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Quoc Thai Nguyen, Laurent Bramerie, Pascal Besnard, Alexandre Shen, Alexandre Garreau, et al.. 24 channels colorless WDM-PON with L-band 10 Gb/s downstream and C-band 2.5 Gb/s upstream using multiple-wavelengths seeding sources based on mode-locked lasers. Optical Fiber Communication conference and National Fiber Optic Engineers Conference 2010 (OFC/NFOEC 2010), Mar 2010, San Diego (CA), United States. pp.OThG6, 10.1364/OFC.2010.OThG6 . hal-00497262

HAL Id: hal-00497262

<https://hal.science/hal-00497262>

Submitted on 2 Jul 2010

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24 channels colorless WDM-PON with L-band 10 Gb/s downstream and C-band 2.5 Gb/s upstream using multiple-wavelengths seeding sources based on mode-locked lasers

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Abstract: A novel WDM-PON delivering 10-Gb/s downstream based on L-band loss-less reflective-amplified-modulator and 2.5-Gb/s upstream based on C-band injection-locked Fabry-Perot laser is experimentally demonstrated for 24 channels over 25-km, using quantum-dash mode-locked laser-based multiple-wavelengths seeding sources.

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OCIS codes: (060.0060) Fiber optics and optical communications; (250.0250) Optoelectronics; (060.4250) Networks

1. Introduction

To meet the bandwidth demand due to the exponential growth of broadband services, wavelength-division-multiplexed passive optical network (WDM-PON) will be one of the most efficient candidates for the next-generation access network [1]. However, the main challenges when deploying this technology in access network consist in the cost and the wavelength-assignment problem of WDM transmitters. Typical low-cost solutions are based on the use of reflective semiconductor optical amplifiers (RSOA) [2] or Fabry-Perot laser diodes (FP-LD) [3] externally injected by a spectrum-sliced amplified spontaneous emission (ASE). But the data rate of these solutions is limited to only 1 Gb/s due to the high intensity noise of ASE source. To upgrade to 10 Gb/s, several expensive solutions are used, such as tunable lasers or external modulation of individual single-mode lasers.

During the last years, many investigations have been carried out with quantum-dash mode-locked lasers (QD-MLL) due to their remarkable properties [4]. Particularly, it can be used as a wavelength comb for WDM source [5]. Taking these advantages for WDM-PON, we propose a cost-effective solution for WDM transmitters. This solution is based on the use of two QD-MLL operating in the C and L bands as multiple-wavelengths seeding sources for colorless components. The colorless component used for downstream (DS) is based on a loss-less reflective amplified modulator (RAM) operating at 10 Gb/s in L-band, which is an integrated R-EAM-SOA [6], while the one for upstream (US) is based on an injection-locked Fabry-Perot laser (IL-FP) directly modulated at 2.5 Gb/s in C-band [7]. This integrated solution presents great advantages: a low intensity-noise compared to the spectrum-sliced ASE source and a low cost compared to the use of multiples single-mode lasers. The architecture of proposed WDM-PON system is firstly described. Then, the intensity noise properties as well as the performances of QD-MLL-injected colorless components are performed. Finally, we assess the feasibility of such a proposal for the bidirectional transmission of 24 WDM channels over 25km SMF fiber in a WDM-PON configuration.

2. WDM-PON architecture proposal

The bidirectional WDM-PON architecture with 24 channels is shown in fig. 1. The 10Gb/s L-band RAM are used as colorless transmitters for DS and 2.5 Gb/s C-band IL-FP are used for US. These colorless transmitters are seeded by two multiple-wavelength sources, which are based on two QD-MLL, optically amplified in order to reach a sufficient power for each individual mode used in the optical injection process. The wavelength comb of QD-MLL must match the channels of the AWG so that each individual mode of QD-MLL is selected by a channel of AWG. The C/L band separators / combiners are used at the Central Office (CO) and the Remote Node (RN) to separate/recombine the DS and US signals.

