30 Gbit/s downstream capacity of cost-effective colourless WDM-PON based on injection-locked Fabry-Pérot lasers

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Q. T. Nguyen, P. Besnard, L. Bramerie, J.-C. Simon, A. Shen, G.H. Duan and C. Kazmierski

A 100 GHz spaced comb, generated by a quantum dash passively mode-locked laser (QD-MLL), is used as a low-noise coherent seeding source for colorless wavelength-division-multiplexed passive optical network (WDM-PON) based on injection-locked Fabry-Perot laser diodes (IL-FP). Error-free downstream transmission over 25 km single-mode fiber (SMF) of 12 WDM channels at 2.5 Gbit/s with 100 GHz channel spacing is experimentally demonstrated.

Introduction: WDM-PON has been demonstrated as one of the most promising candidates for the future broadband access network [1]. However, the most critical issues for practical deployment are the network complexity and its subsequent cost. To overcome this problem, several recent solutions [2][3] have been proposed to implement WDM-PON using low-cost transmitters. These solutions are typically based on spectral slicing of the light output from a broadband incoherent source such as a supercontinuum or an amplified spontaneous emission (ASE) combined with IL-FP [2] or reflective semiconductor optical amplifier (RSOA) [3]. However, the performance of such solutions is limited to 1.25 Gbit/s due to the high intensity noise of spectrum-sliced source (around -105 dBc/Hz) even if the bandwidths of IL-FP and RSOA are higher.

In order to mitigate this limitation, we propose in this letter a novel colorless transmitter solution for WDM-PON. A Fabry-Perot laser diode (FP LD), which is directly modulated at 2.5 Gbit/s, is injection-locked by a single QD-MLL. The FP LD is designed to be polarization-insensitive when it is injection-locked, while the QD-MLL acts as 100 GHz comb generator. The feasibility of such a solution for WDM-PON downstream transmission is assessed for 12 channels over 25 km SMF in the C-band.

Proposed colorless transmitter solution: WDM light source using comb generation by a QD-MLL is attractive because it offers several features such as: low-noise, high thermal stability and broad gain spectrum [4]. Given such advantages, we propose to combine a 100 GHz spaced comb of a QD-MLL with an array waveguide grating (AWG) in a WDM-PON system. The QD-MLL provides a multi-wavelength coherent source that injection-locks the FP LDs used as colorless transmitters.

Our InAs/InP based QD-MLL is cleaved to have a length of 420 µm to achieve a mode spacing of 100 GHz [5]. A wide and nearly flat optical spectrum of this laser is shown in Fig. 1a. Fig. 1b gives the optical spectrum of the IL-FP and of the individual mode of the optically-amplified QD-MLL selected by AWG and used for optical injection. Under injection, the IL-FP is single-mode with a side mode suppression ratio (SMSR) higher than 30 dB.

For a conventional FP LD, the injection-locking by a coherent source strongly depends on the polarization state of the injected signal. To overcome this problem, our FP LD is designed with two sections. The first one is grown to have an active area with a polarization insensitive gain. The second one, which is made of strained InGaAsP material, is used for birefringence compensation [6]. As a result, the polarization state of the output radiation from this FP LD is a combination of TE and TM eigen modes. The optical spectra of these eigen modes are superposed. Consequently, the dependency of injection-locking on the polarization state of the injected signal is attenuated. In our case, when the second section is biased at a current higher than its threshold (around 10 mA), the two families TE and TM are quasi-superposed within the full spectral range from 1545 nm to 1565 nm. However, the polarization-insensitivity is not completely reached since there is usually a slightly different gain between TE and TM modes, which gives rise to small variations on the “1” level of the modulated signal.

One major drawback of using a comb generated by MLL as a WDM light source is the important relative intensity noise (RIN) brought by one individual mode through mode partition noise [5][7], when this noise is compared to single-frequency DFB laser. The RIN is about -110 dBc/Hz at low frequency, as shown in Fig. 1c. Fortunately, this RIN level can be strongly reduced thanks to the injection-locking mechanism in FP LD. Fig. 1c clearly shows that the RIN of IL-FP is lower than the free-running FP LD. These RIN measurements can explain the difference between eye diagrams of the signal from the free-running FP LD and the eye diagrams of the signal from the 2.5 Gbit/s directly modulated IL-FP. As observed in Fig. 1d in the eye diagram of IL-FP, noise-reduction and suppression of relaxation oscillations are obtained thanks to optical injection.

