100 Gb/s Single Channel Transmission Using Injection-Locked 1621 nm Quantum-Dash Laser

M. Talal A. Khan, E. Alkhazraji, Amr M. Ragheb, H. Fathallah, *Senior Member, IEEE*,
K. K. Qureshi, *Senior Member, IEEE*, S. Alshebeili, and M. Z. M. Khan, *Member, IEEE*

***Abstract*— A single channel 100 Gb/s dual–polarization quadrature phase shift keying transmission based on injection-locked broadband quantum-dash Fabry–Pérot laser, and employing external modulation, has been demonstrated. By employing a far L–band ∼1621-nm sub-carrier, −17.4-dBm sensitivity at the bit error rate 3.8×10^{-3} has been obtained after 10 km standard single mode fiber transmission. Besides, an injection locked mode wavelength tunability of ∼23 nm, which translates to ∼50 sub-carriers, is accomplished. These results favor the viability of deploying broadband quantum-dash lasers as unified upstream and downstream transmitters in next generation wavelength division multiplexed-based passive optical networks.**

***Index Terms*— Quantum dash lasers, injection locking, broadband lasers, passive optical networks.**

I. INTRODUCTION

THE explosive increase in the demand for high speed internet and mobile connectivity at the user end, driven recently by existing wavelength division multiplexing (WDM) based optical access networks, will soon experience difficulties meeting up with the extraordinary increase in the transmission capacity in near future [1], [2]. The next generation passive optical networks (NG-PON) solutions such as 100Gbit-PON has been considered as a promising solution for ever-increasing number of subscribers and their broad-band services demand [3]. Besides, this trend dictates a need in the expansion of upstream and downstream transmission window beyond the current C– and near L– bands (<∼1610 nm) which is leveraging on low optical fiber attenuation and amplification opportunity, to achieve cost effective and upgrade flexibility PON [1], [5]. Indeed, the recently proposed colorless PON to realize wavelength independent communication, by employing spectrum sliced and injection locked transmitters is garnering attention. Furthermore, semiconductor optical amplifiers (SOA) [3], [6], Fabry-Perot laser diodes (FP-LD) [7] and weak-resonant-cavity laser diode (WRC-FPLD) [8] based transmitters has appeared to be promising candidates compared to costly externally tunable lasers and distributed feedback (DFB) or distributed Bragg reflector (DBR) lasers [9]. However, directly modulated SOAs are found to be limited by transmission capacity with a maximum of 25 Gb/s transmission over 120 km single mode fiber (SMF) [3]. On the other hand, conventional FP-LDs are typically narrow band and limits on the number of subscribers in PONs and bulk production of transceivers in optical network units (ONUs).

Hence, a unified transmitter exhibiting all these essential requirements is decisive for mass deployment. In this respect, various reports are available in literature with regards to the FP-LD wavelength tunability [10]–[13]. For instance, very recent 20 Gb/s 16-QAM OFDM upstream transmission over 25 km using directly modulated WRC-FP LD is demonstrated, which is capable of ∼26 nm (∼13 nm) C–band (L–band) wavelength tunability (*i.e.* ∼25–30 sub-carriers) via low power optical injection [10], [11]. A directly modulated 2.5 Gb/s ONU transmitter based on antireflection coated Fabry-Perot laser amplifier (AR-FPLA) is reported with a wavelength tunability of 30 nm in C–band encompassing 25 channels [12]. Likewise, a polarization insensitive FP-LDs with ∼35 nm C–band tunability (i.e. ∼17 sub-carriers) and 2.5 Gb/s ON-OFF keying direct modulation is reported over 25 km fiber by injection locking (IL) scheme [14]. In this case, a multi-wavelength mode locked laser diode based on quantum dash (Qdash) active region, whose optical transition are widely tunable from S– to U–band [15], is employed as a coherent seeding source at the central office (CO) for down transmission. In general, most of the reported works exploit direct modulation scheme for simple and cost-effective Gigabit-PONs, nonetheless the bandwidth will be limited by the fundamental properties of the transmitter light source active region (*i.e.* carrier dynamics) which could pose a bottleneck for next generation 100Gbit-PONs, which has been standardized, and 400Gbit-PONs, which is under consideration.

