

# 40 Gb/s NRZ-DQPSK data wavelength conversion with amplitude regeneration using four-wave mixing in a quantum dash semiconductor optical amplifier

Michael J. CONNELLY (✉)<sup>1</sup>, Lukasz KRZCZANOWICZ<sup>1</sup>, Pascal MOREL<sup>2</sup>, Ammar SHARAIHA<sup>2</sup>, Francois LELARGE<sup>3</sup>, Romain BRENOT<sup>3</sup>, Siddharth JOSHI<sup>3</sup>, Sophie BARBET<sup>3</sup>

<sup>1</sup> Optical Communications Research Group, Department of Electronic and Computer Engineering, University of Limerick, Limerick, Ireland

<sup>2</sup> Lab-STICC, UMR CNRS 6285, École Nationale d'Ingénieurs de Brest CS 73862, 29238 Brest Cedex 3, France

<sup>3</sup> Alcatel Thales III-V Laboratory, Route Departementale, 128, 91767 Palaiseau, France

© Higher Education Press and Springer-Verlag Berlin Heidelberg 2016

**Abstract** Differential quadrature phase shift keying (DQPSK) modulation is attractive in high-speed optical communications because of its resistance to fiber nonlinearities and more efficient use of fiber bandwidth compared to conventional intensity modulation schemes. Because of its wavelength conversion ability and phase preservation, semiconductor optical amplifier (SOA) four-wave mixing (FWM) has attracted much attention. We experimentally study wavelength conversion of 40 Gbit/s (20 Gbaud) non-return-to-zero (NRZ)-DQPSK data using FWM in a quantum dash SOA with 20 dB gain and 5 dBm output saturation power.  $Q$  factor improvement and eye diagram reshaping is shown for up to 3 nm pump-probe detuning and is superior to that reported for a higher gain bulk SOA.

**Keywords** differential quadrature phase shift keying (DQPSK), phase modulation, quantum-dash, semiconductor optical amplifier (SOA), four-wave mixing (FWM), wavelength conversion

## 1 Introduction

The constantly increasing demand for data transmission rates leads to a need to improve the effectiveness of bandwidth use. The differential phase shift keying (DPSK) format, despite the potential disadvantage of higher system complexity, offers a number of advantages compared to on-off keying (OOK), such as requiring a 3 dB lower optical signal-to-noise ratio to reach a given bit error rate

[1,2] and improved resilience to fiber chromatic and polarization mode dispersion [3]. Furthermore, constant intensity modulation formats like DPSK are resilient to semiconductor optical amplifier (SOA) pattern-induced crosstalk, which affects OOK signals. The differential quadrature phase shift keying (DQPSK) format is even more attractive. While having lower receiver sensitivity than DPSK [4], it offers the same advantages with the additional advantage of increasing the spectral efficiency by transferring two bits per symbol, which is of particular importance in optimizing the capacity of wavelength division multiplexed transmission systems.

SOAs have been of great interest for many years because of their attractive properties including small-size, high gain and applications in all-optical signal processing systems [5]. SOAs used for advanced modulation data amplification also need to preserve the phase relations between the symbols [6]. Compared to quantum well and bulk SOAs, quantum dot (QD) and quantum-dash (QDash) SOAs have faster dynamic responses, which make them more attractive for use in ultra-fast optical transmission systems [7,8]. QDash SOAs are of interest as an alternative to QD SOAs, since they have some dot-like properties and can more easily be made to operate in the 1.55  $\mu\text{m}$  telecommunications wavelength range, although they have been shown to also have longer gain recovery times in the range of 100 ps [9].

