s should be possible. To assess the performance of the SOA-C at this bit-rate a system experiment is carried out (see Fig. 2). The input signal (λ_1 = 1560 nm) is modulated at 4 Gb/s with a $2^7 - 1$ PRBS sequence and the BER for the converted signal (λ_2 = 1543 nm) is measured at the output. Fig. 7 shows the BER versus the received power for the converted and the incoming signal, which are selected by the output filter. The penalty for λ_1 at the output for passing through the SOA is below 0.5 dB. The penalty of 1.5 dB for the converted signal at λ_2 is due to the smaller extinction ratio (7.8 dB) compared to the signal at λ_1. Note that the sensitivity is determined by the 15 GHz front-end. The coupled signal input power is only −11 dBm which is considerably lower than the power requirements for other types of converters [3]. In this experiment the information is converted over 17 nm but the SOA-C has a potential conversion range that is limited only by its 3-dB gain bandwidth ($\approx$ 40 nm [8]).

Summary

Semiconductor optical amplifiers for high-speed optical wavelength conversion have been demonstrated. The characteristics of the conversion in terms of rise and fall time and extinction ratio have experimentally been investigated. Rise/fall time of 120/70 ps and an extinction ratio up to 11 dB at a coupled input power of −12 dBm is measured. A system experiment demonstrated wavelength conversion over 17 nm at 4 Gb/s.

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BOA: Balanced Optical Amplifier

J-M. P. Delavaux and D. DiGionanni

***Abstract*—We propose a novel and efficient balanced optical amplifier configuration. In this technique, the four ports of a multiplexer coupler are used to combine signal and pump in a symmetric fashion. We demonstrate the use of this single-coupler based design in both 980 nm pumped erbium-doped fiber preamplifier and power booster arrangements. In addition, we show that the BOA design provides pump redundancy, dual pumping while preventing pump cross talk, automatic gain control (AGC) potential and self-gain equalization capability over the whole 1550 nm transmission window.**

I. Introduction

Optical amplifiers are key components for optical communications for the various roles as preamplifiers, regenerators or post-amplifiers. Conventional co- and counter-propagating amplifier designs use three out of four ports of a multiplexer device (e.g., bulk or fiber); the pump port, the signal port and the common port leading to the amplification medium (e.g., rare earth-doped fiber). Generally, the fourth port is blocked or used as a pump or signal tap. In amplifier designs with two or more pumps, each pump requires a separate multiplexer unit increasing optical loss, fabrication complexity and costs. Furthermore, crosstalk between pumps can lead from minor amplifier gain and noise instability to catastrophic failure of the pumps [1]. Insertion of additional isolators to protect the pumps from optical feed back or the use of hybrid pumping [2] of the amplifier configuration reduces this crosstalk problem.

In this letter, we propose an amplifier design, the balanced optical amplifier (BOA), which uses all four ports of a multiplexing device. We demonstrate the use of our design in preamplifier and power booster applications with one or two pumps. The versatility of this amplifier arrangement is illustrated by achieving fiber self-gain flattening of the Er^{3+} spectrum window.

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J-M. P. Delavaux is with AT&T Bell Laboratories, Solid State Technology Center, Breinigsville, PA 18031.

D. DiGionanni is with AT&T Bell Laboratories, Murray Hill, NJ 07974.

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II. Amplifier Design

The schematic of the BOA configuration is shown in Fig. 1. The four arms of a wavelength multiplexer combine pump and signal in a symmetric fashion. The 1550 nm transmission signal is amplified along the two sections of active fiber (l_1 and l_2) on each side of the multiplexer. Signal isolation is provided by input and output isolators. The laser pump (P_1) is divided by a splitter coupler before being launched into opposite leads of the multiplexer to copump fiber l_1 and to counter-pump fiber l_2, respectively. Pump P_2 is used for pump redundancy or pump power supplement.

The new configuration allows for relaxed constraints on both loss and crosstalk. For example, a high insertion loss at 1550 nm wavelength would reduce the gain without degrading the noise figure since both signal and amplified spontaneous emission would be attenuated in a similar amount. Also, in the dual end-pumped EDFA configuration the remainder of unused pump power goes directly into the opposite pump, resulting in an effective typical isolation varying from 3 to 6 dB. In contrast, in this design the two pumps are isolated to the extend of the wavelength multiplexer isolation. Here, for the case of 980 nm pumping, the multiplexer has an isolation higher than 25 dB. In addition, the pump power can be partitioned to achieve optimum pumping of the chosen configuration (e.g., $l_1 < l_2$). Furthermore, to optimize the pump use and ease manufacturing, a spliceless unit could be made of two pieces of active fiber [3], as shown by dashed and solid lines in Fig. 1. Alternatively, a third isolator transparent to both pump and signal (e.g., 1480 nm pumping) would transform the amplifier into an isolated two stage amplifier for combined low noise and high gain (high saturated output power) performance. Finally, the BOA design requires only one wavelength-multiplexer opposed to two in dual conventional pumping designs.

III. Experimental Results

Figs. 2 and 3 shows gain, noise, and saturation power curves at three signal wavelengths for a BOA in a pream-

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