Broad-Band Wavelength Up-Conversion of Picosecond Pulses via Four-Wave Mixing in a Quantum-Dash Waveguide

Bertram Leesti, Aaron J. Zilkie, *Student Member, IEEE*, J. Stewart Aitchison, *Senior Member, IEEE*,
Mohammed Mojahedi, *Member, IEEE*, Ronghua H. Wang, Thomas J. Rotter, Chi Yang, Andreas Stintz, and
Kevin J. Malloy, *Senior Member, IEEE*

***Abstract*—Wavelength up-conversion of 1.6-ps pulses is achieved through four-wave mixing (FWM) in an InAs–InP quantum-dash ridge waveguide laser operating at 1587 nm. The up-conversion efficiency is measured as a function of injection current, for pump–probe detunings in the range 1.8–3.8 THz. The efficiency is found to increase with current up to a point of saturation. The gain at the conjugate wavelength is found to enhance the efficiency. For a detuning of 1.8 THz, an efficiency of -17.6 dB is obtained; this is similar to or higher than reported efficiencies for FWM with continuous-wave signals in quantum dots and dashes, at similar detunings. Further improvement may be obtained through optimization of the pump power.**

***Index Terms*—Nonlinear optics, optical frequency conversion, quantum dots, semiconductor optical amplifiers (SOAs).**

I. Introduction

NONDEGENERATE four-wave mixing (FWM) in semiconductor optical amplifiers (SOAs) is an attractive method for all-optical wavelength conversion, mainly because its operation does not depend on the bit rate or modulation format of the signals used [1]. However, bulk and quantum-well media typically exhibit an asymmetry in their detuning characteristics that makes converting to longer wavelengths less efficient [2], [3]. There is increasing evidence to suggest that this asymmetry can be reduced by using SOAs with quantum dots or dashes in their active regions [4], [5]. This improvement is due to the smaller linewidth enhancement factors characteristic of these structures [4].

Quantum-dot and quantum-dash SOAs, therefore, offer the possibility of obtaining high efficiencies for both wavelength down-conversion and up-conversion through FWM. Previous reports of FWM in these structures have demonstrated the conversion of continuous-wave (CW) signals [4], [5] and short pulses [6], [7], as well as superior symmetry to bulk and quantum-well SOAs [4], [5]. However, actual conversion efficiencies have only been reported using CW signals, for detunings less than 1.5 THz [4], [5]. In this letter, we report on the wavelength up-conversion of picosecond pulses via FWM in a quantum-dash waveguide, up to a much larger detuning of 3.8 THz (corresponding to a 62-nm conversion). The use of short pulses enables higher efficiency than the CW case [1], [8]–[10]. This is because with pulses, higher peak intensities can be obtained for the same level of gain saturation. Here we report an up-conversion efficiency of -17.6 dB at 1.8 THz, which is similar to or higher than previously measured efficiencies for CW FWM in dots and dashes, at similar detunings. Furthermore, we expect our efficiency to increase through optimization of the control pulse energy.

II. Samples and Experiment

The device used in the experiment was a quantum-dash ridge waveguide laser of the type reported in [11]. The laser structure was grown by molecular beam epitaxy on an InP substrate. The active region consisted of five layers of InAs dashes, each embedded in an AlGaInAs quantum well. Waveguiding was achieved by patterning a 5-μm-wide oxide-confined ridge, with the laser cavity aligned perpendicular to the dashes in order to maximize the gain for the transverse-electric (TE) guided mode. The device was cleaved to a length of 2 mm.

The emission properties of the device were tested under dc current injection. Light was generated predominantly in the fundamental TE waveguide mode. Fig. 1 shows subthreshold amplified spontaneous emission (ASE) spectra from the device. The spectral peak experiences a blue shift with increasing current (due to band filling), and is located near 1587 nm for injection above 50 mA. The spectral full-width at half-maximum narrows from 80 to 40 nm over the plotted range. Lasing occurred at a wavelength of 1589 nm, for a bias of 108 mA.

