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Demonstration of L-band DP-QPSK transmission over FSO and fiber channels employing InAs/InP quantum-dash laser source

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ABSTRACT

The next generation of optical access communication networks that support 100 Gbps and beyond, require advances in modulation schemes, spectrum utilization, new transmission bands, and efficient devices, particularly laser diodes. In this paper, we investigated the viability of new-class of InAs/InP Quantum-dash laser diode (Qdash-LD) exhibiting multiple longitudinal light modes in the L-band to carry high-speed data rate for access network applications. We exploited external and self injection-locking techniques on Qdash-LD to generate large number of stable and tunable locked modes, and compared them. To stem the capability of each locked mode as a potential subcarrier, data transmission is carried out over two mediums; single mode fiber (SMF) and free space optics (FSO) to emulate real deployment scenarios of optical networks. The results showed that with external-injection locking (EIL), an error-free transmission of 100 Gbps dual polarization quadrature phase shift keying (DP-QPSK) signal is demonstrated over 10 km SMF and 4 m indoor FSO channels, with capability of reaching up to 128 Gbps, demonstrated under back-to-back (BTB) configuration. On the other hand, using self-injection locking (SIL) scheme, a successful data transmission of 64 Gbps and 128 Gbps DP-QPSK signal over 20 km SMF and 10 m indoor FSO links, respectively, is achieved.

1. Introduction

Over the next few years, the global mobile data traffic is expected to increase sevenfold between 2016 and 2021 according to Cisco forecast [1]. The continuous growth of bandwidth demands requires exploring new techniques to use the available spectrum efficiently or extending it to the available unused wavelength bands. The transmission capacity in existing wavelength division multiplexing (WDM) based optical access networks is limited and will be consumed in the near future. To meet the increasing demand for broadband services, next generation passive optical networks (NG-PON) like 10 Gbps, 100 Gbps, and 400 Gbps, have been considered as promising solutions [2]. In addition, spectrum expansion to L- and U-bands for up- and down-streaming in next generation passive optical networks (NG-PON) is under consideration due to the exhausted C- band communication window. Moreover, an L-band wavelength regime exhibit lower signal attenuation (less Rayleigh scattering) than C-band which would be beneficial for FSO, or hybrid fiber-FSO communication deployment, thus making Qdash-LD an appropriate solution to extend the capacity of future networks [3].

Injection locked sources have been recently introduced for the realization of a cost-effective, wavelength-independent source for next generation colorless WDM-PONs. For instance, injection locked single tunable injection locked FP-LD have been demonstrated as a colorless source for attaining multi-Gbps WDM-PON, however, the reported transmission data rate was limited to 4 Gbps for 25 km-SMF channel due to direct modulation scheme that has inherent long response time [4]. On the other hand, 42.5 Gbps/subcarrier-communication over 100 km-SMF

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channel was achieved using external modulated FP-LD [5]. Moreover, a new study of injection locked weak-resonant cavity FP-LD (WRC-FP-LD) was reported as a source for 28 × 25 Gbps multi-subscriber communication with ~13 nm wavelength tunability [6]. In general, the wavelength tuning range of C-band FP-LDs were was found to be limited [7]. Thus, a broadband laser diodes have recently attracted a major attention as strong candidate for Tbps WDM-PONs and ability to meet up with the future requirements [8]. Moreover, such source also enables large-scale production and deployment of transceivers in optical network units (ONU) and optical line terminal (OLT).

Compared to typical narrow band FP-LD, Qdash-LD are broadband in nature encompassing several stable Fabry Perot (FP) modes. Hence, this new-class of lasers could potentially offer cost-effective solutions for data transmission in WDM PONs. Instead of using an array of LDs, a single Qdash-LD could generate multiple wavelengths, hence, reducing the overall cost of the network [3,9]. In addition, Qdash LDs have a low amplitude and phase noise, making them attractive for transmission of high-speed complex signals that are sensitive to phase noise [10].