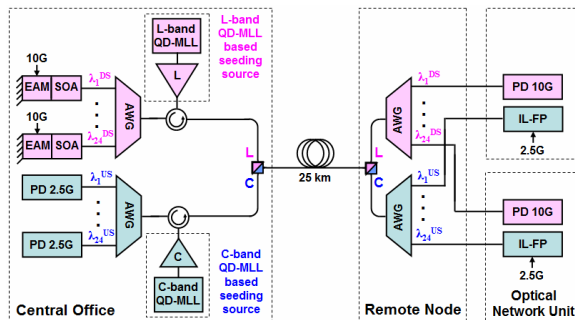


Fig. 1. Proposed bidirectional WDM-PON architecture

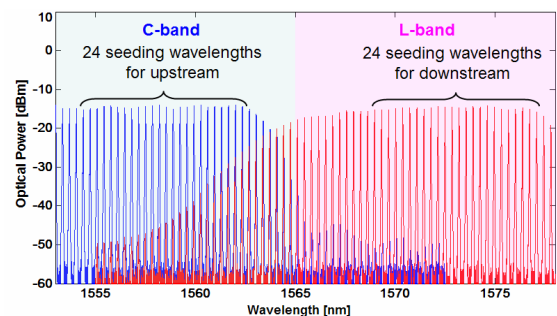


Fig. 2. Optical spectra of C and L band QD-MLL

The wide and flat optical spectra of C and L band QD-MLL are shown in fig. 2. The 6 QD layers InAs/InP-based QD-MLL are mode-locked at a frequency of 42.7 GHz (corresponding to the free spectral range (FSR)). Hence, we use the tunable array waveguide gratings (AWG) to match their channels with the modes of QD-MLL. For practical applications, the mode spacing of QD-MLL compatible to the standardized ITU channel spacing can be obtained by optimizing the cavity length of the laser [5]. From these optical spectra, we chose 24 modes of L-band QD-MLL ranging from 1568 nm to 1577.1 nm for seeding wavelengths in DS and 24 ones of C-band QD-MLL ranging from 1554.05 nm to 1562 nm in US. These two bands are separated by a guard band of 6 nm.

3. QD-MLL-injected colorless components

The RAM is an integrated R-EAM-SOA with a 70 μm EAM section and a 400 μm SOA section, which are separated by a 150 μm passive section [6]. The gain of RAM is about 10 dB on chip. However, due to a coupling loss of 5 dB, the gain of this component is cancelled to nearly 0 dB. The next generation of this component, which is under process, has an improved design and fabrication in order to obtain a higher gain. The FP LD in this experiment is specially designed with two sections: a gain section and a birefringence compensation section [7]. This design aims to reduce the polarization dependence of the injection-locking mechanism thanks to the superimposition of TE and TM modes.

Generally, the relative intensity noise (RIN) of QD-MLL is very low thanks to its small ASE ratio [4]. However, a main drawback when using the wavelength comb of this laser as a WDM source is the increase of RIN of an individual mode due to mode partition noise [5], particularly in the low frequency part as shown in fig. 3(a) and fig. 4(a). To overcome this limitation, the seeding signal (from an individual mode of QD-MLL) that is injected into the RAM is fixed at high power (around -3 dBm, i.e. -8dBm on the chip) in order to achieve the noise reduction in the low frequency region thanks to the gain saturation of the SOA section [8]. Fig. 3(a) shows that the noise reduction is more significant at higher injected power (these injected power do not take into account the 5 dB coupling loss, thus the optical powers injected into the chip are -11dBm, -8dBm and -2dBm respectively). In the case of IL-FP, a strong noise reduction is observed thanks to the injection-locking mechanism in FP LD. This can be explained by the fact that the FP LD is forced to a new lasing regime (a single-frequency regime) under injection-locking. The eye diagrams of RAM at 10 Gb/s and of IL-FP at 2.5Gb/s are inset in fig. 3 and fig. 4 respectively. We find that the eye diagrams when injected by one individual mode of QD-MLL are quite comparable to those obtained in the case when using a low noise external cavity laser (ECL) as the seeding source. These comparisons were performed in the same injection conditions: -3 dBm at 1571 nm in the case of RAM and -5 dBm at 1557 nm in the case of IL-FP.

