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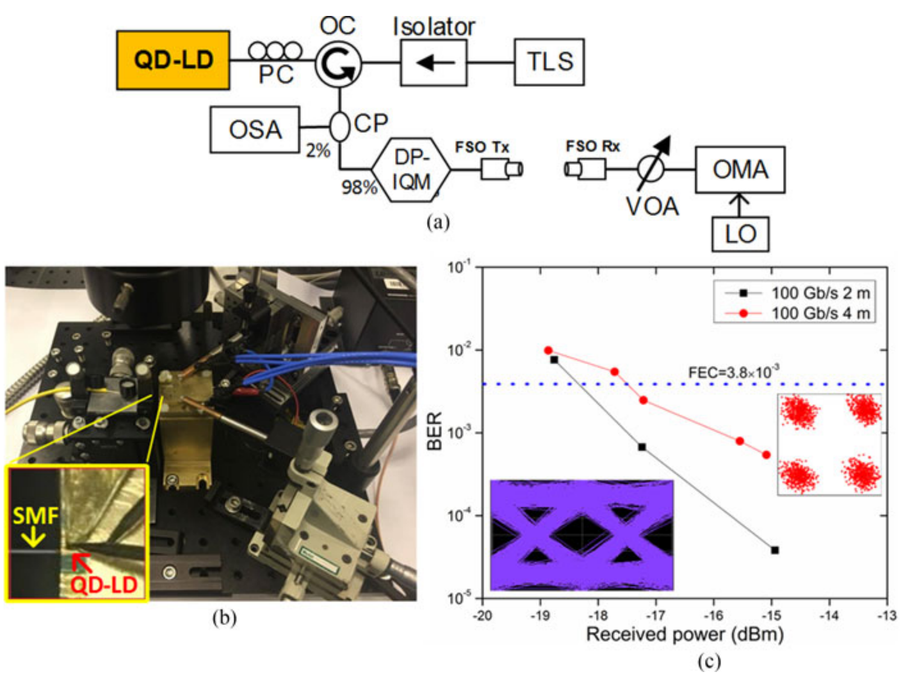
Muhammad Talal Ali Khan
Mohamed Adel Shemis
Amr Mohamed Ragheb
Maged Abdullah Esmail
Habib Ali Fathallah, *Senior Member, IEEE*
Saleh Alshebeili
Mohammed Zahed Mustafa Khan, *Member, IEEE*



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4 m/100 Gb/s Optical Wireless Communication Based on Far *L*–Band Injection Locked Quantum-Dash Laser

Muhammad Talal Ali Khan,[1] Mohamed Adel Shemis,[1] Amr Mohamed Ragheb,[2] Maged Abdullah Esmail,[3] Habib Ali Fathallah,[3] *Senior Member, IEEE*, Saleh Alshebeili,[3] and Mohammed Zahed Mustafa Khan,[1] *Member, IEEE*

[1]Optoelectronics Research Laboratory, Electrical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran 34463, Saudi Arabia
[2]KACST-TIC in Radio Frequency and Photonics for the e-Society (RFTONICS), Riyadh 11421, Saudi Arabia
[3]Electrical Engineering Department, King Saud University, and KACST-TIC in RFTONICS, Riyadh 11421, Saudi Arabia

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Abstract: An indoor 100 Gb/s free space optical communication link using an injection locked ∼1621 nm quantum-dash laser has been experimentally demonstrated. The results are achieved using dual-polarization quadrature phase shift keying (DP-QPSK) and coherent detection over a 4 m indoor free space link. The system exhibited a receiver sensitivity of –17.5 dBm to achieve the bit error rate forward error correction (BER FEC) threshold of 3.8×10^{-3}. This displays the potential of tunable injection locked far *L*-band quantum-dash lasers, with less scattering loss compared to *C*-band counterpart, as promising light sources in both indoor and outdoor future high speed free space optical information and communication technology.