Recently, Qdash-LDs have been proposed for data transmission in PONs and free space optical (FSO) communication. In [11], a demonstration of WDM network showed the possibility of using a Qdash-LD working in the C-band, as an external seeding source, to transmit a 2.5 Gbps OOK signal over a 25-km SMF. Similarly, C-band Qdash LD was utilized in the transmission of 56 Gbps DQPSK signal in a WDM system architecture [12]. In this case, no fiber was used to study its effect on the transmitted signal. Furthermore, by employing a semiconductor optical amplifier (SOA) to reduce the intensity noise, the authors in [10] demonstrated a 112 Gbps aggregated WDM system using C-band Qdash-LD as a light source (*i.e.* single channel 28-Gbps on-off keying (OOK) data signal) over a 100-km SMF. Recently, potential of this light source in data center applications was strengthened by demonstration of a single channel 28 Gbps QPSK signal over polarization division multiplexed 160 channels [13] and 200 Gbps signal over 60 channels, via a single C-band Qdash-LD [3] besides employing a separate local oscillator [14]. All these demonstrations utilized Qdash-LD in mode-locked configuration to improve the device dynamical characteristics. Alternatively, injection-locking technique was also investigated on Qdash-LD to understand the device physics and improve the phase noise and linewidth enhancement factor [15]. Very, recently, we exploited the wide emission tunability of Qdash active region and demonstrated the convergence of external-injection locking and L-band Qdash-LD to demonstrate single channel 64 Gbps [16] and 100 Gbps [17] DP-QPSK signal transmission over 10 km SMF at 1621 nm, thus further validating the potential of this device for future access networks.

In the last few years there has been growing interest to explore other complementary network technologies to reduce the cost of installing fiber-based networks. In this scenario, FSO technology that uses free space as a medium for data transmission have been identified as a promising approach. In fact, FSO is preferred when fiber installation is expensive or impossible. For instance, FSO is a good alternative to optical fibers in the cases of private properties, mountains, rivers, highways, etc. [18]. Under this potential network technology, various reports demonstrated 12 × 90 Gbps data transmission over 100 m-FSO channel employing commercial laser sources, as well as comb source (obtained via commercial devices), in the C-band [18,19]. Moreover, we were the first to propose Qdash-LD as a source in FSO technology. We reported 100 Gbps DP-QPSK data transmission over 4 m indoor free space single channel utilizing a widely tunable externally locked-FP modes Qdash-LD [20] in far L-band.

In this work, we introduced self-injection locking (SIL) technique on Qdash-LD and compared its characteristics with EIL scheme for data transmission, to further strengthen it as a candidate light source for next generation high speed access networks. The device and system performance is evaluated over both, fiber and free space channels, and utilizing both the locking configurations. With high wavelength stability, the injection locking techniques demonstrate device FP mode wavelength tunability of ~21 nm and ~6 nm for the case of EIL and SIL, respectively, and covers both far and mid L-band wavelength window. For the case of EIL, a successful single channel 100 Gbps DP-QPSK signal transmission over 10 km SMF and 4 m free space channel is achieved, with the capability of going beyond 128 Gbps, as demonstrated under BTB configuration. Furthermore, for the case of SIL, 64 Gbps and 128 Gbps DP-QPSK transmission over 20 km SMF and indoor 10 m FSO, respectively, is reported. To the best of our knowledge, this is the highest data rate on the longest FSO channel demonstration employing a bare Qdash-LD in L-band.

2. Injection locked Quantum-dash laser

The employed devices were grown by molecular beam epitaxy over an n-type InP substrate, whose active region is consisted of four-stacks of InAs Qdash-in-a-well structure. The active layers were then separated by InGaAlAs barrier layers of different thickness rather than fixed thickness, in order to increase the intentional active region inhomogeneity; resulting in wide gain bandwidth and hence broadband lasing emission profile [21]. The active region was then sandwiched between separate confinement heterostructure layers and completed with p- and n-cladding layers. Ridge-waveguide lasers were then fabricated from this sample using a standard semiconductor laser fabrication process with open ridges. More details could be found elsewhere [21].

