

Towards Tbps wavelength conversion with a bulk semiconductor optical amplifier

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By utilizing extensive numerical modeling, which takes into account ultrafast carrier dynamics (such as spectral hole burning, carrier heating, two photon absorption, etc.) and optical field propagation, we model Tbps wavelength conversion in a single bulk semiconductor optical amplifier (SOA) followed by a detuned optical bandpass filter.

Introduction

Wavelength conversion received tremendous research efforts in the past several years because it plays an important role in future optical networks employing either optical circuit switching [1] or optical packet switching [2]. Extensive research has been dedicated to semiconductor optical amplifier (SOA) based wavelength converters due to their power efficiency and integration potential. SOA-based wavelength converters, however, suffer from long carrier lifetime (typically ~ns), which limits the operation speed of the device up to 10 Gb/s. By driving the SOA in a push-pull mode, higher bit rate operations have been achieved, for example, 168 Gb/s wavelength conversion using a delayed interference signal converter (DISC) [3].

Recently, a simple wavelength converter, which is composed of an SOA followed by an optical bandpass filter (OBF), has been demonstrated to work at bit rates as high as 160 Gb/s [4], although the SOA has a recovery time longer than 90 ps. After the SOA the leading edges of the (inverted) converted probe pulses are red-shifted, whereas the falling edges are blue-shifted [5]. If the central wavelength of the OBF is blue-shifted with respect to the central wavelength of the probe beam, the converted signal recovers much faster compared to the case where the central wavelengths of the filter and the probe beam coincide [6]. The function of the filter in the wavelength converter is to convert chirp dynamics (phase modulation) into amplitude modulation. Since the chirp dynamics is much faster than gain dynamics, this scheme should work at much higher bit rates.

A natural question to ask then is whether bit rates of 1 Tb/s are feasible. We found that, even using a classical rate equation without the intra-band ultrafast carrier dynamics being taken into account [5], 1 Tb/s wavelength conversion can be achieved. However, since the pulse width used in 1 Tb/s transmission systems is ~300 fs, we also did the simulations by utilizing an extensive numerical model, which takes into account the ultrafast carrier dynamics (such as spectral hole burning, carrier heating, two photon absorption, etc.) and optical field propagation. In this paper we report on the results obtained with the extended model, which also accounts for gain dispersion and group velocity dispersion caused by the waveguide.

Simulation results

A simulation using a classical rate equation model [5] is shown in Fig. 1. The full width at half maximum (FWHM) of the input pulses is 300 fs and the pulse energy is 10 fJ. The power of the continuous wave (CW) probe is 10 mW. This classical model only includes inter-band carrier dynamics. Gain dispersion and group velocity dispersion are not taken into account. The small signal gain of the SOA is 19.6 dB. The linewidth enhancement factor is 4. Since the carrier lifetime is 200 ps in the simulation, patterning effects are clearly observed in Fig.1 (a) because the SOA gain has no time to fully recover in one bit slot (1 ps in this case). If the filter central frequency is 2.5 THz higher than the probe frequency (the FWHM bandwidth of the filter is 1.998 THz.), the result shown in Fig.1 (b) is achieved. The patterning effect is significantly reduced and the original data is converted to a new wavelength with inverted polarity. It is noted that in all the simulations presented in this paper, the optical BPF has a Gaussian transfer function and is realized in the frequency domain using a Fast Fourier Transform (FFT) algorithm.

The simulation results shown in Fig.1 shows the potential of Tb/s wavelength conversion, however, as stated in the introduction, the physical picture has to be refined by simulations from a more advanced model. In the following, an extensive model [8] is employed to carry out the simulations for a bulk SOA. In addition, gain dispersion and group velocity dispersion are also taken into account. A finite-difference beam propagation method (FD-BPM) [7] is adopted. The SOA has a strained bulk active region of 250 μm and active volume of 50 μm^3 , the same as in Fig. 1. The other parameters are: the confinement factor (for TPA): 0.22 (0.5), the linewidth enhancement factor (for TPA): 5(-2), the free carrier absorption coefficients in conduction (valence) band: 1×10^{-9} (0) μm^2 , the carrier lifetime: 300 ps, the gain coefficient: $4 \times 10^{-7} \mu\text{m}^2$, the group velocity: 100 ps/ μm , the waveguide loss: $0.00175 \mu\text{m}^{-1}$, the photon energy :0.8 eV, the carrier-carrier scattering time in conduction (valence) band: 0.1 (0.05) ps and the carrier-phonon relaxation time in the conduction (valence) band: 0.7 (0.25): ps, TPA coefficient: $3.5 \times 10^{-7} \mu\text{m}/\text{mW}$, optical transition state density: $5.3 \times 10^5 \mu\text{m}^{-3}$. The first order gain dispersion coefficient is 6.81×10^{-4} ps/ μm and the second order gain dispersion coefficient is -2×10^{-5} ps²/ μm . The group velocity dispersion coefficient is 2×10^{-6} ps²/ μm . The calculations are performed for 160 mA injection current.

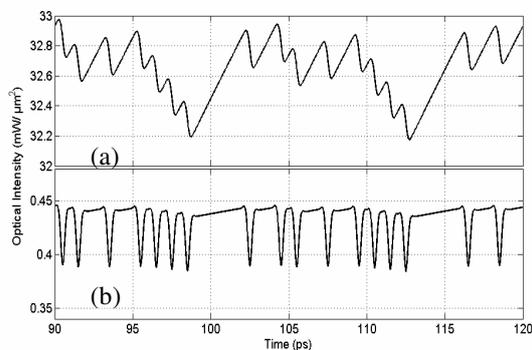


Figure 1 Output waveform from the BPF following the SOA (a) no detuning (b) the central frequency is 2.5 THz higher than the probe frequency.