SOA four-wave mixing (FWM) based wavelength conversion is of particular interest in phase modulated optical communication systems because, in addition to its usual advantages of high conversion efficiency and conversion bandwidth, it is modulation format independent [5]. FWM wavelength conversion of phase modulated data has been experimentally demonstrated for quantum-

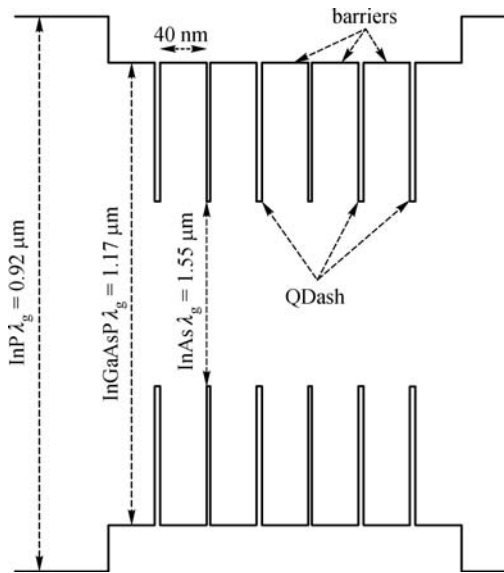
well [10,11], bulk [12] and QD SOAs [13-15] but not to our knowledge for QDash-SOAs.

In this paper, we demonstrate FWM based wavelength conversion for 20 Gbaud (40 Gb/s) NRZ-DQPSK data using a QDash-SOA. We show significantly increased  $Q$  factor and eye diagram reshaping, when compared to the same operation conducted in a bulk SOA [12]. Wavelength conversion was achieved for a positive detuning of up to 3 nm, with significant improvements in the  $Q$  factor for low quality input probe signals.

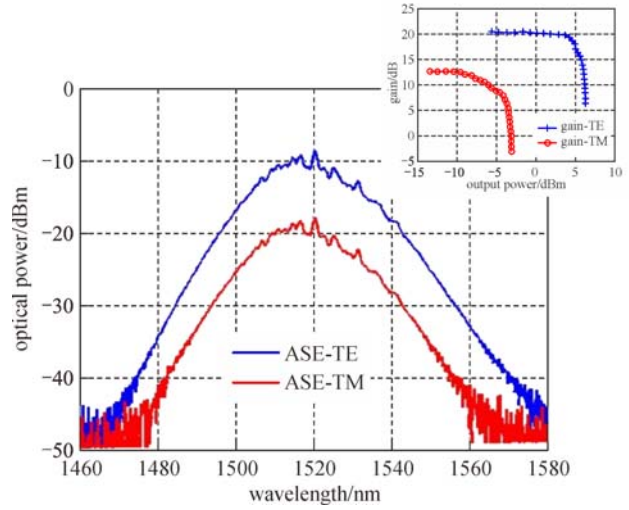
## 2 SOA characteristics

The SOA used is a custom packaged QDash device. The dashes are grown in a dash-in-a-barrier structure where the quantum dash emitting at 1.55  $\mu\text{m}$  is buried in a quaternary barrier of  $\lambda_g = 1.17 \mu\text{m}$  [7]. The structure consists of six dash stack layers as shown in Fig. 1. The SOA is processed using buried ridge stripe technology with a ridge width of 1.5  $\mu\text{m}$ . The waveguides are tilted at  $7^\circ$  and also feature a tilted mode shape converter and antireflection coatings. The SOA is operated at 500 mA bias current, with an unsaturated gain of approximately 20 dB at 1530 nm and saturation output power and polarization sensitivity of 5 dBm and 8 dB respectively. The polarization resolved amplified spontaneous emission (ASE) spectra and gain saturation characteristics are shown in Fig. 2.

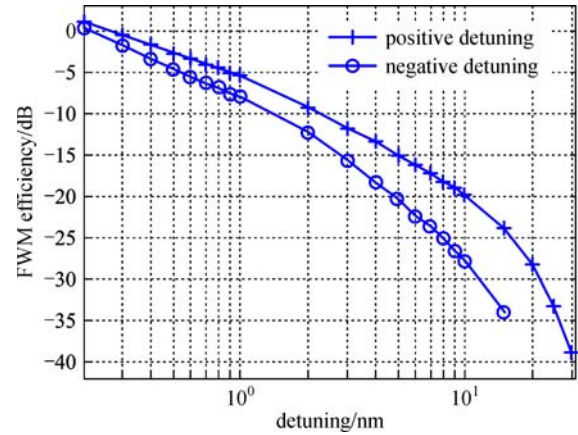
Figure 3 shows the static FWM efficiency of the SOA for different detuning values. The FWM efficiency is defined as the ratio of the output conjugate power to the input probe power. The pump wavelength and power were