2.1. External-Injection locking (EIL)

The EIL experiment was conducted on a bare 4 × 800 μm^2 ridge-waveguide Qdash-LD by coupling one as-cleaved facet power into a lensed SMF. The solid lines in Fig. 1 show the $L-I-V$ characteristics of the device under continuous-wave (CW) mode at 14 °C sink temperature. The exhibited threshold current was ~100 mA with a maximum injected current of 250 mA that provided a maximum SMF coupled power of ~1 mW (~0 dBm) before roll-off. The corresponding free running output spectrum of the laser, observed at 98% output of the 98:2% coupler (CP), without any injection locking, is shown in Fig. 2(a). A wavelength coverage of ~1605–1635 nm is evident with −3 dB lasing bandwidth of ~8–10 nm. Afterwards, injection locking was performed by a fixed CW external tunable laser source (TLS) at ~5.0 dBm by tuning its lasing wavelength to match one of the FP modes of the Qdash-LD. This was accomplished by employing the setup shown in the inset of Fig. 3(a) which consisted of a slave Qdash-LD and an externally TLS, wherein the fixed external-injection power was transmitted through an isolator into the slave laser via a 3-port optical circulator (OC). The measured output spectrums depicted in Fig. 2(a) was observed on an optical spectrum analyzer (OSA) with resolution of 0.06 nm, connected at 98% CP output. Moreover, a polarization controller was also included in the assembly for improving the injection locking efficiency. Fig. 2(a) also depicts an externally locked mode at 1621.4 nm overlapped with the free running emission spectrum, exhibiting a gain of ~9 dB after injection-locking while all other side modes of Qdash-LD's emission are suppressed. Next, we characterized the tunability of the locked modes and successfully achieved a wavelength tunability from 1611.8 to 1633.7 nm with 0.4 nm mode spacing, consisting of ~50 measured modes (*i.e.* ~21 nm tunability). Besides, we also conducted the short-term stability test of the injection-locked mode over a ~20 min observation time. The externally locked FP mode at 1619.68 nm showed a fluctuation of ~0.56 dBm, ~2.5 dB and ~0 nm in mode power, side-mode suppression ratio (SMSR) and mode wavelength, respectively.

2.2. Self-injection locking (SIL)

In this configuration, we utilized a 3 μm ridge-width and 600 μm cavity length laser diode with identical device structure. The dotted lines in Fig. 1 shows the corresponding $L-I-V$ characteristics curve of the employed Qdash-LD exhibiting a threshold current of ~100 mA

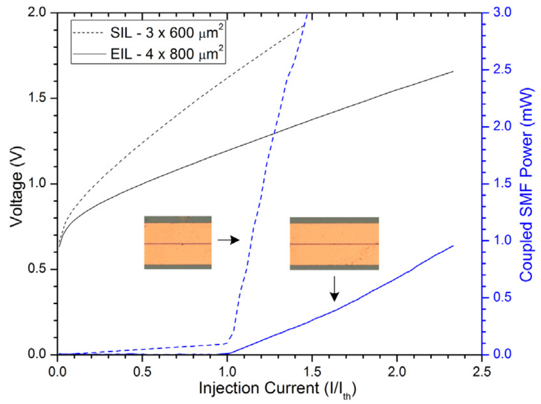

Fig. 1. Light output–injected current–measured voltage (L-I-V) characteristics of free running 4 × 800 μm²(Solid lines) and 3 × 600 μm² (dotted lines) bare Qdash-LD devices used for EIL and SIL, respectively. The measurements were taken at 14 °C heatsink temperature and under CW operation. The insets depicts the microscope images of the bare devices.