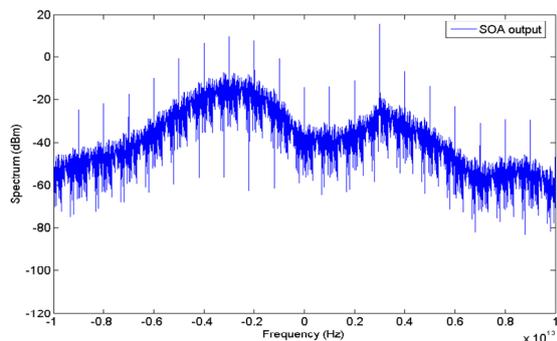


Fig. 2 The spectra of the signal after the SOA

In the simulations the input data is $2^{15}-1$ pseudo-random binary series (PRBS) return-to-zero (RZ) signal. The input pulses are Gaussian and the pulse width is 200 fs (FWHM). The frequency of the probe signal is 3 THz higher than the reference frequency, while the central frequency of the pump is 3 THz lower than the reference frequency. The relative location of the input signals in the frequency domain is shown in Fig. 2, where the spectrum of the output from the SOA is shown for the case that the input pulse energy is 50 fJ and the probe CW power is 5 mW. It can be clearly observed that the spectrum of the probe signal is considerably broadened and spectral spikes around the probe frequency are also visible. We also observe four wave mixing (FWM) components. Note that in Fig. 2 the reference frequency (0 Hz) corresponds to 1550 nm.

In a traditional wavelength converter based on XGM, an optical BPF is employed with the central frequency the same as the probe central frequency. The output waveform from the filter is shown in Fig. 3 (a) and the eye diagram in Fig.3 (b). The filter bandwidth (FWHM) is 2.16 THz. The filter should be wide enough to extract the modulated probe and narrow enough to minimize the crosstalk from the pump channel. When the filter bandwidth is too large, intensity distortions caused by the beating between pump signal and the probe signal can be observed. It is important to note that due to the ultra-fast carrier dynamics, ultra-fast gain recovery is clearly visible at the filter output, which in turn is followed by the slow gain recovery process driven by the inter-band carrier injection. Although the eye diagram is open, the variances for the “1” level (corresponding to “0” in the data) and “0” level” (corresponding to “1” in the data) show that there is still considerable patterning effect.

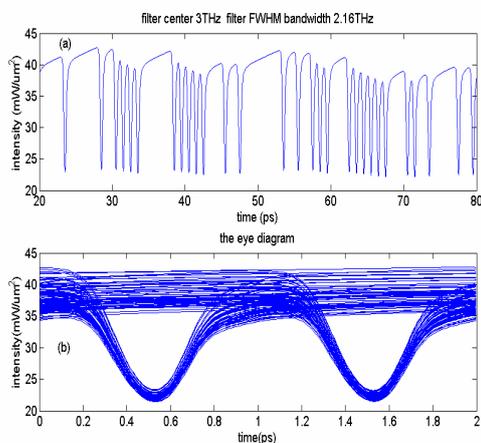


Fig. 3 The waveform (a) and eye diagram (b) of the output signal from a BPF without detuning

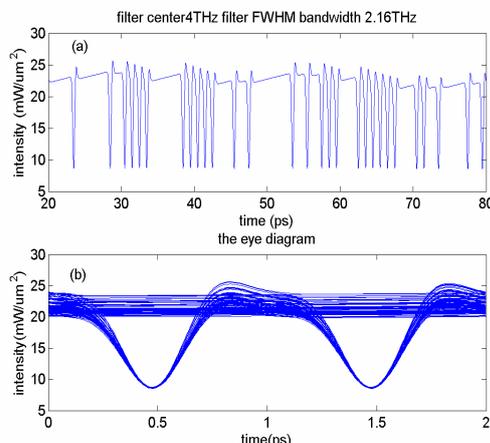


Fig. 4 The waveform (a) and eye diagram (b) of the output signal from a BPF with 1 THz detuning to the

The patterning effect is significantly reduced when we place the BPF at the blue side of the probe wavelength, as presented in Fig. 4. The output waveform from the BPF is shown in Fig. 4 (a) and the eye diagram in Fig. 4 (b). The filter bandwidth is the same as in Fig. 3, however, the central wavelength is shifted 1 THz to the blue side of the probe. It is clear that, by comparing Fig. 4 to Fig. 3, the variances for the “1” level (corresponding to “0” in the data) and “0” level” (corresponding to “1” in the data) are

much smaller when the filter is detuned from the probe wavelength. The reduction is more significant for the “0” level than the “1” level. It is also noticeable that overshoot exists in the trailing edge of the inverted pulse. These behaviors are due to the chirp dynamics of the probe introduced by the pump data signal when they propagate together in the SOA. Detailed analysis is out of the scope of this paper and will be presented somewhere else.

Conclusion

A recently proposed wavelength converter is investigated for 1 Tb/s operation. Employing numerical models with various complexities, we performed extensive simulations, which confirm the possibility of Tb/s wavelength conversion using a single SOA with an optical BPF. The ultrafast chirp dynamics, which are related to the gain recovery governed by intra- and inter- band carrier dynamics, are found to be responsible for the ultra-fast operation of the wavelength converter.

Acknowledgments

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