Index Terms: Quantum dash, broadband laser, inhomogeneous broadening, C– and L–band lasers, optical wireless communication, free space optical communication, indoor communication.

1. Introduction

The massive surge in the commercial demand for unlimited and high-speed broadband wireless access, to accommodate the ever-increasing demands of individual users, has prompted extraordinary growth in the internet traffic demand in the recent decade. Over the next few years, mobile data traffic is expected to increase nearly eight times globally compared to the scenario in 2015 [1]. This relentless continuous growth necessitates development of higher bandwidth and capacity systems and is pushing the current radio frequency (RF) systems into bandwidth limitations and, ultimately, to traffic congestion.

Optical wireless communication (OWC) has been identified as a promising complement to the existing wireless RF solutions, providing large bandwidth and higher data rates with low deployment costs and infrastructure maintenance [2]. OWC in the form of free space optical communication (FSO) relies on line of sight (LOS) communication and can be used in both indoor and outdoor environments, thus, is highly attractive because of its affordability and license free spectrum. In fact, recent demonstrations of FSO in outdoor building-to-building LOS communication, indoor data centers for intra/inter-rack communication, and radio over free space optics (RoFSO) [3]–[5], substantiate the viability of this alternate solution. In the following, we present a brief review of some of the recent FSO achievements that have been reported in literature.

In literature, outdoor FSO work, which has been considered as a promising solution in mobile-wireless backhaul, disaster recovery, metro ring extensions and many more, typically employs near infra-red commercial laser diodes (LDs). For instance, the longest 1–1.5 km FSO link was presented in [6], achieving 100 Gb/s transmission using polarization multiplexed quadrature phase shift keying (QPSK) scheme. A 212 m FSO link based on wavelength division multiplexed 32 distributive feedback LDs (DFB-LDs) in C–band (1535.7–1560.5 nm) has been demonstrated in [7] using on-off keying (OOK) and 40 Gb/s/channel data rate. Likewise, 100 Gb/s transmission capacity per carrier, using 1550 nm LDs, has been reported in [3] and [8] on 120 m and 80 m FSO links, respectively. While the former utilized orbital angular momentum (OAM) multiplexing and QPSK modulation scheme, the latter was based on wavelength division multiplexing (WDM) and DP-QPSK format. Very recently, a record capacity FSO of 320 Gb/s using a single 1550 nm DFB-LD as a carrier and DP-QPSK modulation, has been reported, over 11.5 m outdoor link [9] with a comprehensive overview of the achievements in the FSO system [10].

On the other hand, indoor FSO demonstration with visible light communication (VLC) as well as infra-red LDs has been reported. VLC has a potential in addressing indoor light-based wireless communication (LiFi) applications and solid-state lighting (SSL) concurrently [11]–[13] and hence is taking center stage in indoor FSO solutions. In contrast, interior FSO employing C–band LDs is garnering attention for data centers interconnections and high performance computing (HPC) networks which are currently bandwidth overloaded with fiber technology and suffering from flexibility issue for cable rerouting after deployment. For instance, [14] showed the feasibility of 10 Gbps data center FSO communication up to 20 m link distance in the real environment while [15] concentrated on achieving 360° -steerable 30 m FSO communication in an HPC cluster, utilizing off-the-shelf components. In [16] and [17], long indoor communication over 150 m and 20 m free-space link based on C-band light source, is addressed, and 40 Gb/s per channel transmission is reported. Short communication channels of 1 m, 2 m, and 6 m are considered in [18]–[20], respectively, with corresponding successful transmission of 100 Gb/s (OAM DP-QPSK), 37.2 Gb/s and 10 Gb/s data signals on C–band sub-carriers. Recently, experimental demonstration of indoor FSO link of up to 30 cm for card-to-card 40 Gb/s flexible interconnection [21], comparison of FSO with 60 GHz radio frequency (RF) technology in a recent survey [22], stems the potential of FSO as a promising solution for varied wireless applications [23].