FWM was achieved through a pump–probe experiment [12], 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, at a repetition rate of 82 MHz. These pulses were 1.6 ps in width, and their time-bandwidth product was 1.2 times the transform limit. The probe wavelength λ_q was tuned from 1536 to 1607 nm. The pump wavelength λ_p varied from 1567 to 1576 nm over the tuning range of the probe. The pump

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B. Leesti, A. J. Zilkie, J. S. Aitchison, and M. Mojahedi are with the Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON M5S 3G4 Canada (e-mail: b.leesti@utoronto.ca; aaron.zilkie@utoronto.ca; stewart.aitchison@utoronto.ca; mojahedi@waves.utoronto.ca).

R. H. Wang is with Zia Laser Inc., Albuquerque, NM 87120 USA, and also with the Center for High Technology Materials, University of New Mexico, Albuquerque, NM 87106 USA (e-mail: rhwang@zialaser.com).

T. J. Rotter, C. Yang, A. Stintz, and K. J. Malloy are with the Center for High Technology Materials, University of New Mexico, Albuquerque, NM 87106 USA (e-mail: tjr@unm.edu; chiyang@chtm.unm.edu; andreas@chtm.unm.edu; malloy@chtm.unm.edu).

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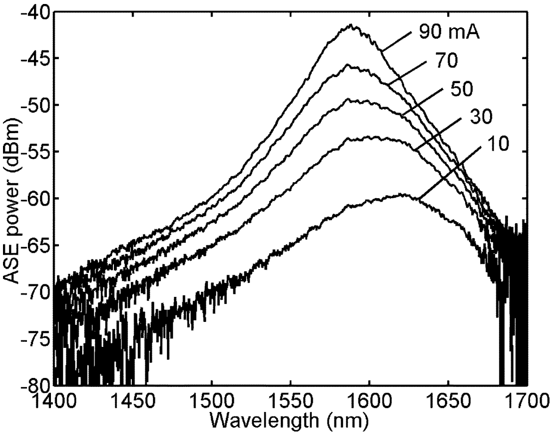

Fig. 1. Subthreshold ASE spectra of the quantum-dash device, obtained from dc current injection in the range 10–90 mA.

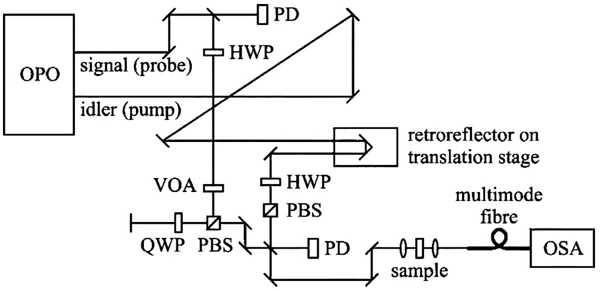

Fig. 2. Setup for the nondegenerate pump–probe experiment used to observe FWM. (OPO: Optical parametric oscillator. PD: Photodetector. HWP: Half-waveplate. QWP: Quarter-waveplate. VOA: Variable optical attenuator. PBS: Polarizing beamsplitter. OSA: Optical spectrum analyzer.)

and probe pulses travelled through optics which controlled their energies, polarizations, and delay relative to each other. They were coupled with a $40X$ objective into the fundamental TE waveguide mode. The time-averaged input powers (before coupling) of the pump and probe were measured to be 75 and 0.23 mW, respectively. The output light was focused into a fiber connected to an optical spectrum analyzer, which was used to record the output spectrum.

Fig. 3 displays two output spectra taken for different pump–probe delays, with $\lambda_q = 1547$ nm and the device biased at 60 mA. When the pump arrives 10 ps after the probe (dotted line), it has no effect on the probe. With the pump and probe temporally aligned (solid line), FWM occurs in the waveguide and a conjugate appears at 1588 nm. The output power in the conjugate was calculated by integrating over its spectrum. The ASE power within the conjugate bandwidth was estimated from a reference spectrum with no conjugate (like the dotted line in Fig. 3). This ASE power was subtracted from the measured conjugate power. The wavelength conversion efficiency was defined as the ratio of the output conjugate power to the input probe power. In calculating this efficiency, we corrected for the 32% reflection loss at each facet.