Experimental demonstration and results: The experimental setup is shown in Fig. 2. In the Central Office, a 300 mA biased QD-MLL is used as a multi-wavelength seeding source. The output signal of this QD-MLL is then amplified via an erbium doped fiber amplifier (EDFA) to get a sufficient power level for each individual mode in order to achieve injection-locking operation of the FP LD. The tunable AWG with 100 GHz channel spacing is then adjusted so that the wavelength of its channels matches that of the QD-MLL modes. 12 modes, available within the 3 dB optical bandwidth of the QD-MLL, are chosen for the 12 WDM channels in the range from 1544.41 nm to 1564.38 nm. The seeding signal passes through a circulator and is then injected into the common port of the AWG. Each output port of the AWG selects an individual mode. They are characterized by a SMSR about 35 dB and offers a power around –5 dBm for the optical injection. The IL-FP was biased at a current of 75 mA for the gain section, and was then directly modulated with a 2Vpp amplitude and 2^{15}-1 PRBS at 2.5 Gbit/s. As previously explained, the bias current of the second section is chosen up to 100 mA, so that optimal wavelength detuning and birefringence compensation, i.e. a maximum injection-locking efficiency, is obtained. At these currents, the optical output-power of the IL-FP is around 3 dBm. The optical signals of IL-FPs are multiplexed by an AWG before propagating inside the optical fiber towards the ONUs (Optical Network Units). The upper-right insert of Fig. 2 gives the spectrum of the 12 selected WDM channels obtained by injection-locking of FP LDs. The transmission medium consists of 20 km of feeder fiber and 5 km of drop fiber. At the remote node, the different WDM channels are separated by a second tunable 100 GHz channel spaced AWG, which is adjusted like the first one. At the ONU, the downstream signal was directly detected by a commercial PIN receiver having 2.5 GHz bandwidth. For this proposed WDM-PON configuration, the total optical budget on the link is 20 dB.

In fig. 3a, typical bit-error-rate (BER) measurements versus the received power are given for back-to-back (BTB) and for downstream transmission over 25 km SMF. For clarity, only 4 WDM channels out of 12 are shown. Error-free transmission is achieved for all of these channels. The maximum power penalty is 0.5 dB. The receiver sensitivity is lower than -19 dBm. It is compared with a reference, which is measured using a low-noise tunable external cavity laser, modulated at 2.5 Gbit/s by a LiNbO3 modulator. A 3 dB difference in sensitivity is measured in BTB configuration. This is due to the higher RIN of the QD-MLL compared to ECL and to the lower extinction ratio compared to LiNbO3 modulator. The sensitivities and penalties at 10^{-9} BER for the 12 WDM channels are dressed in Fig. 3b. These results show a good homogeneity in performances of the 12 channels. An average penalty of 0.3 dB and an average sensitivity of -19.5 dBm are found. Since the output power of IL-FP is 3 dBm, the WDM-PON system can support an optical budget higher than 20 dB.

Conclusion and perspective: We have experimentally demonstrated for the first time a cost-effective approach by using an ITU-grids compatible comb generated by a QD-MLL. This QD-MLL is used as a low-noise, coherent multi-wavelength seeding source for IL-FP based colorless transmitters in WDM-

PON system. Error-free downstream transmission has been obtained at 2.5 Gbit/s over 25 km for 12 channels with 100 GHz channel spacing in C-band. Future work will investigate the possibility to increase the locking sensitivity of IL-FP, in order to apply such a solution for upstream transmission and the possibility to equalize the gain of TE and TM modes in order to achieve a complete polarization-insensitivity. This proposed solution paves the way for low-cost realization of future WDM-PON system with performance beyond 1 Gbit/s.

