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BER measurements at 2.5Gbit/s on wavelength converted signals using double pump FWM in a semiconductor optical amplifier have been performed experimentally for both single- and multiple-input wavelengths. These results were presented at an OSA sponsored conference entitled: Advanced Semiconductor Lasers and their applications" and the results have appeared in print in Trends in Optics and Photonics.

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Final Report

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Spectral Processing on Wavelength Encoded Signals In Semiconductor Laser Amplifiers

Report submitted by

Professor Mario Dagenais
Department of Electrical and Computer Engineering
University of Maryland
College Park, MD 20742
Tel: 301-405-3684
FAX: 301-314-9281
e-mail: dage@eng.umd.edu

to

Dr. Alan Craig
Air Force Office of Scientific Research
Bolling Air Force Base, Bldg. 410
DC 20332-6448
Tel: 202-767-4934

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1. Executive Summary

The goal of this program was to study and optimize all-optical processing of wavelength encoded signals using the process of four-wave mixing in semiconductor laser amplifiers. The all-optical processing functions that were envisioned included logic functions performed on two or multiple wavelength signals. Particular attention was to be devoted to optimizing the nonlinear interaction in semiconductor laser amplifiers. In particular, different types of resonant enhancement of the nonlinearities in strained quantum well structures were to be considered and new types of optical logic gates were to be implemented. This was originally proposed as a three and a half year program. Unfortunately, after one year and a half, the program was cancelled and the different research projects had to stop.

During this one year and a half, we initiated different program for optimizing optical nonlinearities in semiconductor optical amplifiers but, because of the short time, no definite theoretical results were obtained and, the related experimental work could not be carried in time. Fortunately, in a parallel on-going program, we were able to implement a new four wave mixing experiment in a quantum well semiconductor laser amplifier. Single and multiple wavelength conversion using double pump four-wave mixing in a semiconductor laser amplifier was realized at a 2.5 Gb/s data rate. The wavelength converted signal was made wavelength insensitive to the detuning between the pump and probe laser for detunings from -30 nm to 15 nm. Multiple-input wavelength conversion using low pump powers was also demonstrated for the first time with a low penalty of about 1.5 dB. These experiments will now be described.

2. Experimental Results

Wavelength conversion is a key function that will be essential for future optical telecommunication networks using dense wavelength-division-multiplexing (DWDM). Wavelength conversion can be realized all optically by using nonlinear optical phenomena such as cross-gain modulation, cross-phase modulation and four-wave-mixing (FWM) in a semiconductor optical amplifier (SOA) [1]. The FWM is particularly interesting as it offers advantages such as being applicable at high bit rate and as being independent of the input data format. However, the wavelength conversion range using a single pump is limited as the efficiency decreases rapidly with the wavelength shift. To improve the wavelength conversion range, a double-pump scheme was first proposed in 1988 [2]. The principle of operation of such a scheme is based on the fact that the second pump experiences the gain and index modulation created by both the input data and the first pump wavelength. Side-modulation bands around the second pump are thus created, and carry the same information as the input probe. More recently several groups have studied the conversion efficiency of this scheme using CW beams, and have found a nearly flat variation with the wavelength separation between the two pump signals [3,4]. The BER results have also been reported at a fixed wavelength detuning (~80nm) [5]. Additionally, the double-pump scheme has been demonstrated to obtain polarization insensitive wavelength conversion [6].

Simultaneous conversion of multiple input channels is very useful in converting a group of wavelengths from C-band to L-band or vice versa. It is also desirable in order to scale the wavelength conversion capability in a modular fashion as the network evolves. Until this date researchers have used difference-frequency-generation in AlGaAs waveguides [7] and in quasi-phase matched $LiNbO_3$ [8] and FWM in SOA [9] to demonstrate multiple channel wavelength conversion. However, in the first two of these approaches passive waveguides were used which meant that large pump powers (65mW and 110mW respectively) were required to get the wavelength converted signals. In the scheme involving FWM in an SOA, the beating of the pumps were used to create the sidebands around the modulated signal which puts a limit on the range over which wavelength conversion is possible. In this paper, double pump FWM in an active medium (SOA) is proposed to achieve multiple wavelength conversion with a large conversion range and using much lower pump power levels. We report for the first time the bit-error-rate (BER) performance of single and multiple wavelength conversion using the new double pump scheme. The BER performance for different wavelength shifts, both positive as well as negative, will also be given for a single-input wavelength.

