# All-Optical Semiconductor Optical Amplifier-Based Wavelength Converters With Sub-mW Pumping

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***Abstract*— We experimentally study the wavelength conversion of 10-Gb/s return-to-zero signal using interband four-wave mixing inside a semiconductor optical amplifier with 10-ps gain-recovery time. Power of the converted signal exceeds that of the original signal for wavelength shifts of up to 8 nm. Our technique is energy efficient as the required input pump power is <1 mW. We discuss the observed performance of such a wavelength converter in terms of required pump power, conversion efficiency, and optical signal-to-noise ratio of the converted signal. For an 8-nm wavelength shift, the converted data signal exhibits no Q-factor degradation while having 2.7-dB power gain.**

***Index Terms*— Amplified spontaneous emission, four-wave mixing, semiconductor optical amplifiers, wavelength conversion.**

## I. Introduction

The advent of advanced modulation formats involving phase modulation has posed a serious challenge for practical implementation of format-transparent all-optical signal processing of WDM signals [1]. Four-wave mixing (FWM) in semiconductor optical amplifiers (SOAs) is a transparent all-optical technique that can process an optical signal while also amplifying it considerably. In the past decade, most SOA-based wavelength converters have employed intraband FWM, requiring relatively high pump powers [2], because the use of interband FWM in such devices becomes inefficient [3] owing to their relatively large gain-recovery time (close to 150 ps). Indeed, interband FWM in traditional SOAs becomes impractical for wavelength shifts $> 0.1$ nm. We have shown recently [4], [5] that interband FWM becomes practical in SOAs whose gain-recovery time is reduced to near 10 ps through enhanced amplified spontaneous emission (ASE) [6].

In this letter, we present experimental results of a wavelength converter based on such enhanced interband FWM. Although our SOA should work for phase-modulated signals at data rates of upto 50 Gbaud, here we employ it for a proof-of-concept demonstration and use it to convert the wavelength of RZ signals (duty cycle 50%) operating at 10 Gb/s. Using our previous theoretical and experimental optimization results for CW signals [5], we are able to realize efficient wavelength conversion with a net power gain for wavelength shifts of upto 8 nm. Much larger wavelength shifts are possible if a conversion efficiency of $< 100\%$ is acceptable. A major benefit of our wavelength converter is its energy efficiency as the required input pump power is typically $< 1$ mW, without any need of an external assist beam [7].

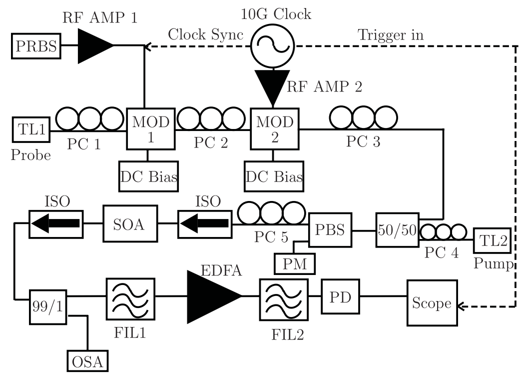


Fig. 1. Experimental setup used for demonstrating wavelength convertion of 10-Gb/s RZ-format signals using interband FWM in an ASE-assisted SOA. PC: polarization controller. PBS: polarization beam splitter. PM: power meter. 50/50: 3-dB splitter. 99/1: 1% power tap. RF AMP: RF amplifier. EDFA: erbium-doped fiber amplifier. FIL: optical filter. MOD: 10-Gb/s intensity modulator. ISO: isolator. OSA: optical spectrum analyzer.

## II. Experimental Setup

Figure 1 shows our experimental setup. The top part of this figure shows how we create the RZ signal whose wavelength needs to be converted. Starting with a CW tunable laser (TL1) and a pseudo-random binary sequence (PRBS) electrical signal, we first create 10 Gb/s NRZ optical data stream using a modulator (MOD 1). This data stream is subsequently passed through a second modulator (MOD 2), set upto carve RZ pulses with 50% duty cycle by applying a sinusoidal voltage at 10 Gb/s [8]. The average signal power at the SOA input is fixed at $-11.7$ dBm in our experiment. This is limited by the maximum tunable laser power and insertion loss of the pulse modulation components. In contrast, the signal wavelength was tuned over a wide range within the SOA bandwidth.

The pump power is obtained from a second tunable laser (TL2) operating continuously at a wavelength fixed at 1574.54 nm to keep it close to the gain peak of our SOA at 1570 nm. The pump and signal beams are combined

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using a 50:50 (3-dB) fiber coupler before they are launched inside our SOA used for wavelength conversion. We employ a commercial SOA (CIP Technologies, model SOA-XN-OEC-1550) designed to reduce the gain-recovery time close to 10 ps through high internal ASE at high drive currents (500 mA). The isolators at the input and output ends of the SOA are used to minimize back reflections. The insertion and coupling losses after the polarization beam splitter (PBS) are estimated to be 3 dB.

