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# Generation of 200 OAM channels for 10 Tbps free space data transmission using POLMUX based WDM and self-injection locked QD-LD

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**Abstract**
Orbital angular momentum (OAM) beams, containing helical phase structures are extensively used as data carriers due to their additional degree of freedom. OAM beam containing different modes with different *l*-values are always mutually orthogonal to each other. The orthogonal property of the OAM-modes reduces the intermodal crosstalk. A 10 Tbps free-space data transmission system enabled with self-injection locked quantum dash-laser diode (QDLD) and successive multiplexing of different wavelengths, OAM modes, and polarisation states of light-wave are proposed and analysed using simulation. Self-injection locked QDLD is used to generate 10 optical carriers, which results in significant reduction in cost and complexity of the system. Combination of wavelength division multiplexing, OAM multiplexing, polarisation multiplexing enhances the number of data channels up to 200. The parallel generation and detection of OAM modes have been performed employing Dammann optical vortex gratings. ($10\times10\times2\times50$) Gbps data has been successfully transmitted over a 10 m free-space optics link. Open eye and clear constellation diagrams with a very low power penalty of 2.1 dB at a bit-error-rate value of $2.2\times10^{-3}$ have been achieved in our proposed architecture, which authenticates the feasibility of the system.

**Keywords** Orbital angular momentum of light · Wavelength division multiplexing · Polarisation multiplexing · Free space optics · Dammann optical vortex gratings

## 1 Introduction

At present time, there is a sharp rise in the demand for large bandwidth and high data rate. Free-space optics (FSO) communication is now partially fulfilling this demand. There are various advantages of FSO communication, for example, lower deployment time, no