**Fig. 1** Dash-in-a-barrier structure, showing six stack layers of InAs QDashes in InGaAsP barriers



**Fig. 2** Unsaturated ASE spectra and polarization dependent gain characteristics (at 1530 nm) for a bias current of 500 mA. The spectral resolution is 1 nm

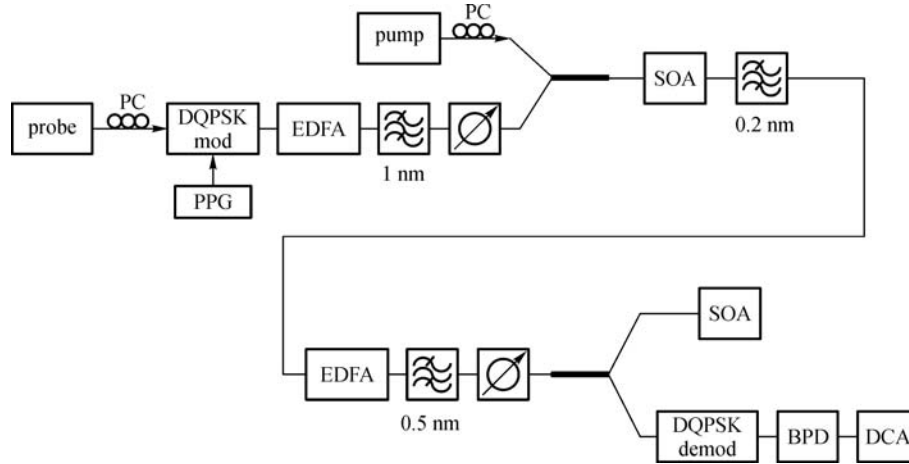


**Fig. 3** Continuous wave (CW) FWM efficiency versus pump-probe detuning for input probe and pump powers of -7 and -4 dBm respectively

1534 nm and -4 dBm respectively. For the purpose of wavelength conversion, it was desired to have the conjugate at the highest possible power level, which was obtained by adjusting the probe power for a detuning of 1 nm. The maximum was achieved for an input probe probe power of -7 dBm. The FWM efficiency was a few dB lower than the one measured for a bulk SOA in our previous work [12].

## 3 Experiment

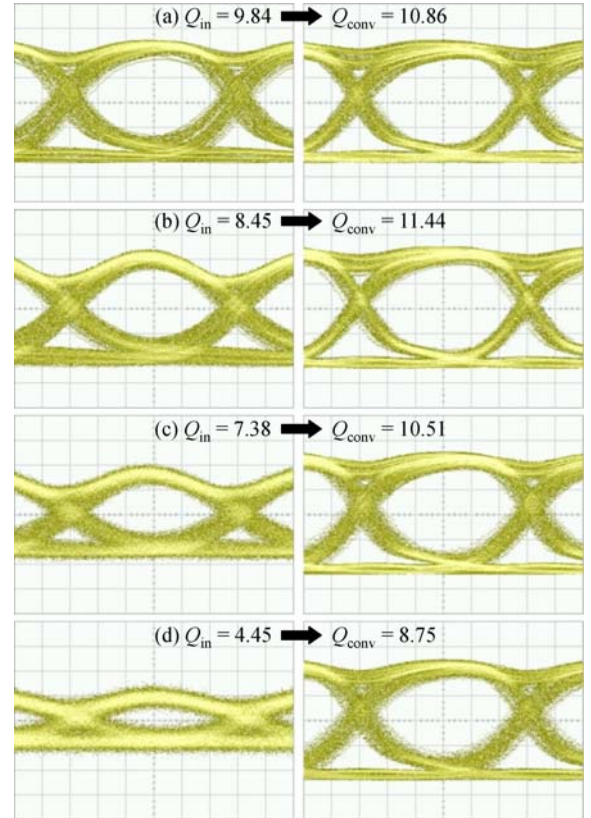
The wavelength conversion experimental setup is shown in Fig. 4. The input pump power is -4 dBm. The probe is modulated by a 20 Gbaud/s (40 Gb/s) non-return-to-zero