EXPERIMENTAL SETUP

Figure 1 shows the experimental setup. One or two Ortel DFB lasers mounted in a WDM transmitter rack are used as the probe [11]. These lasers with a wavelength separation of 1.6 nm are modulated with a pseudo-random sequence of length 2^{23} -1 at 2.5 Gbit/s. A third Ortel DFB laser is used as the first pump. A tunable external cavity laser is used as the second pump. Both pump lasers are operated CW. The polarization of each wavelength is controlled to ensure maximum FWM efficiency. These three or four lasers are connected to an arrayed-waveguide grating (AWG). The AWG has a wavelength spacing of 1.6 nm, a FWHM of about 0.48 nm and an insertion loss of 3 dB. The AWG's output is connected to the input of the SOA. The output of the SOA is analyzed by an Optical Spectrum Analyzer (OSA), or filtered by a similar arrayed-waveguide grating. The filtered signal is sent to a 2.5 Gbit/s SONET receiver.

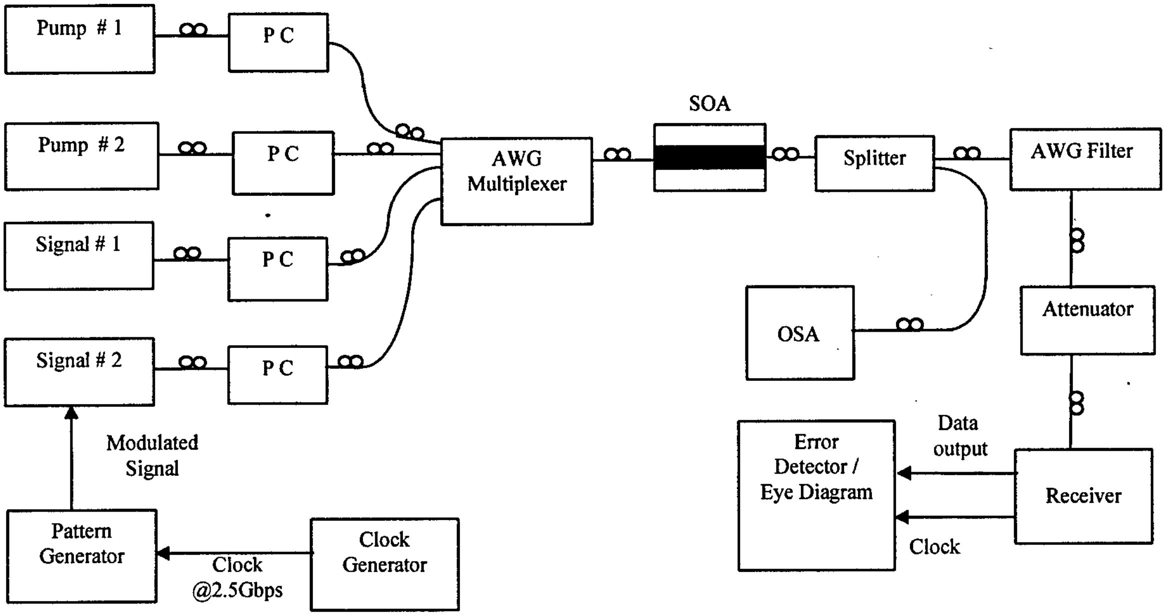


Figure 1: Experimental setup of the double-pumped FWM. PC: polarization controller, SOA: semiconductor optical amplifier, OSA: optical spectrum analyzer, AWG : arrayed waveguide grating

The SOA used for this experiment is a polarization insensitive multiple-quantum-well device with buried ridge structure, incorporating lateral spot-size converters and windows. The length of the device is 940 µm. A 6^0 angle tilted waveguide was used, in combination with the 10 um long InP window, to reduce the back reflection from the facet. The maximum small-signal internal gain is about 30 dB. Fiber-fiber gain of 23dB has been obtained at 1.55 □m using lensed fibers with small numerical aperture. The saturation power at 150 mA is about 7 dbm. Other characteristics can be found in [10].