In this letter, we propose and demonstrate 100 Gb/s dual polarization quadrature phase shift keying (DP-QPSK)

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M. T. A. Khan and M. Z. M. Khan are with the Optoelectronics Research Laboratory, Electrical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia (e-mail: g201409540@kfupm.edu.sa; zahedmk@kfupm.edu.sa).

E. Alkhazraji was with the Optoelectronics Research Laboratory, Electrical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia. He is now with the Electrical and Electronic Engineering Technology Department, Jubail Industrial College, Jubail 35718, Saudi Arabia (e-mail: alkhazraji_e@jic.edu.sa).

A. M. Ragheb is with the KACST-TIC in Radio Frequency and Photonics for the e-Society (RFTONICS), Riyadh 12372, Saudi Arabia (e-mail: aragheb@ksu.edu.sa).

H. Fathallah is with the Electrical Engineering Department, King Saud University, KACST-TIC in RFTONICS, Riyadh 12372, Saudi Arabia, and also with the Computer Department of the College of Science of Bizerte, Carthage University, Tunis 1054, Tunisia (e-mail: habib.fathallah@gmail.com).

K. K. Qureshi is with the Electrical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia (e-mail: kqureshi@kfupm.edu.sa).

S. Alshebeili is with the Electrical Engineering Department, King Saud University, and also with the KACST-TIC in RFTONICS, Riyadh 12372, Saudi Arabia (e-mail: dsaleh@ksu.edu.sa).

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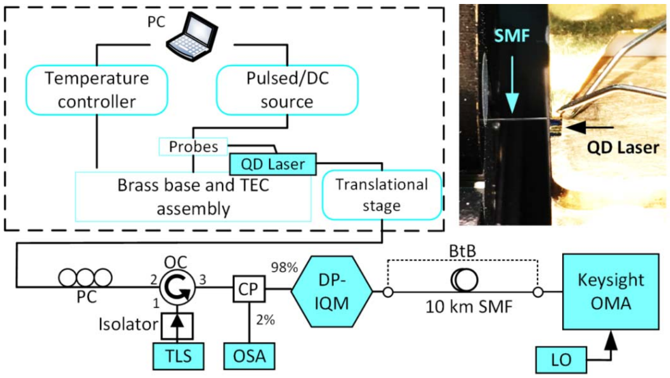

Fig. 1. Experimental setup of 100 Gb/s DP-QPSK WDM transmission via injection locked Qdash FP-LD. The signal transmission is characterized first in a back-to-back (BtB) configuration and then over a 10 km single mode fiber (SMF). Inset: Bare Qdash FP-LD power coupled to a lensed SMF.

externally modulated traffic rate by injection-locked broadband Qdash FP-LD in L–band. Bit error rate (BER) achievement of below forward-error-correction (FEC) limit, after 10 km SMF transmission, stems the potential of this light source as a unified transmitter in next-generation WDM-PONs. Moreover, the Qdash FP-LD, which is an L– and U–band transmitter, is capable of wavelength tuning from ∼1611 to ∼1634 nm (∼23 nm) via optical injection, thus encompassing ∼50 longitudinal modes or sub-carriers. To the best of our knowledge, this is the first demonstration of engaging Qdash FP-LD as a cohesive transmitter capable of providing 100 Gb/s transmission service in the far L–band and lower part of U–band, to each user, without signal amplification.

