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# Single Quantum Dash Mode-Locked Laser as a Comb-Generator in Four-Channel 112 Gbit/s WDM Transmission

**M. Gay, A. O'Hare\*, L. Bramerie, Z. Hao, S. Fresnel, C. Peucheret, P. Besnard**

*Université Européenne de Bretagne, CNRS, UMR 6082 Foton Laboratory, Enssat, CS 80518, 22305 Lannion, France*

*\*Formerly with the School of Physics, Dublin Institute of Technology, Dublin, Ireland*

*gay@enssat.fr*

**S. Joshi, S. Barbet, F. Lelarge**

*III-V Lab, 1 route de Nozay, 91460 Marcoussis, France*

*francois.lelarge@3-5lab.fr*

**Abstract:** We demonstrate 100 km transmission at 28 Gbit/s/channel of 4 DWDM channels using a single quantum-dash mode-locked laser. The amplitude noise of each filtered laser line is improved using limiting amplification in an SOA.

**OCIS codes:** (140.4050) Mode-Locked Lasers; (060.4510) Optical Communications

## 1. Introduction

Various low cost transmitters have been proposed as solutions for wavelength division multiplexed (WDM) passive and broadband optical access networks. These solutions are mainly based on spectral slicing of broadband incoherent [1] or coherent [2, 3] sources. Quantum dash mode-locked lasers (QD MLLs) are attractive because they present very low amplitude and phase noise, high thermal stability and emit a broad optical spectrum [4, 5]. A WDM source with nearly 30 channels on a 40 GHz grid could be realised using a single laser [7]. However, a major limitation in comparison to single-mode lasers when using the wavelength comb of a Fabry-Perot laser diode (FP LD) as a WDM source is the increase of relative intensity noise (RIN) of the selected mode due to mode partition noise [6, 7], particularly in the low frequency range. This limitation was mitigated at 2.5 Gbit/s in [8] thanks to the injection-locking mechanism in a FP LD. However, this solution has never been shown at higher bit rate. A second solution consists in using a semiconductor optical amplifier (SOA) in the gain compression regime to reduce the mode partition noise. It was demonstrated in [9] with a spectrally filtered FP LD at 10 Gbit/s. This technique happens to be particularly attractive since it also provides gain to the selected line and is compatible with photonic integration. To the best of our knowledge, this method has never been assessed with a frequency comb generated by a QD-MLL, that could validate the concept at higher bit rates, for which the RIN contribution becomes more critical.

In this paper, we demonstrate the first WDM transmission of four 100 GHz spaced channels, each modulated at 28 Gbit/s, generated using a single QD MLL followed by an SOA limiting the RIN of each individual filtered mode. Transmission over 100 km of a capacity of 112 Gbit/s with less than 0.5 dB penalty proves the concept.

## 2. Laser structure and characterisations

The active region of the QD MLL is composed of quantum dash layers with InGaAsP quantum wells in a Fabry-Perot (FP) structure [4]. The geometric structure is a buried hetero-structure with an FP cavity length of 420  $\mu\text{m}$ , resulting in a free spectral range of 100 GHz. The chip is placed in a module in order to improve the coupling stability. The optical coupling is realized using bulk lenses. The total coupled power for a bias current of 150 mA is +6 dBm at 22°C, which are the operational conditions used in the following system experiment. Fig. 1(a) shows the optical spectrum at the output of the laser under these conditions. The spectral width is 7.3 nm at -3 dB, covering 10 modes (numbered from 1 to 10 in Fig. 1(a)).

A commercially available SOA, consisting of a 1 mm long InP buried heterostructure, was used for RIN reduction (CIP). It was biased at 180 mA during all the experiments, leading to 20 dB small signal gain and 6 dBm saturated output power.

The RIN of the laser was deduced from measurements of the spectral density of optical noise and electrical power [10]. The results are presented in Fig. 1(b). When all modes are jointly detected, the RIN (green) is below -135 dBc/Hz thanks to the small amplified spontaneous emission noise of this kind of laser [4]. When a single mode is selected, the RIN increases due to mode partition noise. The RIN spectrum of the noisiest line of the frequency comb (channel #8) is shown in purple in Fig. 1(b). The RIN measured when this same selected mode is amplified by the SOA is represented by the blue line in Fig. 1(b). As expected, the RIN decreases in the low frequency range (below 4 GHz) thanks to the SOA gain compression. A similar behavior is observed for all modes, validating the RIN limiting effect of the SOA with our QD-MLL comb-generator. Next, the benefits of this technique will be highlighted in a high-speed WDM transmission experiment.