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requirement of the license, line of sight communication, and so on (Parkash et al. 2016; Huang et al. 2018b, c, a; Mallick et al. 2019; Jiao et al. 2019). Different multiplexing schemes, such as wavelength division multiplexing (WDM) (Hitam et al. 2012; Aladeloba et al. 2013; Mandal et al. 2017; Huang et al. 2018b, c, a; Jiao et al. 2019), polarisation multiplexing (POLMUX) (Wu et al. 2020), space-division multiplexing (SDM) (Richardson et al. 2013) are being widely used to enhance the transmission capacity in FSO communication systems. A 320 Gbps/100 m SDM based FSO link has been demonstrated by Li et al. in the year 2016 (Li et al. 2016). Lu et al. have designed and demonstrated a 280 Gbps FSO link using WDM and SDM techniques (Lu et al. 2016). A 22.5 Gbaud four-level pulse amplitude modulation (PAM4) based 150 m FSO link has been designed using a 3 dB laser of bandwidth 10 GHz and injection locking technique (Li et al. 2017). A bidirectional FSO-wireless communication system has been developed utilising a dual polarisation process; one x-polarised optical sideband modulated with 56 Gbps vestigial sideband-PAM-4 data-rate and another y-polarised sideband is modulated with a 10 Gbps data-rate (Huang et al. 2018b, c, a). A Two-way 10 Gbps wireless-over-fibre and FSO-over-fibre link has been reported (Huang et al. 2018b, c, a). A 1.56 Tbps data rate has been achieved using the 4-quadrature amplitude modulation (QAM) technique (Ullah et al. 2019). Recently, OAM beams are dominating the field of spatial multiplexing. OAM carrying beam has a phase term $exp(il\varphi)$, where $l$ is the topological charge, $\varphi$ is the azimuth angle (Allen et al. 1992). The orthogonality between different $l$-valued OAM beams makes them suitable as data carriers (Willner et al. 2015). The combination of OAM multiplexing with WDM and POLMUX techniques enhances both the transmission capacity and spectral efficiency dramatically (Huang et al. 2014; Willner et al. 2012; Fazal et al. 2012). The utilization of OAM beams has also increased the security, decreased both the crosstalk and bit error rate (BER) value. There are various techniques for the generation and detection of OAM beams. A normal Gaussian beam can be converted into an OAM beam by using different devices, for example, spiral phase plates (SPPs) (Beijersbergen et al. 1994), spatial light modulators (SLMs) (Zhou et al. 2016), meta-surfaces (Chen et al. 2016; Yu et al. 2016), q plates (Cardano et al. 2012; Marrucci 2013), forked gratings (Bazhenov et al.1990; Heckenberg et al.1992) and so on. The OAM beams can also be detected by the devices, which are used for its generation. SLMs are commonly used devices for the generation and detection of OAM beams. SLM, with an inverse phase mask, can easily convert the OAM beam into a Gaussian beam. An 80 Gbps data-rate has been achieved using OAM multiplexing techniques by Li et al. (2017). We have reported a 100 Gbps free-space data transmission system by multiplexing ten 10 Gbps data-carrying OAM beams (Dutta et al. 2021). 400 Gbps free space data transmission system has been designed and demonstrated using OAM multiplexing and quadrature phase shift keying (QPSK) modulation technique (Ren et al. 2016). In our earlier work, 640 Gbps data rate is communicated over 180 m in free space using OAM multiplexing technique (Dutta et al. 2022). Fazal et al. have demonstrated 2 Tbps free-space data transmission system by multiplexing two OAM beams each carrying 25 wavelength channels (Fazal et al. 2012). But the generation and detection process of OAM beams is difficult in the above-mentioned works (Fazal et al. 2012; Li et al.2017; Dutta et al. 2021, 2022; Ren et al. 2016). Recently, Dammann optical vortex grating (DOVG) becomes a promising technique for the generation and multiplexing of the huge number of OAM channels and their parallel detection with uniform power distributions (Zhang et al. 2010; Wang et al. 2011). Zhang et al. have demonstrated $5 \times 5$ DOVG which can transmit and detect OAM beams, having $l$-values between $(-12)$ to $(+12)$ (Zhang et al. 2010). Wang et al. have proposed a DOVG, which is capable to transmit and receive 16 OAM modes simultaneously (Wang et al. 2011). However, in most of these architectures, a huge number of laser sources have been used, which makes the system complicated and costly (Huang et al. 2014; Fazal et al. 2012). A self-injection locked quantum dash-laser diode (QD-LD) may become a promising solution to overcome this complicacy and to make the system cost-effective. A self-injection locked QD-LD provides optical frequency comb lines (OFCLs) with high side mode suppression ratios (SMSRs) and narrow line-width (Shemis et al. 2018; Mandal et al. 2018; Mukherjee et al. 2020). Thus, it offers suitable carrier beams for FSO communication and widens the bandwidth. Along with the complicacy of sources the reported Tbps-scale data transmission systems have a limited transmission length of 1 to 2 m (Fazal et al. 2012).In this paper, a 10 Tbps ($10 \times 10 \times 2 \times 50$ Gbps) free-space data link using the self-injection locked QD-LD and based on WDM, POLMUX, and OAM multiplexing techniques have been proposed and verified using simulation. The utilization of self-injection locked QD-LD makes the system cost-effective compared to the established architectures of this field. Selection of proper modes from the self-injection locked QD-LD results in a significant reduction of crosstalk. DOVG-enabled generation, multiplexing, and detection of OAM beams have been used due to its potential to detect OAM states with uniform power distribution. Sufficient separation between the OAM modes ($\Delta l = \pm 3$) reduces the intermodal crosstalk significantly. Transmission and detection of 200 channels ($10 \times 10 \times 2$) have been performed in the proposed FSO communication system. The efficiency of the system is verified by checking eyes, constellation diagrams, measuring bit error rate (BER) value, and crosstalk with power penalty. MATLAB-2017 and Optisystem-14.0 are utilised to execute the simulation work.