II. INJECTION LOCKED CHIRPED QUANTUM-DASH LASER

The L– and U– band laser diode used in this work was grown by molecular beam epitaxy (MBE) over n-type InP substrate. The active region consists of four-stack of InAs/InGaAlAs Qdash-in-a-well structure with each layer separated by varying barrier thickness of 10, 15, and 20 nm. This intentionally inhomogeneous active region essentially broadens the gain spectrum and hence resulted in an ultra-broadband stimulated emission with −3dB bandwidth spanning ∼50 nm with ∼80 mW single facet power, under pulsed injection current operation. More details of device growth, fabrication, and characterization can be found elsewhere [16]. In this experiment, a bare 4 × 800 μm^2 ridge-waveguide Qdash FP-LD (QD-LD) is utilized and mounted on a brass base with p-side up configuration. For injection locking characterization and communication experiment, the single laser facet optical power is coupled into a lensed SMF, as illustrated in the inset of Fig. 1. The fiber end *L-I-V* characteristics under continuous wave (CW) operation, and at 14°C, is shown in Fig. 2, alongside the free running lasing spectrum. The longitudinal mode spacing and threshold current are 0.35 nm (40 GHz) and 100 mA, respectively. An optical power up to ∼1.0 mW (∼0 dBm) is measured at 250 mA with ∼10 nm lasing bandwidth before roll off, centered at ∼1625 nm. This degradation in the laser performance compared to pulsed current operation is expected since the device active region design is not optimized. With proper growth optimization, the laser performance could be substantially improved, and would be comparable to the pulsed operation [16].

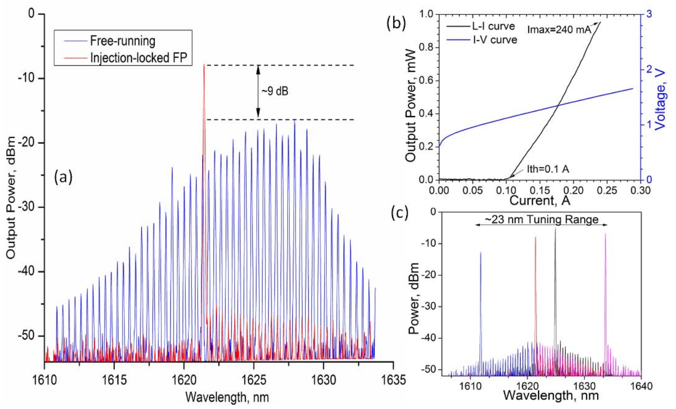

Fig. 2. (a) Qdash laser characteristics under free running mode and injection locked mode, (b) L-I -V characteristic of free running Qdash laser, measured at the SMF end, and (c) Tuning range (1611.8-1633.7 nm) of injection-locked modes of a Qdash laser at different wavelengths, and at a fixed CW external injection of 5 dBm.

A tunable master laser source (TLS) CW injection light, fixed at 5 dBm external injection power (i.e. 5 dBm injection ratio at the SMF end), is transmitted through an isolator to an optical circulator (OC) and polarization controller (PC), and into the QD-LD, as depicted in Fig. 1. Isolator and PC are used to protect the TLS and improve the IL efficiency, respectively. The output spectra of the injection-locked QD-LD is observed at the 2% output of a 2/98 optical coupler (CP) using optical spectrum analyzer (OSA) with a 0.06 nm resolution. The QD-LD is biased at 240 mA and Fig. 2 (a) shows the optical spectrum without TLS injection and with injection when tuned to lock at ∼1621 nm longitudinal mode with ∼ ±10 pm locking range. The measured single mode output power and side-mode suppression ratio (SMSR) are −7.8 dBm and 38 dB, respectively. In addition, a 9 dB gain is exhibited by IL besides reducing the phase noise [6]. Next, the tunability experiment of the QD-LD is performed by fixing the CW injection power at 5 dBm and launching into each longitudinal mode of the QD-LD at different TLS wavelengths. The results are plotted in Fig. 2 (c) which shows a wavelength tunability of ∼23 nm from ∼1611 nm to ∼1634, thus encompassing ∼50 sub-carriers to which QD-LD can be injection locked, if deployed in WDM-PON. It is worth to be noted that the SMSR of each of the IL mode could be unified by varying the injection power besides changing the TLS wavelengths. This would ensure similar transmission performance from each IL mode, when utilized in WDM PONs. Moreover, an improved QD-LD optical power (by optimized device design and packaging) would enable working at lower current bias point which might help in lowering down the CW injection power and improve the locking range, by reducing the reflections between the facets [10], [11], [17].