References

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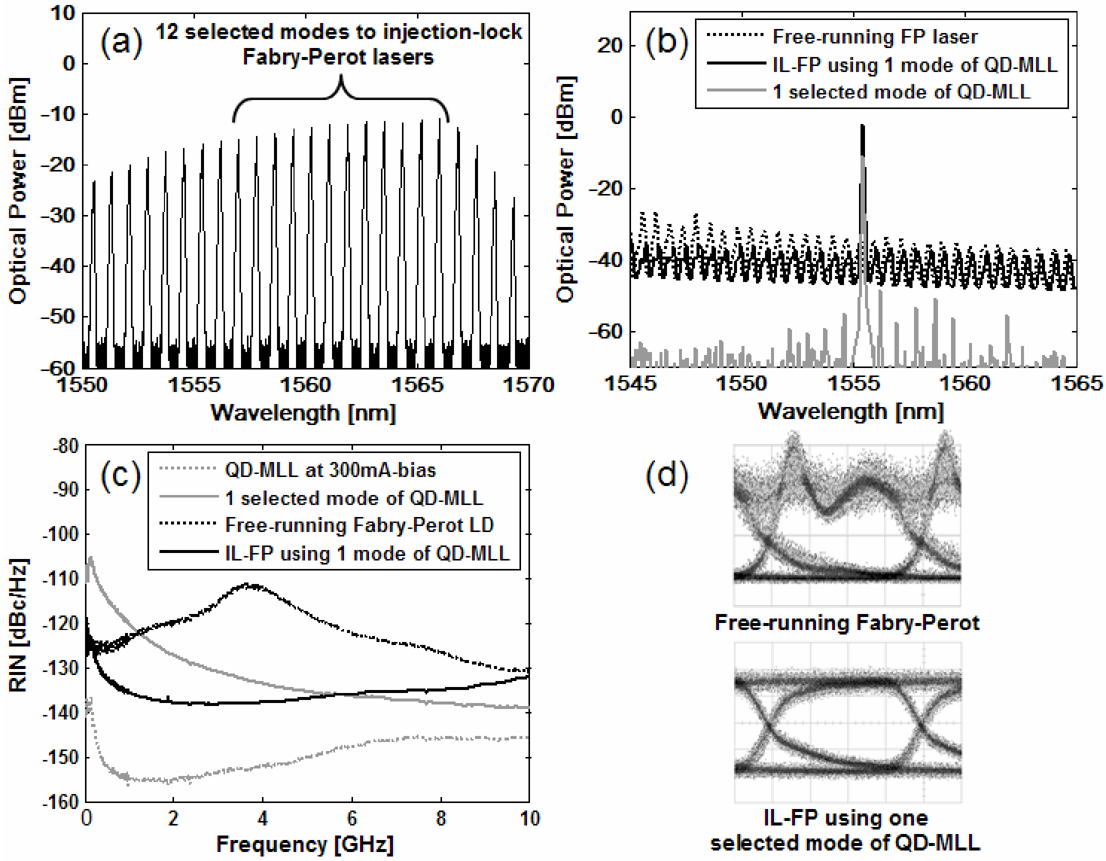
Figure captions:

Fig. 1 Optical spectra (a, b), intensity noise measurements (c) and eye diagrams at 2.5 Gbit/s modulation (d).

Fig. 2 Experimental setup for WDM-PON downstream transmission. Inset : Optical spectra of 12 WDM channels by injection-locking of FP lasers.

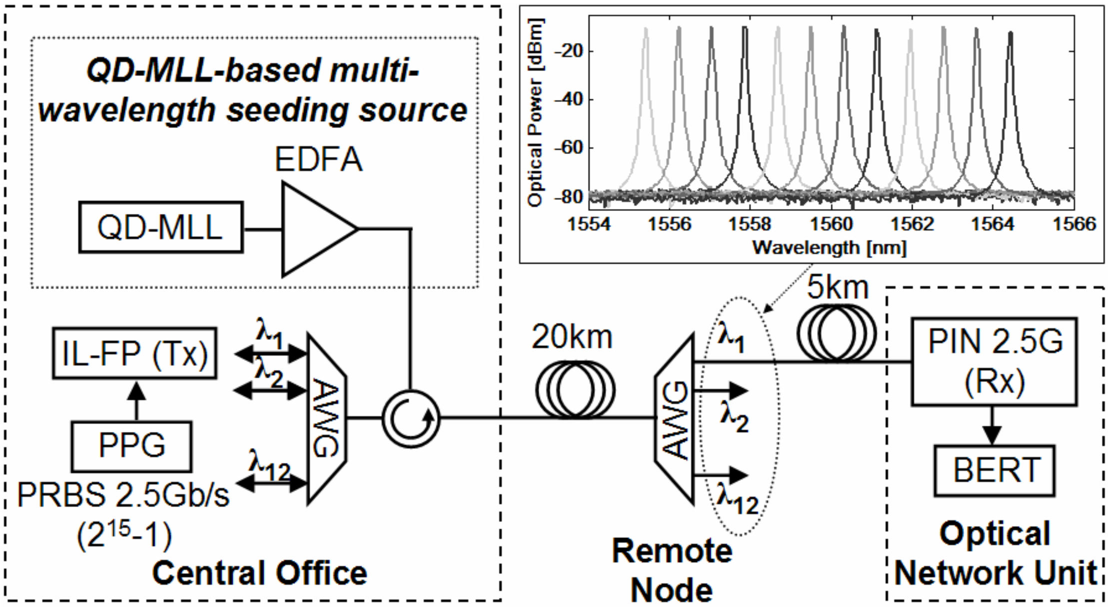
Fig. 3 BER measurements (a), receiver sensitivity and power penalty at 10^{-9} of 12 channels for 25 km (b).