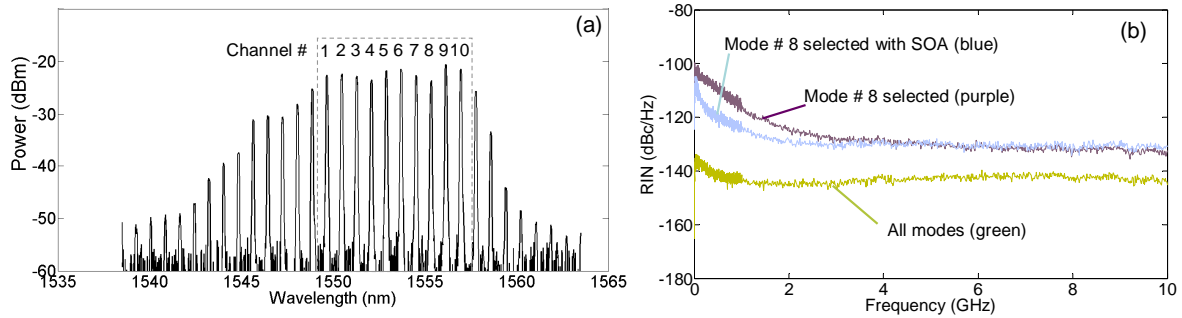


Fig.1 (a) Optical spectrum of the QD-MLL. (b) Relative intensity noise spectra of all jointly-detected modes of the QD-MLL (green), of line #8 alone (purple) and of line #8 alone after amplification by the SOA (blue).

### 3. 4x28 Gbit/s WDM transmission setup

The experimental setup is presented in Fig. 2(a). At the transmitter, the QD-MLL is protected by an isolator and its output is amplified by an erbium doped fiber amplifier (EDFA), which could, in principle, be replaced by an SOA for integration purposes. Four adjacent modes are selected with a multiport filter (corresponding to channels #7 to 10 in Fig. 1(a)). These channels include the spectral line that shows the highest intensity noise (# 8). The programmable filter transfer function consists of four flat-top passband regions spaced by 100 GHz and with 3 dB bandwidths of 60 GHz. Each channel will, in turn, have its RIN reduced by the saturated SOA and be analyzed at the end of the link. The SOA input power varied between -6 dBm and -3 dBm depending on the channel (due to lines power variations of the laser spectrum), corresponding to a gain compression comprised between 5.5 dB and 8 dB.

The four channels are then combined in odd-even pairs with two 3 dB couplers and modulated in the on-off keying (OOK) format by two Mach-Zehnder modulators (MZs), each driven by a  $2^{31}-1$  pseudo random binary sequence (PRBS) at 28 Gbit/s. Adjacent channels are modulated by a different MZ modulator and are uncorrelated. The two pairs of modulated channels are then combined together through a third 3 dB coupler. Their power is equalized using optical attenuators. The channels are then amplified before being injected into the 100 km link made of non-zero dispersion shifted fiber (NZDSF) with a chromatic dispersion of +5 ps/nm/km at 1550 nm. The power per channel is 0 dBm at the link input. Chromatic dispersion is compensated by a dispersion compensating fiber (DCF). The propagation losses are compensated by another EDFA. The channel being investigated is then selected with a 100 GHz 3 dB-bandwidth flat top filter and analyzed at the receiver.