3. RESULTS and DISCUSSION

Figure 2 shows a typical optical spectrum after the SOA for (a) single and (b) double input signal wavelengths for an injection current of 175 mA to the SOA. The power level is about –5 dbm, 3 dbm and 5 dbm, for the input modulated signal, the first pump and the second pump, respectively. One can clearly identify the newly generated conjugate wavelengths around the first and the second pumps. The stronger conjugated signal around the second pump is used as the converted signal. For the double input wavelengths, one can observe a slightly decreased conjugate signal power for the signal #2 due to the reduced FWM efficiency with the increased wavelength spacing. The chosen converted signal is filtered using another arrayed waveguide grating filter which has similar characteristics as the one used to combine the signals. It has been verified from the filtered signal that there is at least a 10dB discrimination between the filtered and the input modulated signal. This discrimination ratio ensures that there is a negligible influence of the input wavelength on the BER measurement of the wavelength converted signal.

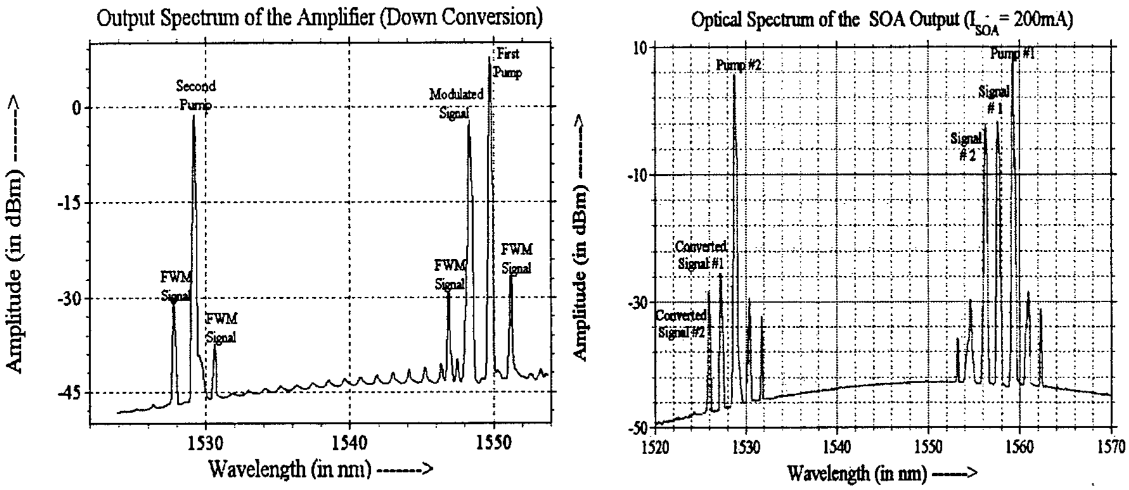


Figure 2: The optical spectrum at the output of the SOA for (a) one and (b) two input signals