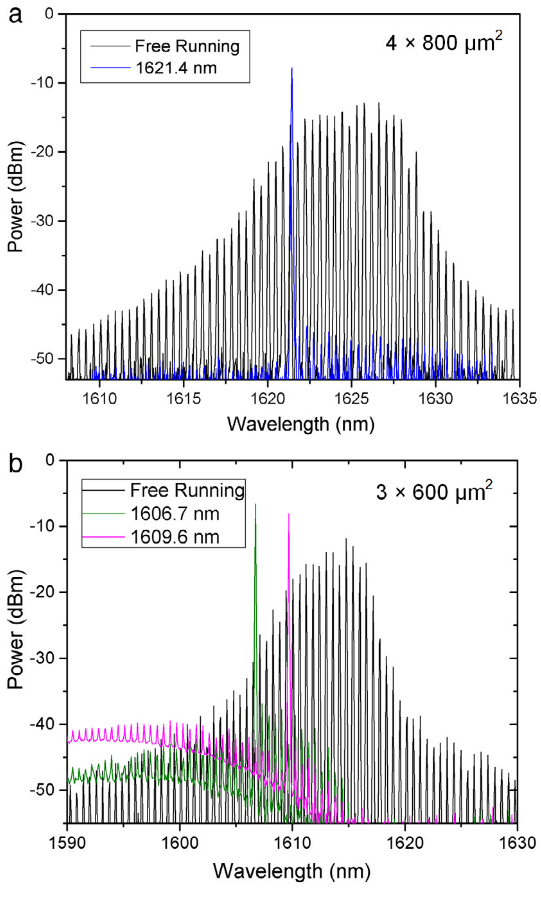

Fig. 2. Free-running spectrum of (a) 4 × 800 μm² Qdash-LD with external injection locked mode at 1621.42 nm and (b) 3 × 600 μm² Qdash-LD with self-injection locked mode at 1606.7 nm and 1609.6 nm. The free running and locked spectrum of (a) is measured at the 98% output of the 98:2% CP while for figure (b), the free running spectrum is measured after coupled laser-SMF end and the locked modes at the 2% output of 98:2% CP.

under CW operation, observed at 14 °C heatsink temperature. A total output coupled power of ~0.5 mW (~ −3 dBm) was measured at 110 mA biasing current. Thereafter, self-injection locking was implemented via a feedback loop, as shown in the inset of Fig. 3, which consisted of an erbium doped fiber amplifier (EDFA) with ~20 dB gain, 3-dB coupler CP, L-band tunable band pass filter (TBPF), in addition to a polarization controller and a 3-port OC. The amplifier was utilized to compensate for the bare laser facet-fiber coupling loss (~13 dB) and the TBPF insertion loss (~7 dB). The optical CP divides equally the self-locked lasing power for utilization in self-injection locking, and as a subcarrier to carry the data signal. The TBPF tunes and filters a single FP mode, which was re-injected into the Qdash-LD via OC for self-locking purpose. Another 98:2% CP was utilized after the 3-dB coupler to monitor the lasing spectrum during optical transmission experiments. Fig. 2(b) illustrates the free running lasing spectrum of the 3 × 600 μm² bare Qdash-LD at 110 mA showing a broadband emission in the wavelength range of ~1605–1620 nm with a total single facet fiber-coupled power of ~ −3 dBm and mode spacing of 0.6 nm. Moreover, the self-injection locking of two separate single FP modes at 1606.7 nm and 1609.6 nm, was achieved via tuning the TBPF to feedback and force stimulated emission of that selected FP mode, as shown in Fig. 2(b). This results in a coherent subcarrier with ~30 dB SMSR and ~10 (−7) dBm mode power, as measured at the 98% output of the 98:2% CP (SMF coupled laser power). Moreover, we also performed stability test on the self-injection locked mode at 1609.6 nm over a 20 min time interval. The results show a variation of less than ~0.2 dBm, ~1 dB and ~0.05 nm in mode power, SMSR and wavelength, respectively. Besides, self-injection locked subcarrier showed a tunable wavelength range of ~6 nm centered at 1606.7 nm, showing ~10 different available FP modes with 0.6 nm spacing. It is worth mentioning that this limitation of wavelength tuning range was imposed majorly by the restriction of the limited operating window of the L-band EDFA 1570–1610 nm, which reduced the injection ratio considerably. Hence, tunability extending beyond 20 nm, corresponding to >30 tunable subcarrier, could be achieved by either employing an appropriate L-band EDFA (operating wavelength ~1605–1625 nm) or improving the SMF coupling efficiency to near practical values of ~ −5 to −6 dB, which would possibly eliminate the need of an amplifier.