III. RESULTS

Output spectra were recorded for $\lambda_q > \lambda_p$ and for $\lambda_q < \lambda_p$. For $\lambda_q > \lambda_p$, the conjugate experienced low gain and was weak in comparison to the ASE background. In that case, the wavelength down-conversion efficiency was estimated to be less than -36 dB, although measurement of the conjugate power was not reliable. However, for $\lambda_q < \lambda_p$, the conjugate was near the gain peak of the device, and thus, the up-conversion efficiency was enhanced by amplification. Because the pump wavelength could not be tuned, it was not possible to obtain equally efficient down-conversion in this experiment.

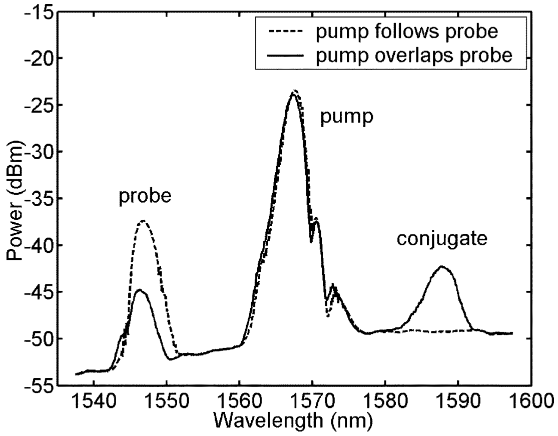

Fig. 3. Output spectra taken for two different delays between pump and probe, with $\lambda_q = 1547$ nm and an injection current of 60 mA. When the pump arrives 10 ps after the probe (dotted line), it has no effect on the probe. When the pump and probe are temporally overlapped (solid line), FWM occurs between the pulses and a conjugate signal appears.

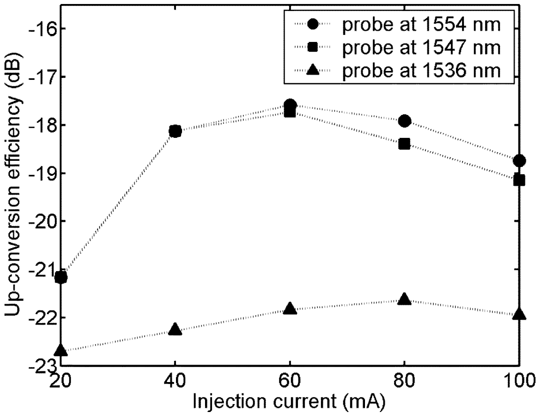

Fig. 4. Wavelength up-conversion efficiency plotted as a function of the injection current for different probe wavelengths.

In Fig. 4, the up-conversion efficiency is plotted as a function of the injection current, for $\lambda_q = 1554, 1547$, and 1536 nm. Note that these correspond to conjugate wavelengths (λ_c) of 1583, 1588, and 1598 nm, respectively. The resulting conversion spans $(\lambda_c - \lambda_q)$ are 29, 41, and 62 nm. The efficiency shows a significant dependence on the injection current. At zero bias (not shown), the conjugate is absorbed and has negligible output power (a few nanowatts). As the bias is increased, the pulses see increased gain, which leads to increased efficiency. However, the efficiency saturates at a certain bias ($\sim$60 mA for $\lambda_q = 1554$ nm), and decreases beyond that. Although more work is needed to verify the cause of this saturation, it may be related to carrier-induced shifts in the gain peak, or gain saturation by ASE [1].