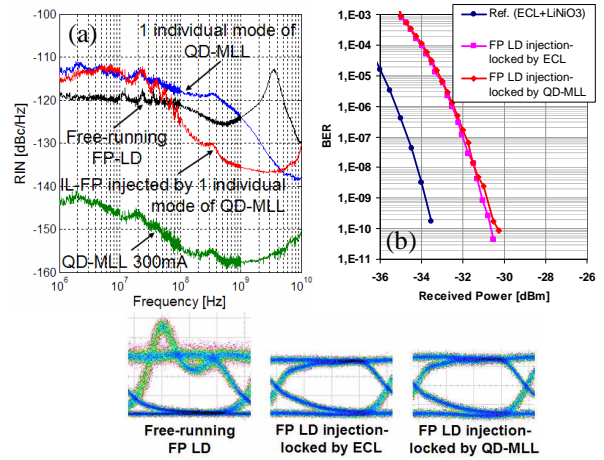
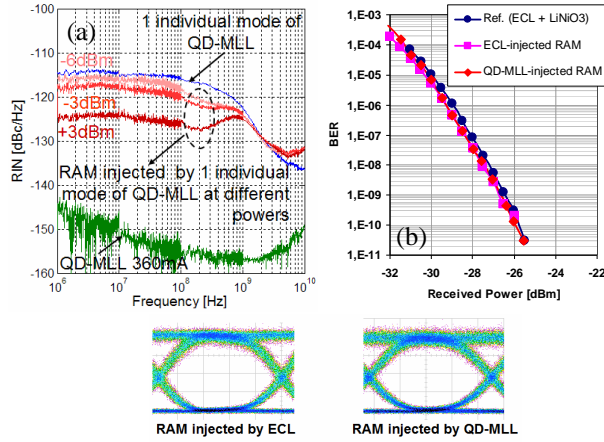


Fig. 3. Intensity noise properties (a) and performances (b) of RAM. Fig. 4. Intensity noise properties (a) and performances (b) of IL-FP. The performances in back-to-back (BTB) configuration of RAM and of IL-FP are shown in fig. 3(b) and fig. 4(b) respectively. We compare their performances when injected by one individual mode of QD-MLL with those when injected by an ECL. For both components, the performances are perfectly the same between QD-MLL-injection and ECL-injection: a sensitivity of -26.5 dBm at 10 Gb/s for RAM and of -31dBm at 2.5Gb/s for IL-FP is found. These results show that the multiple-wavelengths seeding source based on QD-MLL is well suitable as seeding source for colorless WDM-PON architecture up to 10 Gb/s.

4. WDM-PON experiment and results

Fig. 5 presents the experimental setup used for DS and US transmission in a WDM-PON configuration based on the proposed colorless components solution. The transmission medium consists of 25 km SMF fiber. In the CO, a 360 mA-biased L-band QD-MLL amplified by an erbium doped fiber amplifier (EDFA) with 20 dBm output power in the L-band is used to provide the multiple-wavelengths injection source for RAM in DS, while in the C-band, a 300 mA-biased QD-MLL associated to an 20 dBm EDFA are used for IL-FP in US. As mentioned above, since the FSR of QD-MLL (42.7 GHz) is not compatible to the standardized channel spacing, the tunable AWG in use here are adjusted to fit the selected modes of QD-MLL. In these operating conditions, the bandwidth at -3 dB of each AWG channel is round 0.23nm. Thus, an individual mode of QD-MLL selected by a channel of AWG has a side mode suppression ratio (SMSR) of 35 dB.

For DS transmission, the optical power of each individual mode of QD-MLL injected into the RAM is about -3 dBm (thus ~ -8 dBm inside the chip). Due to the loss of AWG and circulator, the power DS signal is around -9 dBm at the output of the port 3 of the circulator. The SOA section of RAM is polarized at 160 mA. Its EAM section is biased at -1.5 V, modulated with a 4 Vpp amplitude and $2^{31}-1$ PRBS at 10 Gb/s. The DS signal is reached by an APD at the optical network unit (ONU). For US transmission, the seeding source propagates on 25 km fiber before injecting into the FP LD at the ONU. Thus, the injected power in the FP LD is as low as -10 dBm. However, the injection-locking is still maintained at this injected power. The FP LD is biased at 65 mA and has an output power of 2 dBm under optical injection. It is directly modulated with a 2 Vpp amplitude and $2^{31}-1$ PRBS at 2.5 Gb/s. The US signal propagates on the same 25 km fiber with the seeding signal and reached by an APD at the CO.