## 2 Simulation setup

Figure 1 shows the proposed setup of the FSO data transmission system using self-injection locked QD-LD and multiplexing of OAM beams along with WDM and POLMUX techniques. In this work, the self-injection locked QD-LD is composed of a QD-LD, an optical circulator (OC), an erbium-doped fibre amplifier (EDFA), a coupler (CP), and a tuneable band pass filter (TBPF). To set up the self-injection locked QD-LD, at first the output laser beam from the QD-LD is fed to the EDFA through the second port of the optical circulator and then half of the amplified laser beam is fed back into the laser using a 3 dB coupler. A TBPF is placed in the feedback path to select appropriate modes and powers, which need to be re-injected into the active region of the laser cavity. Ten 50 GHz spaced optical modes (1550.8–1554.4 nm) having a high side mode suppression ratio (SMSR > 35 dB) are obtained from a self injection-locked QD-LD centred at 1552 nm. Researchers may face several difficulties in using the self-injection locked QD-LD as a WDM source, since relative intensity noise (RIN) of the chosen modes get increased due to the mode partition noise, especially at a lower frequency. In the proposed system the RIN value is restricted within-135 dBm/Hz as shown in Fig. 2. The selected 10 modes from the self-injection locked QD-LD are combined using a $1 \times 10$ arrayed waveguide grating (AWG). Then the multiplexed signal is amplified by an EDFA, and each mode is modulated with a 50 Gbps QPSK signal. The multiplexed signal is split into 10 branches and each branch is converted into one of the ten OAM modes ($l = \pm 3, \pm 6, \pm 9, \pm 12, \pm 15$) using a 10-order DOVG. Thereafter the multiplexed OAM channel is split into two orthogonal polarisation states using a polarisation beam splitter (PBS). After that, the two branches are combined again