III. 100 GB/S DP-QPSK TRANSMISSION EXPERIMENT

The latter blocks of Fig. 1 represent the data transmission experimental setup. Once, the QD-LD is injection locked, the selected sub-carrier with mode power −5dBm is fed to

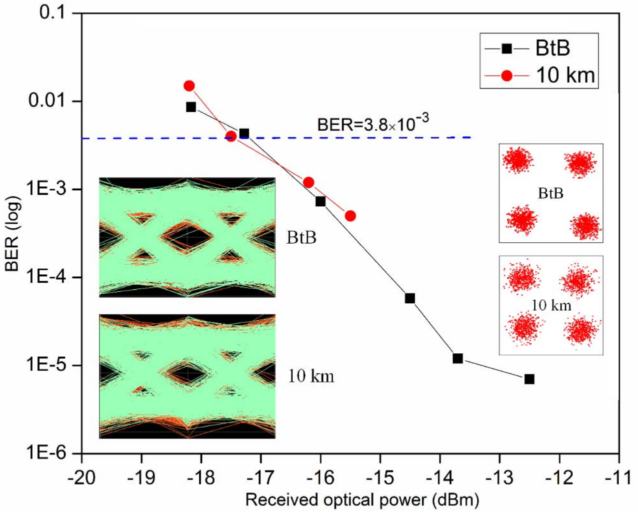

Fig. 3. Bit error rate as a function of received optical power for 100 Gbit/s after 10 km SMF transmission Insets: Eye diagrams and constellation diagrams of 100 Gbit/s data rate for BTB and over 10 km transmission.

the dual polarization IQ (DP-IQ) modulator (with ∼10 dB insertion loss) via the 98% output of the CP and modulated with DP-QPSK scheme at 16 and 25 Gbaud. Pre-processing of the signal was performed using Matlab by generating a pseudo random binary sequence (PRBS) with a length of $2^{11} - 1$ and mapped into QPSK constellation by an arbitrary wave generator (Keysight AWG M8195A). A sampling rate of 64 GSa/s is used to generate four channels multi-level signal, two channel for individual polarization, employed as a digital to analog converter (DAC). The output of four signals are driven, through a four channels linear amplifier of 20 dB gain over 32GHz flat bandwidth, into the four RF inputs of DP-IQ modulator. Then, we used Keysight optical modulation analyzer (OMA-N4391A) for further analysis and detection. The signal transmission is characterized first in a back-to-back (BtB) configuration and then over a 10 km single mode fiber (SMF). A far L–band sub-carrier at ∼1621 nm is selected for DP-QPSK signal transmission with root raised cosine (RRC) pulse shaping filter having 0.35 roll-off factor. The corresponding error vector magnitude (EVM) BER results at 25 (100) Gbaud (Gb/s) transmission in both configurations are presented in Fig.3. To achieve a BER of 3.8×10^{-3} (FEC threshold) [3], a received power of −17.2 dBm is required for 100 Gb/s date rates, in BTB case. On other front, the corresponding receiver sensitivity of −17.4 dBm is noted after 10 km transmission, with power penalty of ∼0.2 dB. This might be attributed to the variations in the OMA sensitivity because of the extreme far L-band wavelength operation. In addition, since the measurements are performed with a bare QD-LD by coupling the light into a lensed SMF, any transmitter (injection locked mode) power variation could also lead to receiver sensitivity fluctuations. The insets of Fig.3 show the eye diagrams and QPSK constellations for 100 Gbit/s at −15.5 (-16) dBm for 10 km (BtB) transmission.