In this paper, we demonstrate the feasibility of employing far L–band InAs/InP quantum-dash (Qdash) Fabry-Perot broadband LD as a source in FSO. We report a single channel 100 Gb/s free space transmission over 4 m indoor channel using DP-QPSK scheme and injection-locked (IL) Qdash LD (QD-LD). To the best of our knowledge, this is the first report employing a ∼1621 nm externally modulated QD-LD to establish a 4 m interior FSO link within ∼0 dBm available power link budget of the QD-LD. Clear eye diagrams and BERs are achieved over a 2 m and 4 m channels while keeping the transmitted power considerably below the eye-safety limit. We believe that QD-LDs would possibly be more efficient in both indoor and outdoor FSO compared to their 1550 nm commercial LDs counterpart since the former sources are less prone to scattering losses [24].

2. Quantum-Dash Laser Injection Locking Characterization

The QD-LD was grown by molecular beam epitaxy (MBE) over n-type InP. The active region composed of a four-stack InAs/InGaAlAs dash-in-a-well structure in which each layer is separated by varying barrier thickness values of 10 nm, 15 nm, and 20 nm. This intentionally inhomogeneous active region broadens the gain spectrum and, hence, results in an ultra-broadband lasing emission.

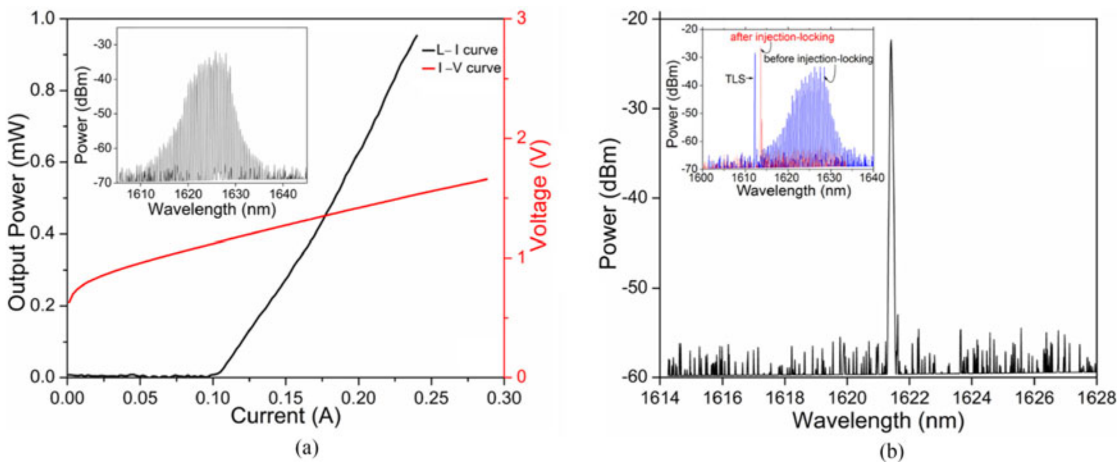

Fig. 1. (a) Light output–injected current–measured voltage (*L-I-V*) characteristics of free running QD-LD measured at SMF end. (Inset) Free-running spectra of the QD-LD at 240 mA CW current, (b) injection-locked mode (1621.42 nm) of the QD-LD utilized for data transmission experiment (from 2% output of the 2/98 power splitter). (Inset) Optical spectra of QD-LD with/without injection locking. The master TLS laser linewidth is visible.