In Table 1, we show a comparison between the two locking techniques that were used to generate the subcarrier laser modes. Thus, the lasing wavelength, mode spacing and the number of tunable subcarriers are subject to the cavity length, as well as the biasing current and temperature. However, larger number of tunable subcarriers could be achieved via an optimized Qdash-LD with broad emission (>50 nm lasing bandwidth) and higher power, and at room temperature operation [21]. In addition, higher stability in SMSR and mode power was observed in the SIL scheme that is attributed to the self-feedback loop, as well as the mode wavelength, which is close to the central wavelength (measured at the full-width at half-maximum) of the Qdash-LD device. However, higher SMSR and, thus, mode coherency were observed for EIL scheme. This could be due to the higher injection power of ~5 dBm in the EIL scheme.

3. Experimental results and discussion

In order to assess the capability and efficiency of the injection locked FP modes generated from the Qdash-LD in communication networks, we conducted an experimental work to transmit a high data rate signal over two channel types; SMF and FSO link as shown in Fig. 3. The injection-locked sub-carrier generated from both configurations (98% output of the optical coupler) is injected into the dual polarization In-phase Quadrature-phase modulator (DP-IQM), while the remaining 2% output power was observed via the OSA concurrently. A pseudo random binary sequence (PRBS) with a pattern length of 2^{11}-1 was mapped into a DP-QPSK modulation scheme with various symbol rates (*i.e.* 16, 25, 32, and 44 Gbaud) using 65 GSa/s arbitrary waveform generator (Keysight AWG M9581 A). Then, the generated multilevel signals were carried on the coherent injection locked subcarrier using DP-IQM and transmitted through the SMF or FSO channel. At the receiver side, the output-received signals were analyzed and detected through a Keysight optical modulation analyzer (OMA N4391A) equipped with both phase tracking and chromatic dispersion compensation algorithms. A variable optical attenuator (VOA) was also utilized at the receiver to test the receiver sensitivity, *i.e.* BER versus received power.

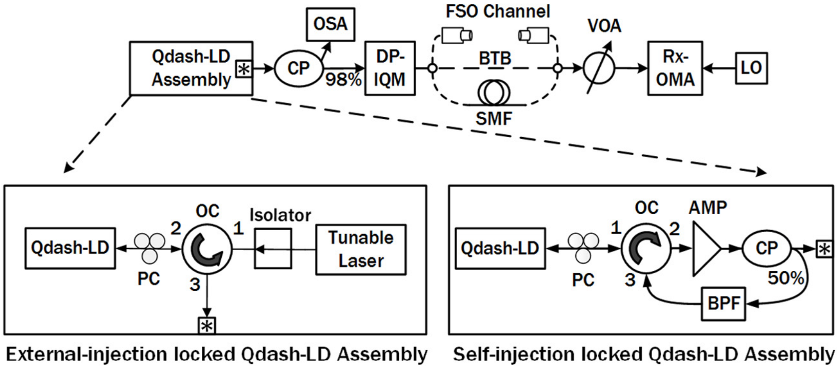

Fig. 3. Experimental communication setup employing external-injection locking (left inset) and self-injection locking (right inset) schemes. OC: optical circulator, AMP: amplifier, CP: coupler, BPF: band pass filter, PC: polarization controller, OSA: optical spectrum analyzer, DP: dual polarization, IQM: in-phase quadrature phase modulator, BTB: back-to-back, VOA: variable optical attenuator, SMF: single mode fiber, OMA: optical modulation analyzer, LO: local oscillator.