**Fig. 4** Experimental setup. PC, polarization controller; PPG, pulse pattern generator; OSA, optical spectrum analyzer; BPD, balanced photodetector; DCA, digital communications analyzer

(NRZ)-DQPSK  $2^{15} - 1$  pseudo random bit pattern using a commercial modulator (Photline-MODBOX). The signal is amplified by an erbium doped fiber amplifier (EDFA) and its ASE reduced by a 1 nm filter. A 0.2 nm filter at the SOA output is used to select the conjugate signal and reduce the SOA ASE, the output of which is amplified by an EDFA followed by a 0.5 nm filter. The DQPSK demodulator (Optoplex) consists of two delay-line interferometers that convert inphase (I) and quadrature (Q) components of the signal into intensity changes. The optical signals from the interferometer outputs are detected by balanced 23 GHz bandwidth photodiodes (Discovery Semiconductors Laboratory Buddy) and sent to an 80 GHz electrical bandwidth Agilent 86100C digital communication analyzer. The demodulated I and Q components show almost identical performance. To this effect we concentrate on the I component for analysis purposes. The influence of the probe input power on the quality of the wavelength converted signal for a detuning of 1 nm was examined. The pump wavelength and power were set to 1534 nm and  $-4$  dBm, respectively. The probe wavelength was set to 1535 nm. The input conjugate signal power to the demodulator was fixed at  $-4.5$  dBm by adjusting the EFDA gain. The input probe and conjugate eye diagrams are shown in Fig. 5. The probe  $Q$  factor increases with an increase in the probe power; whereas the wavelength converted signal  $Q$  factor is highly dependent on the output conjugate power reaching its maximum for an input probe power of  $-10$  dBm as shown in Fig. 6.

In contrast to the bulk SOA [12], where the converted eye diagram was degraded, large improvements in the converted signal were obtained for all the investigated input probe powers, resulting in a 2.63 dB improvement for the maximum converted  $Q$  factor (from 8.45 to 11.44) for a probe input power of  $-10$  dBm and a maximum improvement of 5.87 dB (from 4.45 to 8.75) for a probe input power of  $-20$  dBm (the minimum investigated



**Fig. 5** Eye diagrams of input (left) and converted (right) signals for probe power of: (a)  $-6$  dBm; (b)  $-10$  dBm; (c)  $-15$  dBm; (d)  $-20$  dBm. The detuning is 1 nm. The horizontal scale is 8.3 ps/div

value). The quality of the converted signal for different detuning values was measured. Because non-tunable filters were used, the pump and probe wavelengths were adjusted in order to maintain the conjugate signal at 1533.04 nm. The pump and probe powers were kept at  $-4$  and  $-10$