Figure 1



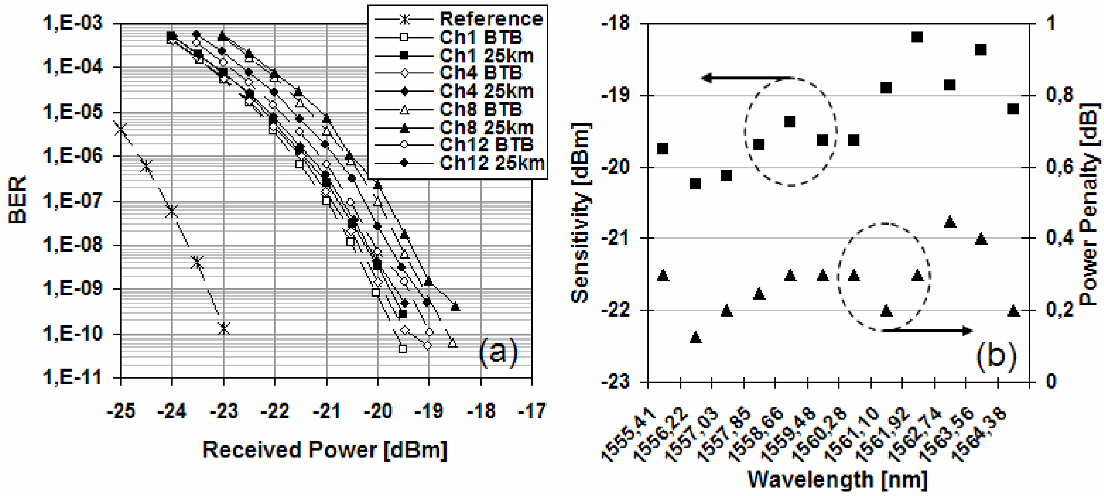
(a)
12 selected modes to injection-lock Fabry-Perot lasers
Optical Power [dBm]
Wavelength [nm]
(b)
Free-running FP laser
IL-FP using 1 mode of QD-MLL
1 selected mode of QD-MLL
Optical Power [dBm]
Wavelength [nm]
(c)
QD-MLL at 300mA-bias
1 selected mode of QD-MLL
Free-running Fabry-Perot LD
IL-FP using 1 mode of QD-MLL
RIN [dBc/Hz]
Frequency [GHz]
(d)
Free-running Fabry-Perot
IL-FP using one selected mode of QD-MLL

Figure 2



QD-MLL-based multi-wavelength seeding source
EDFA
QD-MLL
IL-FP (Tx)
PPG
PRBS 2.5Gb/s
(2^15-1)
λ1
λ2
λ12
AWG
Central Office
20km
AWG
λ1
λ2
λ12
Remote Node
5km
PIN 2.5G
(Rx)
BERT
Optical Network Unit
Optical Power [dBm]
-20
-40
-60
-80
1554
1556
1558
1560
1562
1564
1566
Wavelength [nm]

Figure 3



1,E-03
1,E-04
1,E-05
1,E-06
1,E-07
1,E-08
1,E-09
1,E-10
1,E-11
BER
-25 -24 -23 -22 -21 -20 -19 -18 -17
Received Power [dBm]
Reference
Ch1 BTB
Ch1 25km
Ch4 BTB
Ch4 25km
Ch8 BTB
Ch8 25km
Ch12 BTB
Ch12 25km
(a)
-18
-19
-20
-21
-22
-23
Sensitivity [dBm]
1
0,8
0,6
0,4
0,2
0
Power Penalty [dB]
1555,41
1556,22
1557,03
1557,85
1558,66
1559,48
1560,28
1561,10
1561,92
1562,74
1563,56
1564,38
Wavelength [nm]
(b)