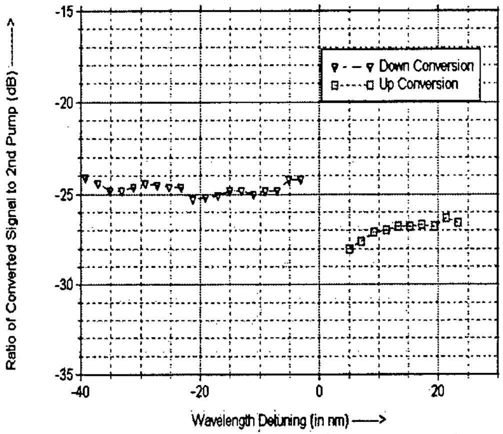
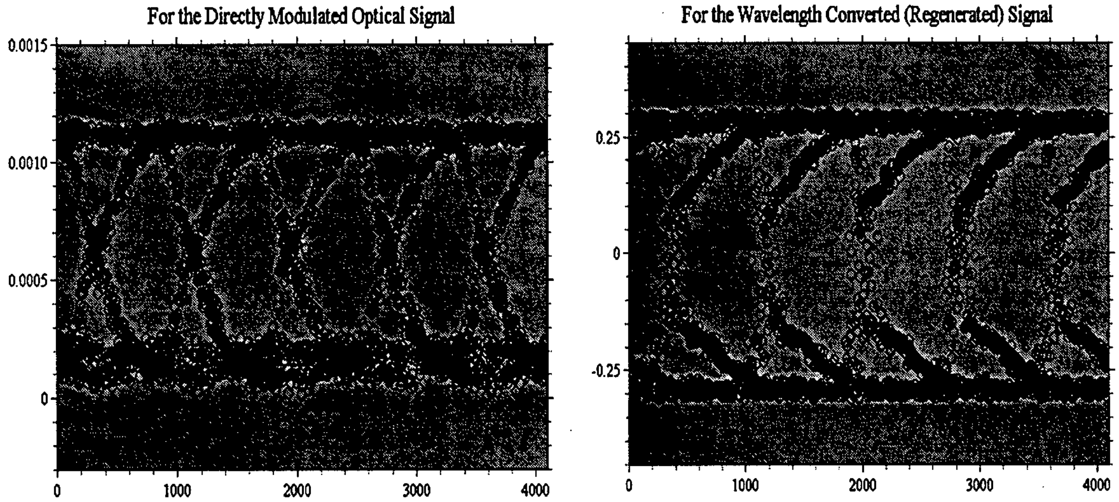


Figure 3: Power ratio between the converted signal and the second pump versus wavelength separation between the two pumps.

Figure 3 shows the ratio between the converted signal power and the second pump power for an injection current of 175 mA to the SOA. We can see that for a wavelength shift from -40nm to 25nm between the two pumps, this ratio does not change more than 4 dB. It is worth noting that the ratio is with respect to the second pump output power, instead of the input signal power. Such a definition allows us to compensate for the variation of the amplifier gain of the second pump signal over the large wavelength range. In this measurement, the input power level for all wavelengths is kept fixed. The result shown in figure 3 implies that for a given input signal wavelength, the conversion ratio shows a much smoother variation compared to the single pump scheme for which a 20dB variation has been observed for the same wavelength conversion range (from -40nm to 25nm) [12].

Figure 4 shows the eye diagrams for the input data and the converted signal with the double-pump scheme. The converted signal has a different waveform than the input data as it has been regenerated by the receiver. One can observe here an open eye diagram for both the signals indicating a low bit-error-rate.


For the Directly Modulated Optical Signal

For the Wavelength Converted (Regenerated) Signal

Figure 4: Eye diagrams of (a) the input data, and (b) the regenerated converted signal

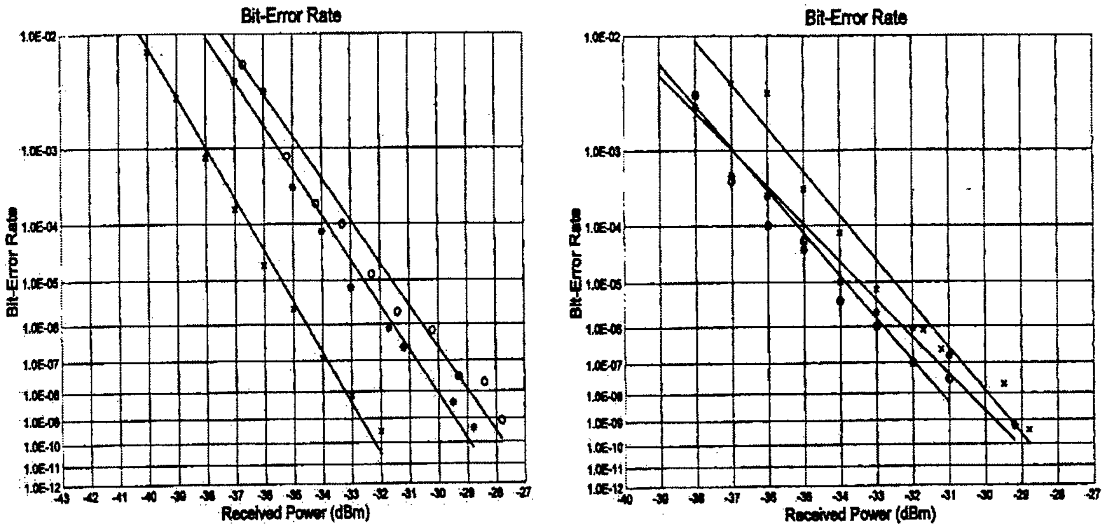


Figure 5: BER performance for different configurations. (a) BER for the directly modulated signal(x), single pump(o) and double pump(*), b) BER of double pump scheme with up conversion of 10nm(x) and 5nm(o), and down conversion of 21nm(*).