A clear open eye with no eye compression further affirms the potential of Qdash laser as a unified transmitter in WDM-PONs. It is noteworthy to mention that the mode spacing of the IL modes of the QD-LD, and hence the PONs, could be altered to align with WDM standards (coarse-WDM or dense-WDM) by essentially selecting a proper cavity length and current injection. Hence, with a tunability of ∼50 sub-carriers, a single QD-LD would provide a transmission capacity of ∼5Tb/s if all these modes are simultaneous IL by an external seeding QD-LD working under mode locked scheme (QD-MLL) [14], when deployed at OLT for down streaming. Concurrently, a QD-LD in the ONU would enable 100 Gb/s upstreaming, thus facilitating a possible route towards next generation 100Gbit-PONs. Notice that this transmission result is achieved without any signal amplification. Hence, with an optimized QD-LD device together with an appropriate far L-band amplifier before transmission, would potentially boost the QD-LD injection locked mode transmitted power, enabling not only longer transmission distances (>10 km) but also higher transmission rates (>100 Gb/s).

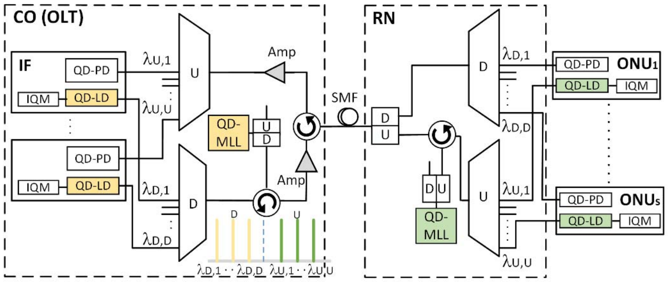

Fig. 4. Proposed colorless NG-PON based on QD-MLL as seeding source and QD-LDs and QD-PDs transceivers at ONU/IF-OLT with 100 Gb/s data traffic capacity. The inset shows the broadband lasing spectrum of QD-LD and QD-MLL with half of the spectrum for downstream (DS) and half for upstream (US) transmission (symmetric bandwidth case).

In Fig. 4, we propose a possible such WDM-PON capable of 100 Gb/s transmission capacity and exclusively includes Qdash based active devices *i.e.* ultra-broadband QD-LDs as unified transmitters, possible Qdash based broadband photodiodes (QD-PDs) as unified receivers, and broadband QD-MLL as external seeding light sources. Two QD-MLLs are utilized, one at the OLT situated at CO and other at the remote node (RN). The former is used as an external source of IL at the OLT for down transmission while the latter is used to realize injection-locking at the ONU for up transmission via different wavelength band compared to the downstream signal wavelength band, to avoid any crosstalk. If we consider the FEC threshold receiver sensitivity of −17.4 dBm for 100 Gb/s upstream and downstream transmission, the total transmitted power in the proposed NG-PON, employing an appropriate 20 dB gain far L-band amplifier at CO (downstream) and RN (upstream), would be ∼5 dBm Hence, the estimated power budget of the proposed NG-PON is ∼22.4 dB (10 km fiber and connectors loss of ∼2.4 dB, multiplexer/de-multiplexer loss of ∼14 dB, circulator of ∼2 dB, the U/D multiplexer/de-multiplexer and other connectors loss of ∼2.5 dB). It is to be noted that the power budget could further be improved by employing an optimized QD-LD with broad lasing bandwidth and high SMF coupled optical power. A single SMF could serve as a channel for bi-directional transmission without any cross talk [1]–[3] since two different lasing wavelength bands, from the ultra-broadband emission of the QD-LD, could be used for down traffic and up traffic, as illustrated in the inset of Fig. 4. Moreover, this architecture would enable utilization of identical transceivers in ONUs and in interface cards (IF) at the OLTs, thus, unifying the transmitters and significantly reducing the cost by mass production and deployment.

IV. CONCLUSION

We have proposed and demonstrated the feasibility of employing L– and U–band Qdash laser as light transmitters for next generation 100 Gbit–PONs. By externally modulating 100 Gb/s DP-QPSK signal to the ∼1621 nm injection locked laser light, a measured sensitivity of −17.4 dBm under BER FEC limit is measured. This demonstration dictates the potential employment of QD-LDs as universal light sources for both down transmission and up transmission, besides functioning as multi-wavelength seeding sources for IL, in next generation 100 Gb/s WDM-PONs, as proposed in Fig. 4.

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