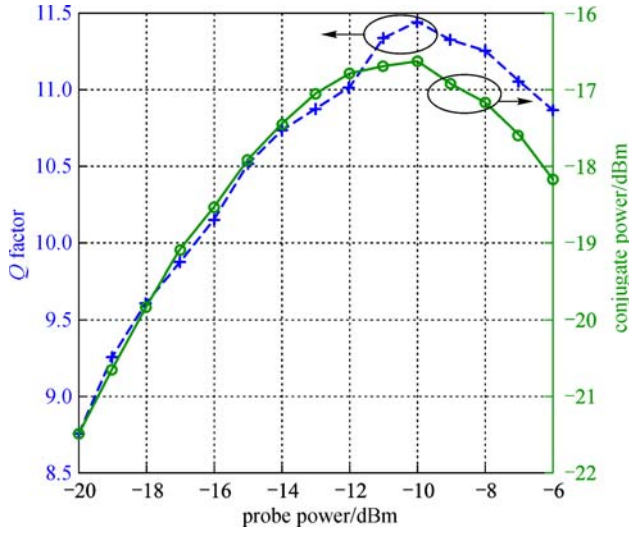


Fig. 6 Converted signal  $Q$  factor and power for a detuning of 1 nm

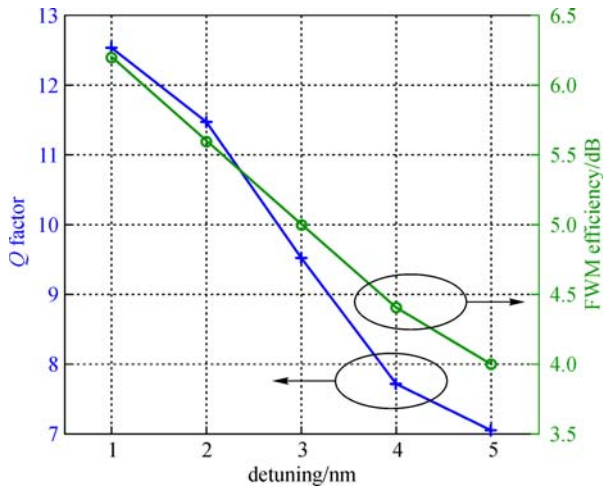


Fig. 7 Converted signal  $Q$  factor and FWM efficiency vs. detuning range

dBm respectively. The input  $Q$  factor was 8.45. The converted signal power was set to its maximum. The resulting  $Q$  factor and FWM efficiency are shown in Fig. 7. As expected, the maximum obtainable  $Q$  factor value decreases along with the conjugate power. For detunings up to 3 nm the  $Q$  factor was improved, reaching a maximum value of 12.52 for 1 nm down-conversion. Figure 8 shows a comparison of the eye diagrams for the input and converted signal for different detunings. A clear improvement in the eye diagram shape is seen for low detuning values.

## 4 Conclusions

40 Gb/s NRZ-DQPSK FWM wavelength conversion in a

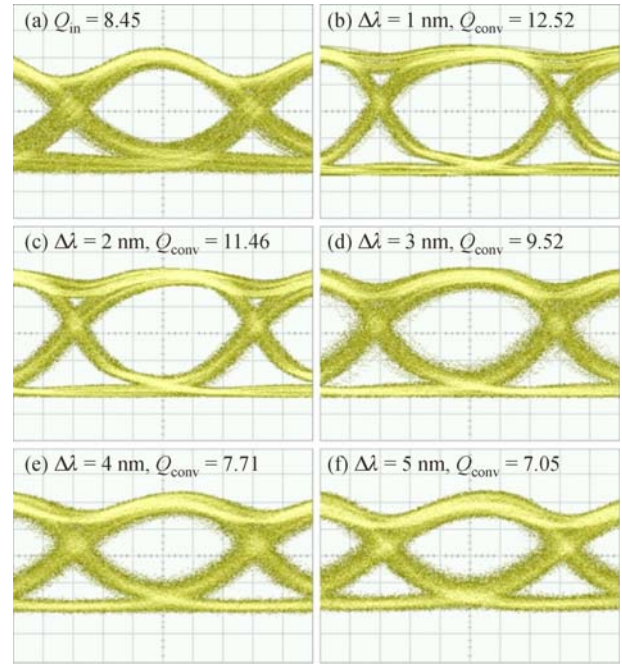


Fig. 8 Eye diagrams for: (a) input probe and (b)–(f) wavelength converted signals for various positive detunings. The horizontal scale is 8.3 ps/div

QDash-SOA was demonstrated. Lossless wavelength conversion was achieved for positive detunings up to 3 nm, with significant improvements in the  $Q$  factor as well as eye diagram reshaping. The results are a noticeable improvement over similar experiments carried out using a bulk SOA [12]. The physical reasons for such improvements are probably linked to faster gain dynamics in QDash-SOAs compared to that in bulk SOAs. More theoretical work is required to determine the exact physical mechanisms leading to the FWM signal improvements.