At the SOA output, a 99:1 fiber coupler facilitates simultaneous acquisition of the spectral and temporal data. The 1% branch of the coupler is connected to an optical spectrum analyzer (OSA); total attenuation in the OSA branch was estimated to be 26.7 dB at 1575 nm with negligible wavelength dependence in the wavelength range of interest (1565–1585 nm). In the 99% branch, the first filter (FIL1) is a tunable filter whose tunable bandwidth is set to 0.5 nm. It's center wavelength is set as the wavelength of the idler generated inside the SOA through the FWM process. This filter has an out-of-band suppression in excess of 50 dB. We amplify the idler using an erbium-doped fiber amplifier (EDFA) and use the second optical filter with a 3-dB bandwidth of 1 nm (FIL2) to reject the out-of-band portion of ASE noise added by the EDFA. A photodiode with a 22 GHz bandwidth was used to detect the incoming data stream at the converted wavelength.

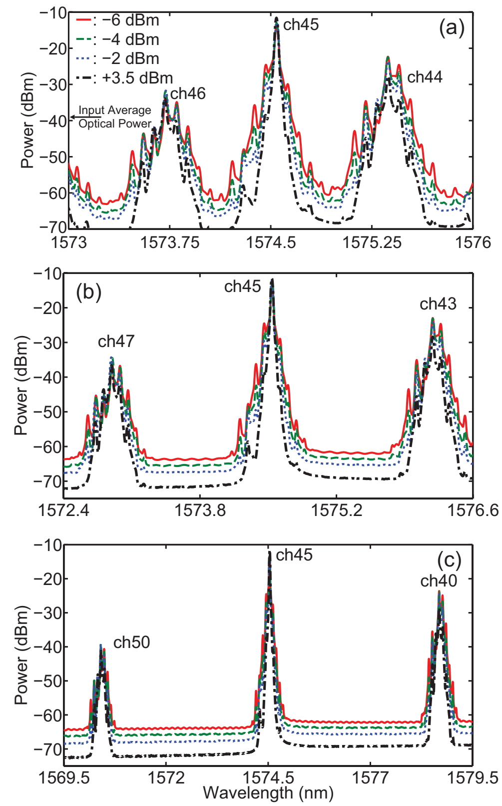


Fig. 2. Measured output spectra for four different input pump powers at a fixed signal power of −11.7 dBm. The pump wavelength corresponds to channel 45 of the L-Band ITU grid. The 10-Gb/s RZ-on-off keying (OOK) probe signal is red shifted from the pump wavelength. Wavelength conversion from (a) channel 44 to 46, (b) channel 43 to 47, and (c) channel 40 to 50.

## III. Experimental Results

In this section, we present the spectral and temporal data that was used to characterized the performance of our wavelength converter. Figure 2(a)–(c) shows the FWM spectra for three different wavelength shifts realized by tuning the signal laser. To make our results relevant to actual telecommunication systems, we indicate in this figure the channel numbers by using the International Telecommunication Union's (ITU) grid for the L-band channels, spaced apart by 100 GHz. On this grid, our pump wavelength corresponds to channel 45 (ch45), while the signal and idler wavelengths can vary from channel numbers 40 to 50. More specifically, parts (a)–(c) in Fig. 2 correspond to frequency shifts of 200, 400 and 1000 GHz, respectively. In each case, the four spectra correspond to four different pump powers ranging from −6 dBm to +3.5 dBm. The pump power was varied to find the pump power level that provides the optimum performance. It can be seen that a pump power below 1 mW (0 dBm) is better from the standpoint of enhanced power conversion efficiency.

The physical mechanism behind this somewhat counter-intuitive observation can be understood by noting that the optical pump produces not only FWM but is also amplified considerably by the SOA as it propagates through the device. At high input pump powers, the intense input optical pump begins to saturate the SOA so much that the resulting depletion of ASE compromises its effectiveness to shorten the gain-recovery time [4], [5]. This problem becomes less severe at reduced pump powers, resulting in enhanced wavelength conversion efficiency. However, the pump spectra in Fig. 2 exhibit multiple sidebands at low pump powers. This is a manifestation of signal-induced cross-phase modulation (XPM) that cannot be ignored at low pump powers. Moreover, when the pump and signal powers become comparable, the FWM process becomes more complicated because one cannot neglect pump depletion [3], [9]. In practice, the input pump power should be 8–10 dB larger than the average input signal power. If this condition is not met, then the input signal will start acting as the pump and the FWM product which is red-shifted from the signal will increase in intensity at the cost of the intended converted signal.

One may ask what limits the magnitude of wavelength shift in our experiments. The answer is provided by the conversion efficiency (CE), defined as the ratio of the average power of the converted channel to that of the original channel. The CE decreases in Fig. 2 as wavelength shift increases, as expected from theory [3], [5] and it ultimately limits the maximum wavelength shift. Another important question is how the optical signal-to-noise ratio (OSNR) of the signal is affected during its wavelength conversion [1], [10]. In practice, a wavelength converter should provide a high OSNR together with a high CE, both of which depend on the pump power used to initiate FWM.