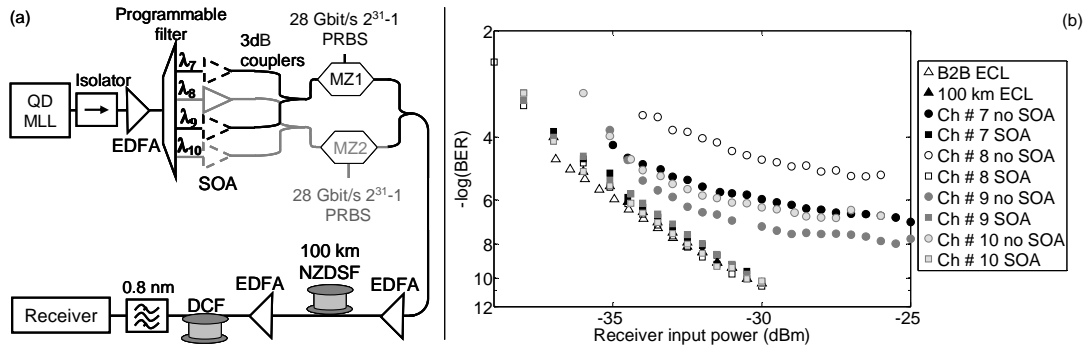


Fig.2 (a) Setup for system experiments. (b) Bit error rate as a function of receiver input power in back-to-back (B2B), after 100 km WDM transmission for channels #7, 8, 9 and 10 without the use of the SOA and with SOA.

### 4. Results

Fig. 2(b) presents the bit error rate (BER) evolution as a function of the receiver input power for different configurations. The open triangle curve is a reference curve obtained using an external cavity single mode laser (ECL) in a back-to-back (B2B) experiment (transmitter directly in front of the receiver). The full triangle curve is obtained with the ECL after 100 km transmission over the same link, showing no significant degradation. The circle curves are obtained for each investigated channel after 100 km transmission without the use of the SOA. Error floors appear between  $10^{-5}$  and  $10^{-8}$ , depending on the channel, because of the increased RIN when a single mode is selected. The square curves are those obtained after the introduction of the SOA. These curves are close to the case of the single mode laser curve, showing less than 0.5 dB penalty at a BER of  $10^{-9}$ . This shows that the RIN reduction

in the 0-4 GHz range produced by the SOA leads to penalty removal and error floor suppression in the transmission experiment, allowing the transmission of 4 WDM channels at 28 Gbit/s using a single laser.

In order to further investigate the condition of operation, the impact of the input power to the SOA on the transmission quality of channel 9 is studied next. For that, the setup presented in Fig. 2(a) is used with the SOA placed at the output of channel 9 and with a variable power in front of the SOA. The BER as a function of receiver input power is measured at different SOA input powers and the power penalty at a BER of  $10^{-9}$  is calculated with respect to the single mode laser reference after 100 km (Fig. 3). It can be observed that, at power levels higher than -7 dBm, corresponding to a gain compression larger than 5.5 dB, the transmission penalty is smaller than 1 dB. This should therefore be the SOA minimum input power condition for the RIN to be suitably reduced. As a consequence, considering a QD-MLL laser generating 10 channels and 5 dB losses in the channel demultiplexer, the required power level in front of the SOA remains compatible with the use of a single SOA as a booster stage before the demultiplexer. This makes a potential integration possible.

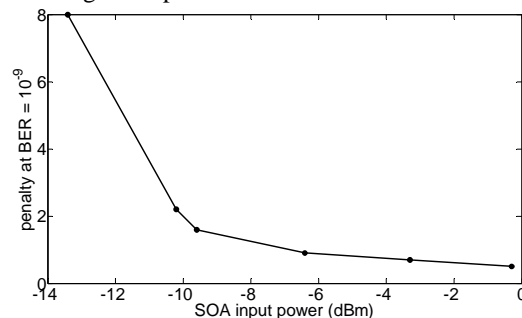


Fig.3 Penalty at a BER of  $10^{-9}$  after 100 km transmission as a function of input power to the SOA.

## 5. Conclusion

In conclusion, we have achieved for the first time the transmission of four WDM channels with 100 GHz spacing using a single QD-MLL laser followed by an SOA as a WDM transmitter. The total capacity of 112 Gbit/s was reached with 28 Gbit/s per channel modulation over a distance of 100 km. The SOA was used as a limiting amplifier for mode partition noise reduction, leading to no appreciable penalty after 100 km for all four WDM channels compared to a single mode external cavity laser. It is worth noting that the scheme could be extended to the ten modes available from this laser, thus offering a total capacity of 280 Gbit/s with a single laser. This would require using a wavelength demultiplexer instead of the 4-channel filter. This work demonstrates that the use of a single QD-MLL followed by an SOA as a WDM transmitter is a cost-effective solution for WDM passive optical networks.

## 6. Acknowledgements

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