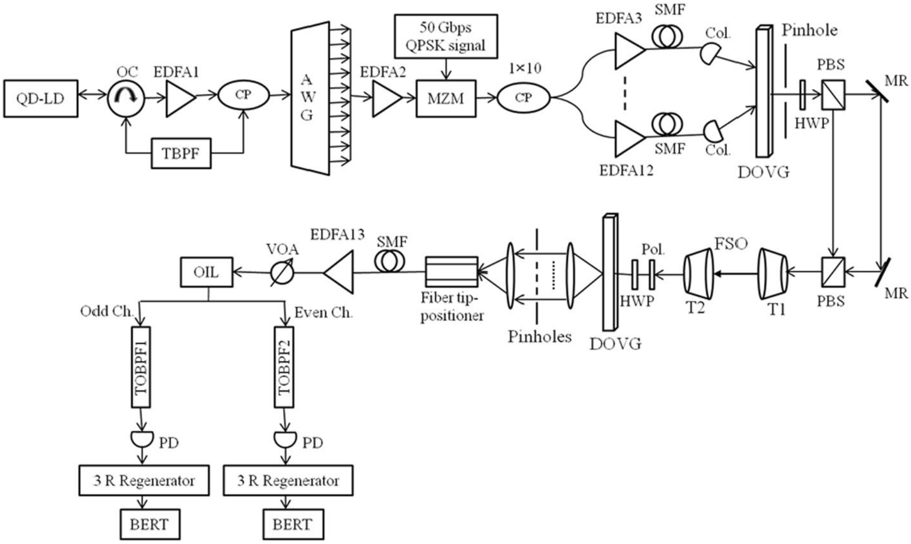



**Fig. 1** Block diagram of the proposed free-space data transmission system

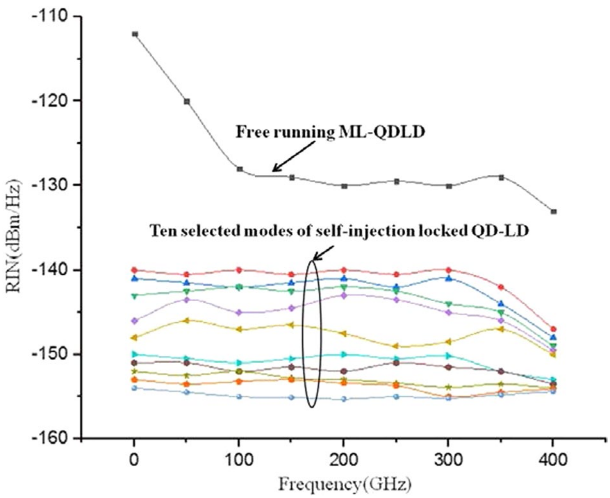



**Fig. 2** Variation of RIN of free-running ML-QDLD and ten modes of self-injection locked QD-LD

using another PBS and transmitted over the FSO link, which consists of two telescopes. Thus, a total of $(10 \times 10 \times 2)$ i.e. 200 data channels have been transmitted over a single FSO link. After passing through the FSO link the polarisation de-multiplexing is carried out employing a polariser and then passed through an half wave plate (HWP) before transmitting through DOVG to convert the OAM beams into Gaussian beams. The HWP is used to optimise the polarisation states of different modes before transmitting through the DOVG. Pinhole apertures have been used to filter the Gaussian beams from the OAM beams. Then the beams are focused using a lens and coupled into the fibre using a fibre-tip-positioner. After that, the signal is amplified by another EDFA and the noise is attenuated by a variable optical attenuator (VOA) and fed to an optical interleaver (OIL) to separate the odd and even channels. After the selection of appropriate wavelength channels using a tuneable optical band-pass filter (TOBPF), each channel is detected by photo detector. Then the signal is passed through 3R-regenerators and fed to the BER tester to check the BER value and eye diagrams. A computer-generated $(1 \times 10)$ DOVG having transition points within a period of 0.10838, 0.11857, 0.19679, 0.23559, 0.31524, 037300, and efficiency of 83%have been utilized for the proposed system (Zhou and Liu 1995). The phase structure of the DOVG for the OAM generation process can be described as (Zhou and Liu1995; Wang et al. 2011),

$$F = \sum_{n=-\frac{N}{2}}^{\frac{N}{2}} U_n exp\left[in\left(\frac{2\pi x}{\tau} + \Delta l \times \varphi\right)\right] \tag{1}$$

where $N$ = total no. of diffraction orders, $\tau$ = period of the grating, $n$ = diffraction order of a particular beam, $\varphi$ = azimuth angle, $\Delta l$ = separation between two OAM modes. $\left|U_n\right|^2$ = normalized power of the n-th order beam. As per Eq. (1), a Gaussian beam incident on the DOVG will be diffracted into N orders, each with equally distributed energy and a topological charge of $n \times \Delta l$. In the proposed architecture the incident Gaussian beams are converted into the superposition of OAM beams. The transmittance function for the generation of N superimposed OAM beams is given by Zhou and Liu (1995), Zhang et al. (2010), Wang et al. (2011),

$$T = \sum_{n=-\frac{N}{2}}^{\frac{N}{2}} U_n exp[in\Delta l \times \varphi] \tag{2}$$

At the receiver section, to convert the OAM beams into Gaussian beams, another DOVG is used such that an OAM beam, having a topological charge $n' \times \Delta l$ will be diffracted into N orders after being incident on the DOVG. The phase structure of the DOVG for this diffraction can be represented as (Zhou and Liu 1995; Zhang et al. 2010; Wang et al. 2011)-

$$F' = \sum_{n=-\frac{N}{2}}^{\frac{N}{2}} U_n exp\left[in \times \left(\frac{2\pi x}{\tau} + \Delta l \times \varphi\right) + in'\Delta l \times \varphi\right] \tag{3}$$

Thus $-n'$th order diffraction beam will be transformed to the Gaussian shape corresponding to the incident OAM beam.

## 3 Results and discussion

The optical spectra of selected ten modes from the self-injection locked QD-LD with a spacing of 50 GHz (1550.8–1554.4 nm) are shown in Fig. 3. Each mode is obtained with sufficiently high side-mode-suppression-ratios (> 35 dB) due to the most advantageous injection locking performed in the proposed system. Figure 4. shows the phase profiles of OAM beams having topological charges $l = \pm 3, \pm 6, \pm 9, \pm 12, \pm 15$. This variation in phase structures maintains the orthogonality between different OAM beams. The OAM of the light waves can be estimated from their phase structures.