Besides, self-pulsation has also been observed from this class of lasers, as has been reported in literature by other groups [25]. These interesting features are highly attractive as a comb source in WDM and optical access networks. The laser device structure growth, fabrication and characterization can be found in [26]. In this work, a bare $4 \times 800\,\mu\text{m}^2$ ridge-waveguide QD-LD is utilized as an optical source and is mounted on a temperature controlled brass base with p-side up configuration. The optical power from one of the laser facets is butt coupled into a lensed standard single mode fiber (SMF). The fiber end *L–I–V* characteristics under continuous wave (CW) operation at 14 °C is shown in Fig. 1(a). An optical power up to $\sim$1.00 mW ($\sim$0 dBm) is measured at an injection current of 240 mA. The broadband free running lasing spectrum at this current injection is shown in the inset of Fig. 1(a), with central lasing wavelength (calculated at the full width at half maximum) located at $\sim$1625 nm and -3 dB bandwidth $\sim$7–10 nm. Note that, under pulsed current operation, the bandwidth and optical power of these chirped QD-LDs is $\sim$30–50 nm and $>$80 mW, respectively. This degradation in the laser performance under CW operation compared to pulsed mode is expected and has been attributed to the non-optimized growth of device active region [27]. With an optimized laser device structure design and growth optimization, QD-LD is expected to perform similar in both CW and pulsed operation. The inset of Fig. 1(b) illustrates the optical spectra of QD-LD without injection and with injection at $\sim$1613 nm. A clear master tunable laser source (TLS) line is visible in the inset before injection locking, while after injection locking, all the side modes of QD-LD are suppressed, leading to a high power IL single mode operation [28]. Fig. 1(b) depicts the 1621.42 nm IL mode of the QD-LD when the TLS is wavelength tuned with a CW injection power of $\sim$4.5 dBm, corresponding to an injection ratio of $\sim$4.5 dBm at the coupled SMF end. However, it is to be noted that the injection ratio would be significantly low at the laser facet end considering a fiber coupling efficiency of $\sim$4%. The measured single mode output power (taken from 2% output of the power splitter) and side-mode suppression ratio (SMSR) of this IL single FP mode is –22.25 dBm and 31 dB, respectively. This mode, when taken from 98% output of the power splitter, exhibited a mode power of ~-5.2 dBm, and has been utilized as a carrier for the subsequent data transmission experiments.

Next, the tunability of the QD-LD IL mode is performed by fixing the TLS CW injection power at $\sim$4.5 dBm and varying the wavelength with $\sim$1.0 nm tuning step. The results are plotted in Fig. 2(a) which shows a wavelength tuning range of $\sim$20 nm from $\sim$1613.6–1633.7 nm comprising of $\sim$20 measured modes from the available $\sim$40 modes. A fluctuation of $\sim$3.2 dB and $\sim$3 dBm in SMSR and output power, respectively, is observed across the tuned IL modes. Also, notice that the output

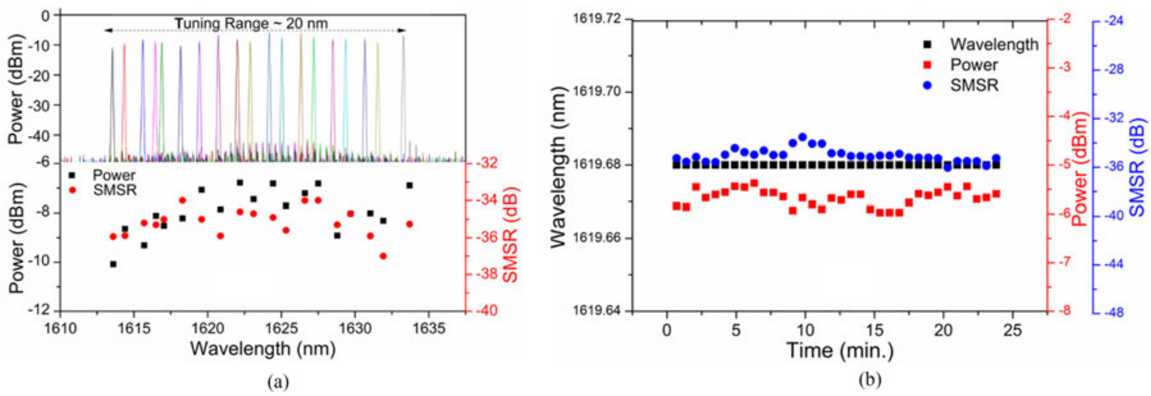

Fig. 2. (a) Tunability of the injection-locked modes at different wavelengths of the QD-LD with ~1 nm tuning steps and at a fixed CW external injection of ~4.5 dBm. The corresponding output power and SMSR of the IL mode are also plotted as a function of the locked mode wavelength. (b) Short term stability test of the 1619.68 nm IL mode, in terms of wavelength, output power, and SMSR variations.