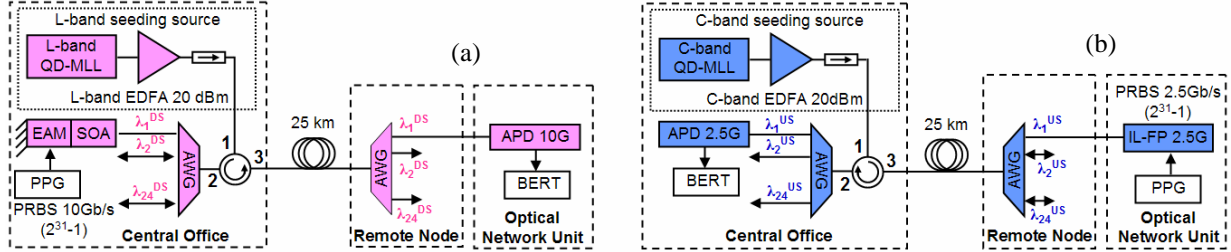


Fig. 5. Experimental setup for DS (a) and US (b) WDM-PON transmission.

The performance of 10 Gb/s DS and 2.5 Gb/s US are shown in fig. 6(a) and fig. 6(b) respectively. For clarity, we only show 4 chosen channels (Ch01, Ch08, Ch16, Ch24) among 24 WDM channels. Error-free (BER < 1E-9) is achieved for all these channels for both DS and US. A power penalty of 1.5 dB at BER of 1E-9 is observed for 25 km transmission of 10 Gb/s DS signal and a sensitivity of -24 dBm in the worst case is found for these channels, which allows an optical budget of 21 dB to be achieved (because of -3 dBm at the RAM output). This optical budget can be improved when using an L-band EDFA with higher output power in the seeding source. For 2.5 Gb/s US transmission, a sensitivity of -29 dBm is obtained in the worst case, which corresponds to an optical budget of 31 dB. A power penalty of 2 dB at BER of 1E-9 and an error floor between 1E-9 and 1E-10 are observed. This degradation is due to the contribution of Rayleigh backscattering of 25 km fiber which is a noise source at the detection.

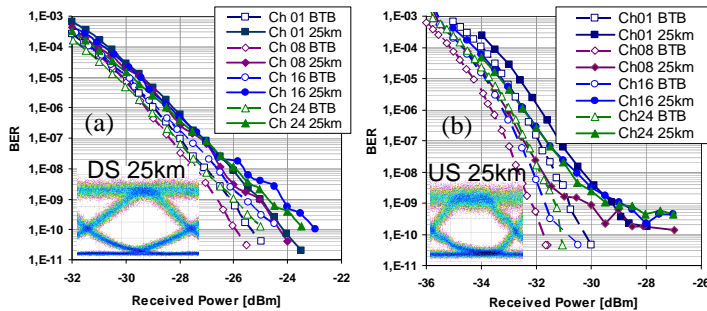


Fig. 6. BER measurement results for 10 Gb/s DS (a) and 2.5 Gb/s US (b) transmissions

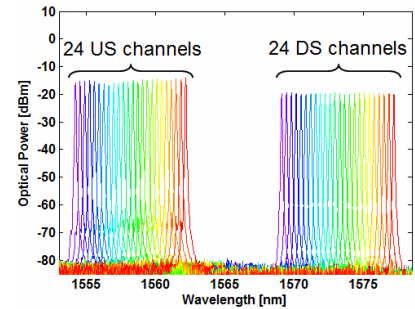


Fig. 7. Wavelength allocation of proposed WDM-PON

Fig. 7 shows the wavelength allocation of proposed WDM-PON system. The optical spectrum is measured channel by channel. Since each channel is filtered two times by AWG, the SMSR at the reception is very high.

5. Conclusion

We proposed and experimentally demonstrated the feasibility of a cost-effective transmitter solution for high capacity WDM-PON. This solution is based on the use of reflective colorless components (loss-less RAM and IL-FP) combined with the low-cost multiples wavelength seeding source based on QD-MLL. A total of 240 Gb/s (24x10Gb/s) capacity for DS and 60 Gb/s (24x2.5 Gb/s) for US are successfully transmitted error-free in a WDM-PON configuration with 25 km reach, supporting an optical budget of 21 dB. The future work will be carried out to improve the performance of colorless components, particularly to increase the gain of RAM and the data rate of IL-FP. With this improvement, this novel concept would be very promising for cost-effective and high capacity optical access network.

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