Highly Nondegenerate Four-Wave Mixing with Picosecond Pulses in a Quantum-Dash Waveguide

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Nondegenerate four-wave mixing (FWM) in semiconductor optical amplifiers (SOAs) is an attractive method for all-optical wavelength conversion because of its transparency to bit rate and modulation format [1]. However, bulk and quantum-well SOAs typically exhibit an asymmetry in their detuning characteristics that makes converting to longer wavelengths less efficient [2]. There is increasing evidence to suggest that this asymmetry can be reduced by using SOAs with quantum dots or dashes in their active regions [3], [4]. This improvement is attributed to the smaller linewidth enhancement factor in these structures [3]. More work is needed to understand the bandwidth limitations of quantum dots and dashes for FWM-based wavelength conversion. To our knowledge, conversion efficiencies for dots and dashes have been reported only for frequency detuning less than 2 THz, and only with continuous-wave (CW) signals, which is typically less efficient than with short pulses [1], [5]. In this letter, we report on the wavelength up-conversion of picosecond pulses by FWM in a quantum-dash SOA. The conversion efficiency was measured up to 3.9-THz detuning, and a maximum of –18 dB was achieved up to 2.5 THz.

The device used in the experiment was a quantum-dash ridge waveguide laser of the type reported in [6]. The laser structure was grown by solid-source molecular beam epitaxy upon an InP substrate. The active region consists of five layers of InAs dashes, each embedded in a separate compressively strained AlGaInAs quantum well. Waveguiding was achieved by patterning 5-μm-wide oxide-confined ridges, with the laser cavities aligned perpendicular to the dashes for maximal gain. The device was cleaved to a length of 2 mm. Fig. 1 shows subthreshold amplified spontaneous emission (ASE) spectra from the device. The spectra are very broad, and have a peak at 1587 nm for moderate injection levels.

FWM was achieved through a nondegenerate pump-probe experiment, the setup for which is illustrated in Fig. 2. The pump and probe pulses were supplied by the idler and signal of an optical parametric oscillator. These pulses had a width of 1.6 ps, and a repetition rate of 82 MHz. The probe wavelength λ_q was tuneable from 1460 nm to 1630 nm, while the pump wavelength λ_p was fixed at 1567.5 nm. The pump and probe beams travelled through optics which controlled their polarizations and levels of attenuation. They were combined and coupled with a 40X objective into the fundamental TE mode of the waveguide. The input pump and probe powers (before coupling) were measured to be 75 and 0.23 mW, respectively. The output light was coupled into a multimode fibre leading to an optical spectrum analyzer. The delay between the pump and probe was controlled with a retroreflector on a translation stage. When the pump and probe were temporally aligned, FWM occurred in the waveguide and a conjugate signal could be seen in the output spectrum.

Fig. 3 displays output spectra with the probe wavelength at 1547 nm and the device biased at 60 mA. With the pump and probe temporally aligned, the conjugate can clearly be seen at 1588 nm. Spectra were taken for $\lambda_q > \lambda_p$ and for $\lambda_q < \lambda_p$. For $\lambda_q > \lambda_p$, the conjugate experienced low gain and was negligible compared to the ASE noise. For $\lambda_q < \lambda_p$, the conjugate was near the gain peak of the device, and was amplified. The power in the conjugate was calculated by integrating over its spectrum and correcting for ASE noise by subtracting a reference spectrum with no conjugate (taken with the pump and probe temporally misaligned). The conversion efficiency, defined as the ratio between the output conjugate power and the input probe power, was calculated with the inclusion of the 30 % reflection loss at each facet. The resulting efficiency is plotted in Fig. 4, for the $\lambda_q < \lambda_p$ case, as a function of the magnitude of the frequency detuning $\Delta f = f_p - f_q$ for different levels of current injection. Note that $\Delta f < 0$ in Fig. 4 since wavelength up-conversion is occurring. As the current is increased, the efficiency increases but peaks near 60 mA, and begins to decrease beyond that due to gain saturation by ASE. This behaviour is consistent with pulsed FWM experiments in bulk SOAs [1]. The peak efficiency is –17.8 dB, for a detuning of –1.7 THz. Between –2.5 THz and the maximum detuning of –3.9 THz, the efficiency appears to decrease with a –20-dB/decade slope, although more data are needed to confirm this. The efficiency is affected by the gain experienced by the conjugate. For –1.7 and –2.5-THz detuning, the conjugate is very close to the gain peak of the device, while for –3.9 THz, the conjugate is red-shifted from that peak, and is amplified less. Even at –3.9 THz, the efficiency of –22 dB is higher than values reported in CW FWM experiments on quantum-dot and quantum-dash SOAs near –1-THz detuning [3],

[4]. This is remarkable considering that no attempt was made to optimize this value with respect to the input pump power. Since a very strong pump was used (causing significant gain saturation), reducing its power would likely further increase the efficiency [5]. The improved efficiency seen in this experiment was achieved through the use of picosecond pulses, and by virtue of the fact that the conjugate was near the gain peak of the device.