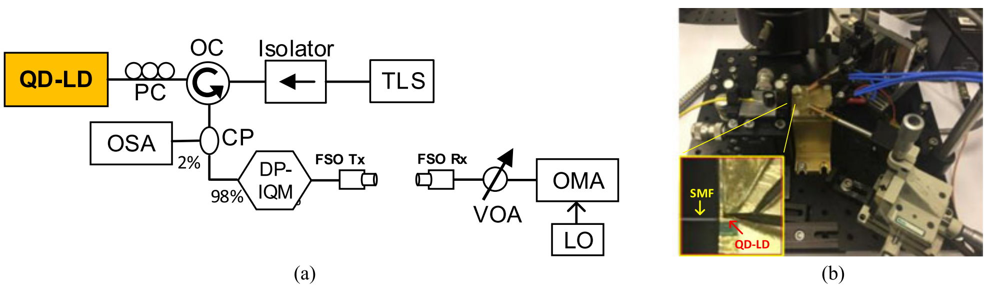

Fig. 3. (a) Experimental setup of 100 Gb/s DP-QPSK transmission employing externally modulated IL QD-LD and (b) bare QD-LD characterization setup with inset showing the zoomed in version of the bare QD- LD coupled to a lensed SMF that is used in the optical wireless communication experiment.

power and SMSR variation between ~1619.6–1627.5 nm is minimal, whereas, these fluctuation increase towards the shorter and longer wavelength extremes. This might be due to the smaller output powers of QD-LD Fabry-Perot modes that resides at the edges of the −3 dB lasing spectrum (see insets of Fig. 1). These variations could be unified by varying the TLS CW power at each wavelength locked mode since this has been fixed at ~4.5 dBm in our case. Besides, a short-term stability of the injection-locked QD-LD mode is also conducted and found to be stable throughout the observation time of 24 minutes. The IL mode was at 1619.68 nm with −5.7 dBm output power. The power, SMSR and wavelength variations of IL QD-LD mode are found to be ~0.5 dB, ~2.5 dB and 0 dB, respectively, as shown in Fig. 2(b). These results indicate that multiple IL QD-LD modes, with similar mode power and SMSR, could be deployed as promising carrier signals in WDM FSO [7] and FSO based passive optical networks [20] with similar performance characteristics.

3. Experimental Setup

Fig. 3(a) depicts the block diagram of FSO setup while Fig. 3(b) shows the bare QD-LD probing and characterization setup. A master TLS at fixed ~4.5 dBm external power is injected into an optical circulator (OC) via an isolator, and through a polarization controller (PC) into the slave QD-LD. The isolator and PC in the experimental setup are used to protect the TLS and to improve the injection locking efficiency, respectively. The 1621.42 nm injection-locked QD-LD mode is observed at the 2% output (see Fig. 1(b)) of a 2/98 power splitter and combiner (CP) using optical spectrum analyzer (OSA) with 0.06nm resolution). The remaining 98%, which corresponds to mode power of ~−5.2 dBm, is fed in to a dual-polarization in-phase and quadrature (DP-IQ) modulator for modulation purpose. Pre-processing (pattern generator, modulation, over-sampling) of the signal