Figure 3 shows the CE (left axis) and OSNR (right axis) measured as a function of pump power for three frequency shifts, $\Delta\nu$, shown in Fig. 2. The CE is close to 10 dB for $\Delta\nu = 200$ GHz, but is reduced to near 2.5 dB for $\Delta\nu = 1000$ GHz (wavelength shift 8 nm). We see that the OSNR is improved at high pump powers while CE has a broad maximum at pump

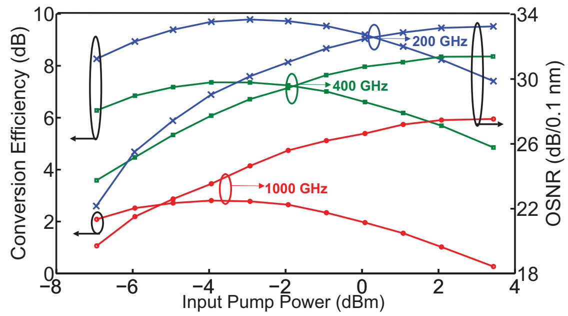


Fig. 3. Conversion efficiency and OSNR of the idler measured as a function of input pump power at a fixed signal power of −11.7 dBm for three frequency shifts of 200 GHz (blue), 400 GHz (green), and 1000 GHz (red).

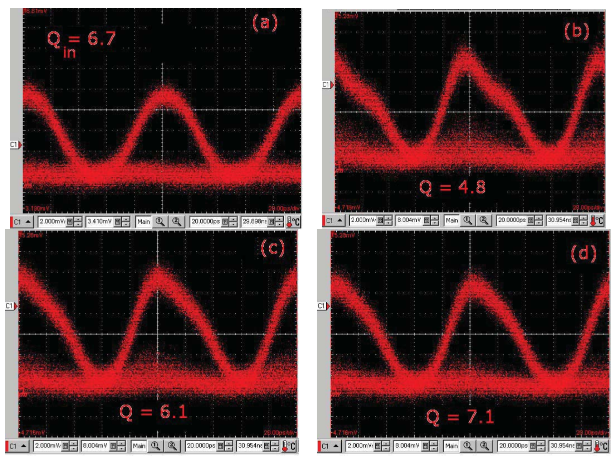


Fig. 4. Eye-diagram for (a) 10-Gb/s RZ-OOK input data channel with 50% duty cycle and −11.7-dBm power, and the converted channel with an 8-nm wavelength shift using a pump power (b) −6 dBm, (c) −4 dBm, and (d) −2 dBm.

power levels near 0.5 mW (−3 dBm) and begins to degrade in the high pump power regime where OSNR is the highest. However, the OSNR values do not degrade much at the power level at which CE peaks. For example, OSNR degrades by less than 3 dB and has values of 32 dB and 28 dB for frequency shifts of 200 and and 400 GHz, respectively. Even in the case of 1000 GHz shifts, the OSNR is close to 26 dB at a pump power of −2 dBm. These numbers suggests that the optimum power performance of this kind of wavelength converter is realized when the pump power is reduced to below 1 mW and is adjusted to maximize the CE. Note that the CE is plotted in the range of 0 to 10 dB, indicating that the power of converted channel is larger than the input channel power in all cases. The important point is that a net power gain is realized with sub-mW optical pumping levels in our experiments.

As a final check on the performance of our wavelength converter, we have measured the eye diagrams of the original and converted channels. Part (a) of Fig. 4 shows the input data channel corresponding to −11.7 dBm average optical power at the SOA input. The measured Q-factor for the input data channel was 6.7. Parts (b)–(d) show the eye-diagrams for converted data channel with a frequency shift of 1000 GHz (wavelength shift 8 nm) at pump powers of −6, −4, and −2 dBm, respectively. The quality of converted channel is comparable to that of the input channel at the optimum pump power of −2 dBm. In fact, the measured Q-factor of 7.1 is slightly better than that of the input channel. However, the quality degrades progressively as the input optical pump power is progressively reduced. At the lowest pump power of −6 dBm, Q = 4.8 and there is a significant distortion in the converted data channel due to enhanced nonlinear effects in the presence of ASE. These results further indicate that it is important to optimize the input pump power.

## IV. Conclusion

To conclude, we have carried out a proof-of-concept demonstration of a wavelength convertor that employs inter-band FWM inside an SOA designed for fast gain recovery through enhanced ASE. More specifically, we show efficient wavelength conversion with a net power gain over an 8 nm wavelength-shift range of a 10-Gb/s RZ-format signal (50% duty cycle) using sub-mW pump powers. Much larger wavelength shifts are possible if a conversion efficiency of $<100\%$ is acceptable. We measured the conversion efficiency and the OSNR as a function of pump power and found that both of them can be made relatively large by optimizing the input pump power. This optimum value was chosen to be −2 dBm in our experiments. At this pump power, the OSNR of the converted signal with an 8 nm wavelength shift was 26 dB, while the power gain was 2.7 dB. These numbers indicate that ASE-assisted SOAs with a fast gain recovery time are ideally suited for energy-efficient wavelength conversion in modern telecommunication systems.

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