In Fig. 5, the up-conversion efficiency is plotted as a function of the frequency detuning $\Delta f = c|1/\lambda_p - 1/\lambda_q|$, for different injection currents below the point of efficiency satu-

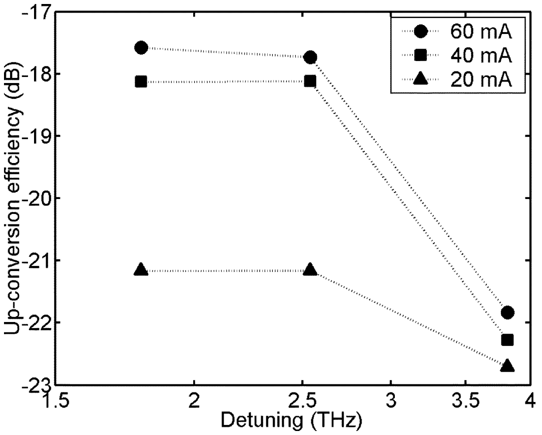

Fig. 5. Wavelength up-conversion efficiency plotted as a function of the pump–probe detuning, for different injection currents below the point of efficiency saturation. The detunings of 1.8, 2.5, and 3.8 THz correspond to $\lambda_q = 1554, 1547$, and 1536 nm, respectively ($\lambda_p \approx 1568$ nm).

ration. The detunings of 1.8, 2.5, and 3.8 THz correspond to $\lambda_q = 1554, 1547$, and 1536 nm, respectively ($\lambda_p \approx 1568$ nm). These detunings are likely to be similar to the bandwidth of spectral hole burning (SHB) in this device. As such, we expect that the frequency response of SHB has a significant effect on the shape of the detuning characteristics in Fig. 5. However, without precise knowledge of the SHB time constant, it is difficult to predict what this effect should be. The gain spectrum of the device also governs the shape of these curves [13]. The efficiency appears to be enhanced by the gain at the conjugate wavelength. For detunings of 1.8 and 2.5 THz, the conjugate (at 1583 and 1588 nm, respectively) is close to the gain peak; for a 3.8-THz detuning, the conjugate (at 1598 nm) is red-shifted from that peak, and is amplified less.

The highest up-conversion efficiency we obtained is -17.6 dB, for a detuning of 1.8 THz and a 60-mA bias. This value is similar to or higher than (up and down) conversion efficiencies reported in CW FWM experiments on quantum-dot and quantum-dash SOAs, at similar detunings [4], [5]. Note that our values have been obtained without optimization of the input pump power. In [10], the authors found that the optimal pump energy (where gain saturation began to counter the benefit of increased pulse intensity) was $\sim$50 fJ for FWM between 2-ps pulses in a bulk InGaAsP SOA. Since our pump energy was estimated to be $\sim$50 pJ (after coupling into the waveguide), it is reasonable to expect that reducing this quantity would further improve the efficiencies obtained here. Note also that with our maximum efficiency, we measured a signal-to-background ratio [(SBR) defined as the ratio of the output conjugate power to the ASE power within the conjugate bandwidth) of 1.2 dB. However, this measurement depends on the pulse repetition rate used; for example, we expect the SBR would increase by $\sim$20 dB for a 10-GHz repetition rate.

In summary, wavelength up-conversion of picosecond pulses was achieved via FWM in a quantum-dash waveguide, for detunings in the range 1.8–3.8 THz. The up-conversion efficiency was found to increase with the injection current, up to a point of saturation. The gain at the conjugate wavelength was found to enhance the efficiency. Our maximum efficiency was similar to or higher than reported values for CW FWM in quantum dots and dashes, at similar detunings. We attribute this performance to the use of picosecond pulses, and to the fact that the conjugate was near the gain peak of the device. These results show that quantum-dash SOAs are suitable for broad-band FWM-based wavelength up-conversion. In future studies, we plan to directly compare the performances of quantum wells, dots, and dashes (in terms of efficiency, SBR, and bit-error rate), using both CW and pulsed inputs, and fully characterize the effects of varying the bias and pump power.

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