Figure 5 shows the BER as a function of the input power to the receiver for different configurations (1) back-to-back, (2) single pump and (3) double pump with up conversion of 10nm(x) and 5nm(o), and down conversion of 21nm(*).One can see that there is a 3 dB penalty between the wavelength converted signal and the back-to-back configuration. It is important to note that there is no extra penalty between the single pump and double pump scheme (for equal intensity pump), and the penalty for different wavelength shifts does not change if we take into account the measurement accuracy and stability.

Figure 6 shows the BER against the received power for the scheme with two input signals. One can see that the penalty for the converted signal is about 1.5 dB for the first wavelength 6(a) and 3 dB for the second wavelength 6(b). That difference of penalty comes from the fact that the signal-to-background ratio for the second converted signal is about 3 dB less than that of the first one (due to the difference in the conversion

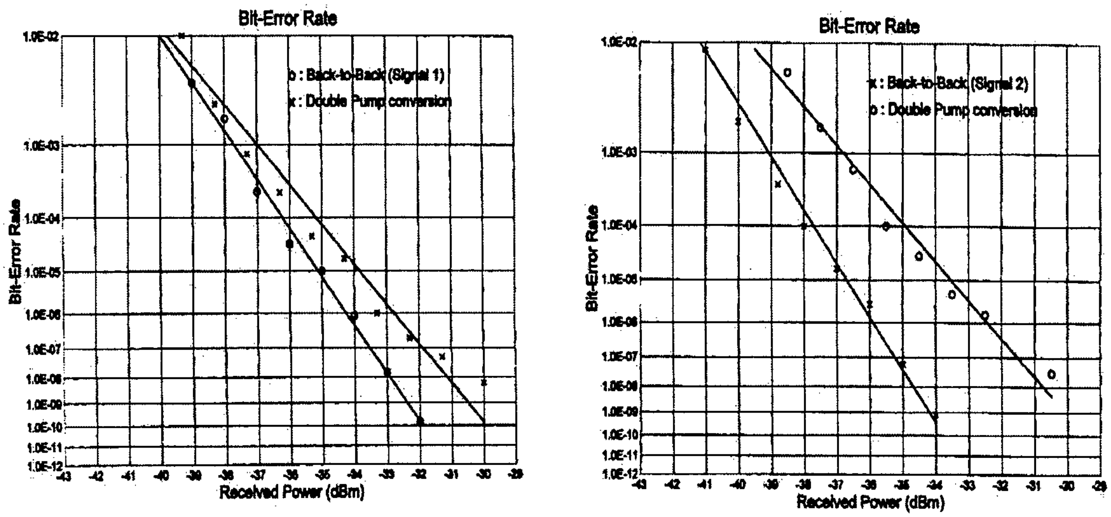


Figure 6: BER plots for the back-to-back and converted signals (a) first and (b) second wavelengths

efficiencies).

4. CONCLUSION

In conclusion, BER measurements at 2.5Gbit/s on wavelength converted signals using double pump FWM in a semiconductor optical amplifier have been performed experimentally for both single- and multiple-input wavelengths. It is found that the wavelength-converted signal can be made wavelength insensitive for detuning from -30nm to 15nm. We have also seen that the double pump scheme enables us to perform multiple-input wavelength conversion with very low penalty. These results demonstrate the potential system application of double pump FWM scheme in future optical networks. These results were presented at an OSA sponsored conference entitled: "Advanced Semiconductor Lasers and their applications" and the results have appeared in print in Trends in Optics and Photonics, Vol. 31, Advanced Semiconductor Lasers and their Applications, Leo Hollberg and Robert J. Lang, eds. (OSA, Washington, DC, 2000).

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