**Acknowledgements** This research was supported by Science Foundation Ireland Investigator Grant 09/IN.1/12641.

## References

1. Gnauck A H, Winzer P J. Optical phase-shift-keyed transmission. *Journal of Lightwave Technology*, 2005, 23(1): 115–130
2. Cho P S, Achiam Y, Levvyurista G, Margalit M, Gross Y, Khurgin J B. Investigation of SOA nonlinearities on the amplification of high spectral efficiency signals. In: *Proceedings of Optical Fiber Communication Conference (OFC)*, 2004, 1: 211–212
3. Wang J, Kahn J M. Impact of chromatic and polarization-mode dispersions on DPSK systems using interferometric demodulation and direct detection. *Journal of Lightwave Technology*, 2004, 22(2): 362–371
4. Ho K P. *Phase-Modulated Optical Communication Systems*. Berlin:

Springer, 2005

5. Connelly M J. Semiconductor Optical Amplifiers. Berlin: Springer, 2007
6. Bonk R, Huber G, Vallaitis T, Koenig S, Schmogrow R, Hillerkuss D, Brenot R, Lelarge F, Duan G H, Sygletos S, Koos C, Freude W, Leuthold J. Linear semiconductor optical amplifiers for amplification of advanced modulation formats. *Optics Express*, 2012, 20(9): 9657–9672
7. Akiyama T, Sugawara M, Arakawa Y. Quantum-dot semiconductor optical amplifiers. *Proceedings of the IEEE*, 2007, 95(9): 1757–1766
8. Lelarge F, Dagens B, Renaudier J, Brenot R, Accard A, van Dijk F, Make D, Le Gouezigou O, Provost J, Poingt F, Landreau J, Drisse O, Derouin E, Rousseau B, Pommereau F, Duan G. Recent advances on InAs/InP quantum dash based semiconductor lasers and optical amplifiers operating at 1.55  $\mu\text{m}$ . *IEEE Journal of Selected Topics in Quantum Electronics*, 2007, 13(1): 111–124
9. Zilkie A J, Meier J, Mojahedi M, Poole P J, Barrios P, Poitras D, Rotter T J, Yang C, Stintz A, Malloy K J, Smith P W E, Aitchison J S. Carrier dynamics of quantum-dot, quantum-dash, and quantum-well semiconductor optical amplifiers operating at 1.55  $\mu\text{m}$ . *IEEE Journal of Quantum Electronics*, 2007, 43(11): 982–991
10. Porzi C, Bogoni A, Contestabile G. Regeneration of DPSK signals in a saturated SOA. *IEEE Photonics Technology Letters*, 2012, 24(18): 1597–1599
11. Porzi C, Bogoni A, Contestabile G. Regenerative wavelength conversion of DPSK signals through FWM in an SOA. *IEEE Photonics Technology Letters*, 2013, 25(2): 175–178
12. Krzeczanowicz L, Connelly M J. 40 Gb/s NRZ-DQPSK data all-optical wavelength conversion using four wave mixing in a bulk SOA. *IEEE Photonics Technology Letters*, 2013, 25(24): 2439–2441
13. Matsuura M, Calabretta N, Raz O, Dorren H J S. Simultaneous multichannel wavelength conversion of 50-Gb/s NRZ-DQPSK signals with 100-GHz channel spacing using a quantum-dot SOA. In: *Proceedings of 37th European Conference on Optical Communication (ECOC)*, 2011, 1–3
14. Contestabile G, Yoshida Y, Maruta A, Kitayama K. Coherent wavelength conversion in a quantum dot SOA. *IEEE Photonics Technology Letters*, 2013, 25(9): 791–794
15. Contestabile G, Yoshida Y, Maruta A, Kitayama K. Ultra-broad band, low power, highly efficient coherent wavelength conversion in quantum dot SOA. *Optics Express*, 2012, 20(25): 27902–27907



**Michael J. Connelly** obtained his Ph.D. degree in electronic engineering from the National University of Ireland, Dublin in 1992 and is a senior member of the IEEE. He is a Senior Lecturer in electronic engineering and leader of the Optical Communications Research Group at the University of Limerick. He is author of the book *Semiconductor Optical Amplifiers* and

has published many papers on SOAs, optical communication systems and optical metrology. The current research interests of his research group include: SOA modeling, SOA based all-optical signal processing, optical coherence tomography and interferometric laser vibrometry.