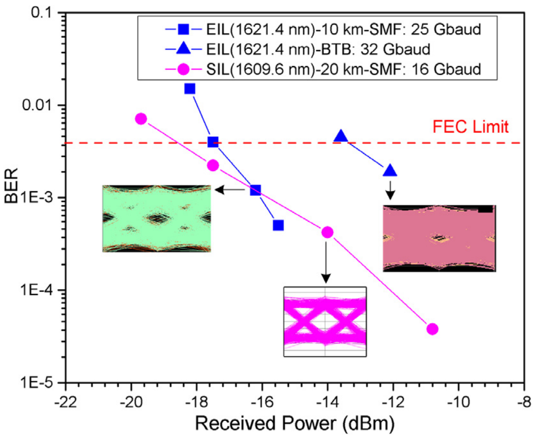

Fig. 4. Measured BER versus received optical power for fiber communication channel considering both EIL and SIL configurations. The insets show the corresponding eye-diagrams at the indicated received power values.

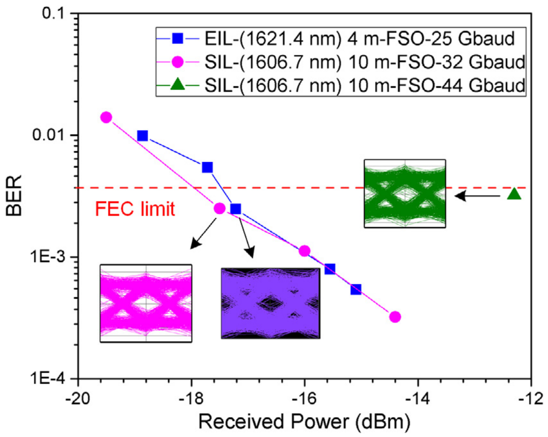

Fig. 5. Measured BER versus received optical power for FSO communication channel considering both EIL and SIL configurations. The insets show the corresponding eye-diagrams at the indicated received power values.

3.1. Fiber communication channel

We started our communication experiment by transmitting the aforementioned modulated signals over SMF utilizing the generated subcarriers via both EIL and SIL schemes. In the former case, DP-QPSK signals with 25 Gbaud (100 Gbps) and 32 Gbaud (128 Gbps) symbol rates were generated and carried on a far L-band 1621.4 nm externally locked subcarrier without employing any signal amplification, over 10 km SMF and BTB configuration, respectively. On the other hand, for the latter scheme, 64 Gbps DP-QPSK data was transmitted over 20 km SMF employing 1609.6 nm self-seeded Qdash-LD subcarrier. The transmission performance of both the schemes could be inferred from Fig. 4, which plots the measured error-vector-magnitude (EVM)-bit-error-rates (BER) values versus the received power for both cases. Superior operation from self-seeded Qdash-LD is observed compared to the EIL scheme with a receiver sensitivity of ∼ −19 dBm in the former case compared to ∼ −18 dBm in the latter case, to reach the BER below the forward-error-correction (FEC) threshold of 3.8 e−3. This improvement in the receiver sensitivity, in the SIL case, could possibly be due to a lower operating symbol rate in addition to the aforementioned higher stability in locking behavior. On the other hand, the log (BER) improvement per dBm received power is found to be superior in the EIL scenario (0.55/dBm) when compared to the SIL scheme (0.25/dBm). This is partly ascribed to the longer fiber channel of 20 km in the former case compare to 10 km for the latter and hence subjected to increased fiber dispersion, besides high SMSR of ∼38 dB in the former case compared to ∼30 dB in the latter case. The insets in Fig. 4 show the corresponding eye diagrams at a received power of ∼ −16 dBm and ∼−14 dBm for EIL and SIL, respectively, showing open eyes, which is an indicator of error-free transmission. In addition, it is worth mentioning that we were able to push the data rate to 128 Gbps (32 Gbaud) on EIL Qdash-LD subcarrier for transmission in BTB configuration, as depicted in Fig. 3, with a receiver sensitivity of ∼−14 dBm. Unfortunately, the subcarrier mode power could not be amplified because of the unavailability of an EDFA at 1621 nm, and thus was the limiting factor for increasing the channel length and data rate.