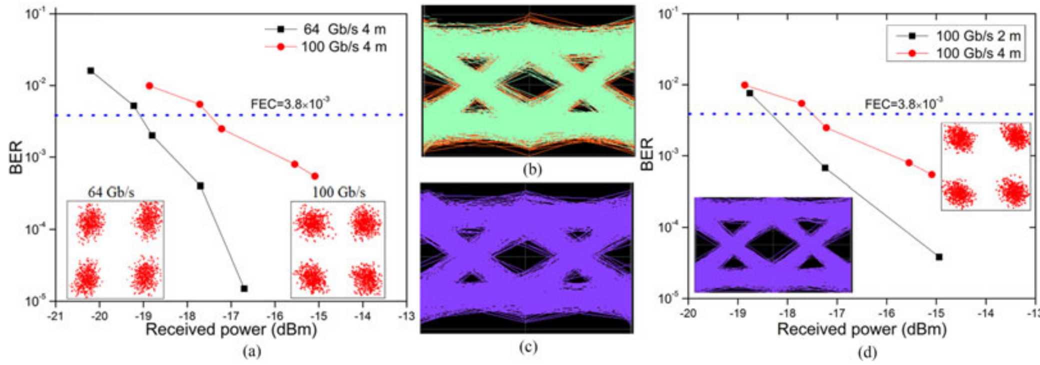

Fig. 4. (a) Measured BER curves of the IL QD-LD-based FSO link over 4 m channel length and at transmission rate of 64 and 100 Gb/s. (Insets) Corresponding QPSK constellation below FEC limit. The corresponding eye diagrams of (b) 64 Gb/s and (c) 100 Gb/s transmission rates. (d) Comparison of the measured BER curves of the IL QD-LD-based FSO link over 2 m and 4 m long free space channels and at 100 Gb/s transmission. (Insets) Eye diagram and QPSK constellation of achieved with 2 m channel link below FEC limit.

was performed using MATLAB. We have used a $2^{11} - 1$ pseudo random binary sequence (PRBS) data stream in QPSK format. These signals are driven into the DP-IQ modulator and later detected using optical modulation analyzer (OMA) Keysight N4391A) [9], [10].

The FSO channel is composed of two SMF collimators, one is utilized for transmitting the modulated laser beam into the free space and the other is used for reception of the beam. The collimator includes aspheric lens operating in the wavelength range of 1050–1620 nm and has a beam diameter of 3.6 mm. Initial alignment of the FSO link has been accomplished manually using visible green light laser (520 nm). Later, 2-D translation stages are used to further fine align the signal into the reception collimator SMF. We measured the free space channel loss over 2 m and 4 m distance by transmitting a known power of 5.5 dBm using 1550 nm laser. The received power after the reception collimator is measured and the loss is deduced. This high channel loss with increasing channel distance is primarily attributed to the manual alignment system which can be further improved by precise alignment or piezo alignment techniques. After signal coupling into the reception collimator SMF, a variable optical attenuator (VOA) is employed before sending the signal into OMA for detection. We calculated the accessible emission limit (AEL) for eye-safety for our current experimental setup, according to: $AEL = MPE \times \pi r^2$; where the first and second terms on the right hand side correspond to the maximum permissible exposure and the beam area [19]. For a 4 m distance, the beam area is 0.14309 cm^2 and MPE is 0.1 $\mathrm{W/cm}^2$ [29], thus, the maximum AEL is ~14.3 mW (~11.55 dBm). In our experiment the estimated maximum transmitted optical power is −13 to −16 dBm which is way below the AEL eye-safety limit.

4. Results and Discussion

We transmitted a CW 1621.42 nm IL DP-QPSK signal into the indoor 4 m FSO link with different Gbaud rates. A root raised cosine (RRC) pulse shaping filter with roll-off factor of 0.35 is used at both the transmitter and receiver ends. The maximum achieved baud rate is 25 Gbaud corresponding to 100 Gb/s with 2.96 b/s/Hz spectral efficiency. In Fig. 4(a), the measured error vector magnitude (EVM) BER versus the received signal power at 16 (64) and 25(100) Gbaud (Gb/s) is presented. The corresponding signal constellations and the eye diagrams is illustrated in the inset of Fig 4(a), and Fig 4(b)–(c). To achieve a bit error rate forward error correction (BER FEC) threshold of 3.8×10^{-3}, received powers of −17.5 dBm and −19 dBm are required for 100 and 64 Gb/s transmission rate, respectively. Appropriately separated signal constellations and clear eye diagrams are observed for both transmission rates (Fig 4(b) and (c)), thus demonstrating the feasibility of building 4 m/ 100 Gb/s FSO with a QD-LD without the use of signal amplification. In addition, the performance of