These results show that quantum-dash SOAs, operating near 1550 nm, can achieve efficient wavelength conversion at large detuning via FWM with picosecond pulses. In this work, the up-conversion efficiency was evaluated up to 3.9-THz detuning. An efficiency of –18 dB was achieved up to 2.5 THz, which amounts to a 40-nm conversion span.

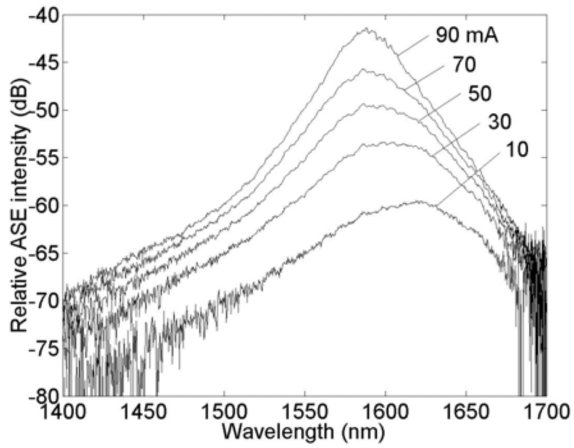

Fig. 1. ASE spectra taken at injection currents of 10–90 mA.

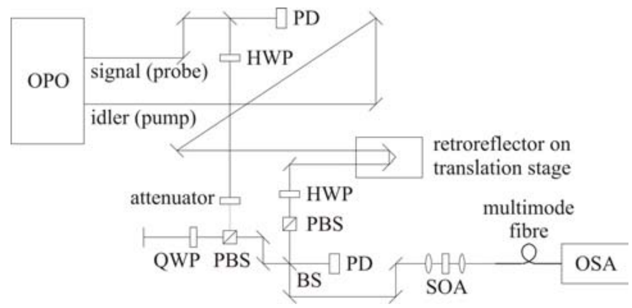

Fig. 2. Setup for the FWM experiment. OPO = optical parametric oscillator, PD = photodiode, HWP = half-waveplate, QWP = quarter-waveplate, PBS = polarizing beamsplitter, BS = beamsampler, OSA = optical spectrum analyzer.

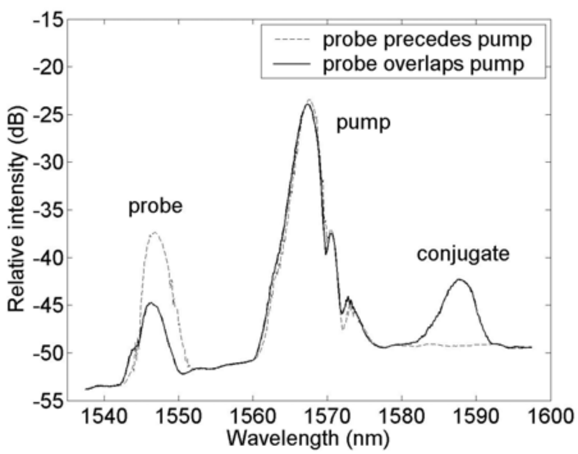

Fig. 3. Output spectra taken for two different delays between pump and probe.

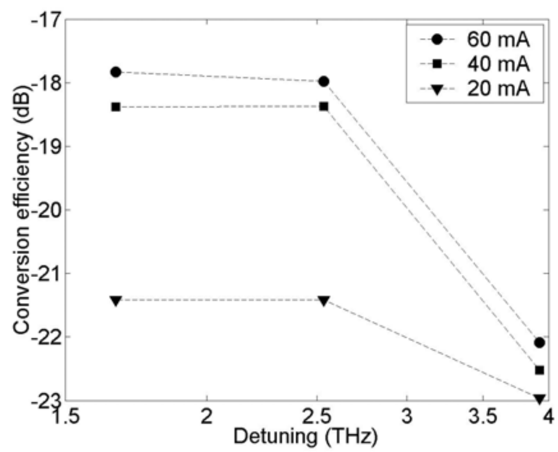

Fig. 4. Conversion efficiency as a function of frequency detuning for different injection currents.

References

[1] S. Diez, C. Schmidt, R. Ludwig, H. G. Weber, K. Obermann, S. Kindt, I. Koltchanov, and K. Petermann, IEEE J. Select. Topics Quantum Electron **3**, 1131 (1997).

[2] K. Kikuchi, M. Kakui, C.-E. Zah, and T.-P. Lee, IEEE J. Quantum Electron. **28**, 151 (1992).

[3] T. Akiyama, H. Kuwatsuka, N. Hatori, Y. Nakata, H. Ebe, and M. Sugwara, IEEE Photon. Technol. Lett. **14**, 1139 (2002).

[4] A. Bilenca, R. Alizon, V. Mikhelashvili, G. Eisenstein, R. Schwertberger, D. Gold, J. P. Reithmaier, and A. Forchel, Electron. Lett. **38**, 1350 (2002).

[5] J. Mørk and A. Mecozzi, IEEE J. Quantum Electron. **33**, 545 (1997).

[6] R. H. Wang, A. Stintz, T. J. Rotter, K. J. Malloy, L. F. Lester, A. L. Gray, T. C. Newell, and P. M. Varangis, in Proceedings of the Annual Meeting of the Lasers and Electro-Optics Society 2001, p. 405.