3.2. FSO communication channel

In this demonstration, an indoor FSO link was established via two optical collimators, one for data transmission and one for reception, with the distance between them serving as the channel. The collimators' alignment was accomplished manually first, using visible light signals, and then fine tuning alignment was performed by two-dimensional manual translation stages. For the case of EIL subcarrier, 4 m long FSO link was assembled and a DP-QPSK signal with 25 Gbaud (100 Gbps) was modulated using 1621.4 nm externally locked subcarrier. On the other hand, 10 m FSO channel was implemented for SIL Qdash-LD subcarrier at 1606.7 nm and modulated with 32 Gbaud (128 Gbps) and 44 Gbaud (176 Gbps) modulating signals. Fig. 5 summarizes the results by plotting the corresponding measured BER versus received power for both the injection locking schemes. A receiver sensitivity of ∼ − 18 dBm was achieved in both the cases with clear open eyes below the FEC threshold, as depicted in the insets of Fig. 5. This is ascribed

Table 1
Comparison of Qdash-LD's modes generated using SIL and EIL.

	SIL	EIL
Device	$3 \times 600\ \mu\text{m}^2$	$4 \times 800\ \mu\text{m}^2$
Mode tunability	∼6 nm	∼21 nm
Free spectral range (FSR)	70 GHz	46 GHz
Modes Spacing	0.6 nm	0.4 nm
No. of tunable modes	10	50
Measurements	@ 1606.7 nm/1609.6 nm	@ 1621.4 nm
SMSR	∼30 dB	∼38 dB
FWHM	∼0.05 nm	∼0.06 nm
Mode power[a]	−7 dBm	−8 dBm
Mode Power stability[b]	∼0.2 dB	∼0.5 dB
SMSR stability[b]	1 dB	2.5 dB
Wavelength stability[b]	0.02 nm	0 nm

[a] Locked mode power is calculated at the laser-SMF coupling terminal, and before the EDFA for the SIL case.

[b] Stability is measured over 20 min.

to the high self-seeded mode power compared to the externally locked subcarrier, which resulted in similar receiver sensitivities in spite of the former carrying high-data rate (132 Gbps) compared to the latter (100 Gbps). Moreover, the slope of the log(BER) curve is found to be similar in value for both the locking techniques (0.3/dBm) which further supports our former postulation since in this case, the locked-subcarrier underwent longer transmission channel length of 10 m besides high data rate. Lastly, to test the maximum achievable data rate via self-locked FP mode, we transmitted 176 Gbps (44 Gbaud) DP-QPSK signal over 10 m indoor FSO channel and successfully recovered the signal with ∼−12 dBm receiver sensitivity. The corresponding clear open eye, shown as an inset in Fig. 5, further demonstrates a successful transmission. Unfortunately, due to the power limitation, the received power could not be varied to further evaluate the performance characteristics. It is worth mentioning at this instance that, to the best of our knowledge, 128 Gbps is the highest data rate value over 10 m long indoor FSO channel ever reported, employing an L-band subcarrier.

4. Conclusion

In summary, we experimentally demonstrated both self- and external-injection locking on Qdash-LD for future high-speed optical data transmission. Using external-injection locking, a successful DP-QPSK transmission of 100 Gbps was achieved over 10 km SMF and 4 m FSO communication channels with capability of reaching 128 Gbps. Additionally, the self-injection locking allowed the transmission of 64 Gbps and 128 Gbps over 20 km SMF and 10 m indoor FSO link, respectively, with ∼ − 18 dB receiver sensitivity. These demonstrated results show the promising employment of Qdash-LD as a candidate light source for high-speed access networks, particularly 100G and 400G next generation passive optical networks.

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