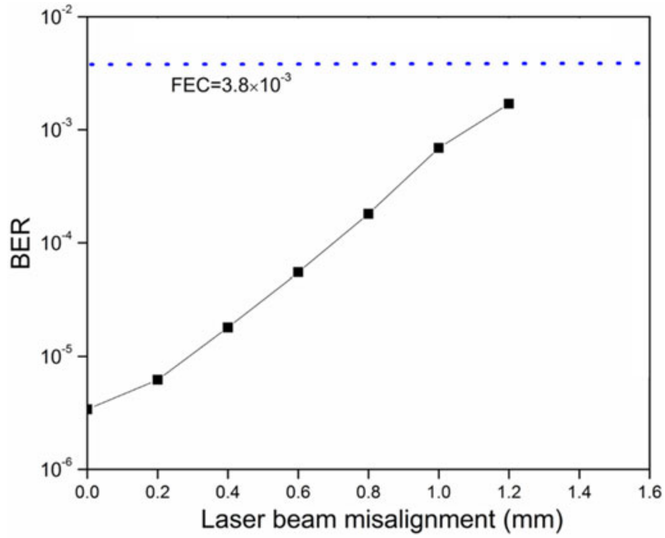

Fig. 5. BER values of 4 m/64 Gb/s IL QD-LD FSO link under laser beam misalignment condition.

DP-QPSK 100 Gb/s QD-LD IL modulated signal is tested over different channel length scenarios, and the results are depicted in Fig. 4(d). The insets of Fig. 4(d) show the eye diagram and QPSK constellation achieved with 2 m channel link. A receiver sensitivity of −18.3 dBm is noted for the short link, translating to ∼1.0 dB received power improvement at FEC threshold compared to the long channel. Reducing the channel length from 4 m to 2 m noticeably improved the transmission performance, as a result of higher received optical power level, and affirms the wide open eye and better BER for the 2 m link case. It is noteworthy to mention that by precise collimators' alignment, the free space channel loss could further be reduced, thereby enabling to realize longer indoor FSO link within the available ∼0 dBm power budget of the QD-LD. Moreover, with improved power budget by employing a proper far L-band amplifier in the system, QD-LD has a potential to address not only long indoor channels but long outdoor communication links as well.

A laser beam propagates through the free-space channel between the SMF collimators as if the fibers were connected smoothly. In practice, this is not the case and we expect misalignment to occur. To estimate the error margin of this optical misalignment on 4 m/64 Gb/s FSO transmission system, we intentionally moved the reception collimator horizontally with a step size of 0.2 mm and measured the BER. The results are shown in Fig. 5. The measured BER values are found to increase under increasing misalignment of optical beam. To achieve BERs below the FEC limit, we estimated the maximum beam displacement to be ∼1.6 mm (∼42% of the beam diameter), that can be tolerated. Hence, all these investigations support the potential of QD-LD as a source in FSO with possibility of outperforming the conventional 1550 nm sources with their inherent less scattering loss; a non-trivial issue in long outdoor optical LOS communication.

5. Conclusion

We have addressed a single channel 100 Gb/s 4 m indoor free space transmission system by employing DP-QPSK scheme and external modulation. Through a systematic investigation of IL bare QD-LD as a carrier, and taking into consideration eye-safety limits and available ∼0 dBm source power constraints, low BER and clear open eye diagrams are achieved with −17.5 dBm receiver sensitivity. This shows that broadband QD-LD with lasing emission encompassing far L–band, are promising sources in both indoor and outdoor FSO. Moreover, this new class of laser devices, compared to 1550 nm LDs, is expected to perform better due to less Rayleigh scattering effect, thus providing high-speed transmission and longer free space distance.

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