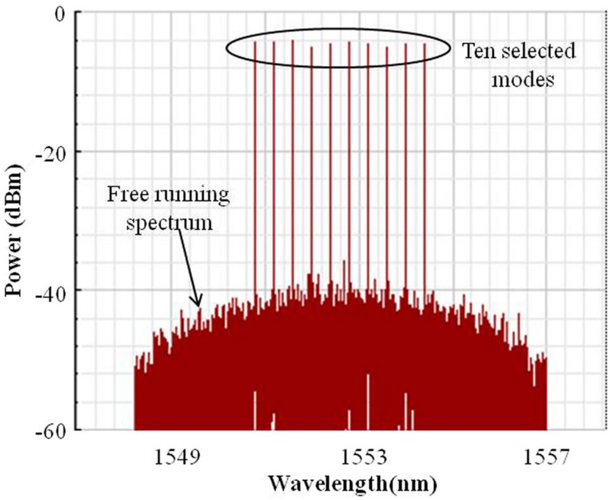



**Fig. 3** Optical spectra of selected ten modes of the self-injection locked QD-LD

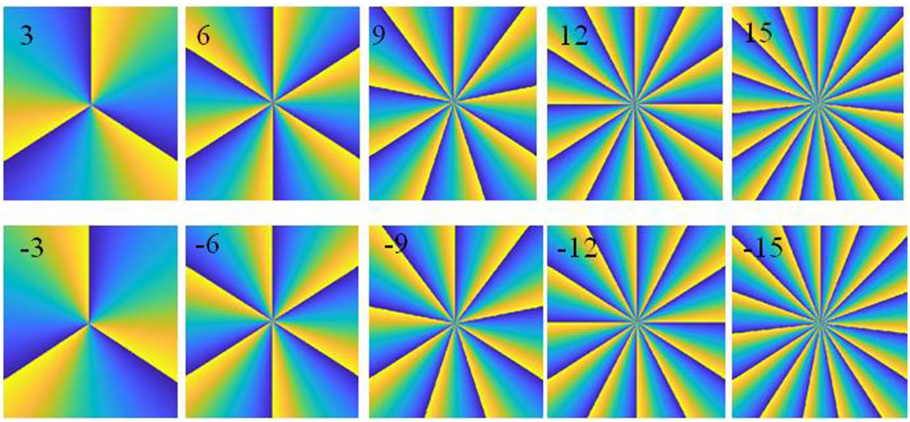
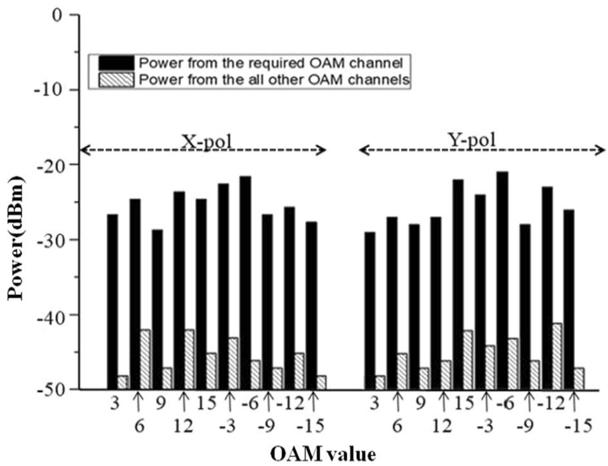



**Fig. 4** Phase profiles of OAM beams having topological charges ($l = \pm 3, \pm 6, \pm 9, \pm 12, \pm 15$) respectively

Figure 5 shows the power received from the desired channel ($P_d$) and power from all other channels ($P_{oth}$), which induces crosstalk to desired OAM beam. The crosstalk is defined as the ratio of $P_d$ to $P_{oth}$. The crosstalk is bounded in between − 14.6 and − 23.07 dB for the proposed system. Figure 6 shows the power penalty of OAM + 9 in X-polarisation with crosstalk and without crosstalk. Figure 6. depicts that an additional power penalty of ~ 0.4 dB is induced on OAM + 9 because of the crosstalk due to all other OAM modes. The crosstalk can be significantly reduced using higher-order DOVG. Figure 7 shows the variation of BER as a function of optical signal to noise ratio (OSNR) for (1) back-to-back, (2) without modal and wavelength crosstalk, and (3) with modal and wavelength crosstalk. For condition (2) only one set of OAM beams is on, while the adjacent wavelength channels are off and for condition (3) all the OAM

**Fig. 5** Measurement of crosstalk for all the OAM modes contained by channel-1



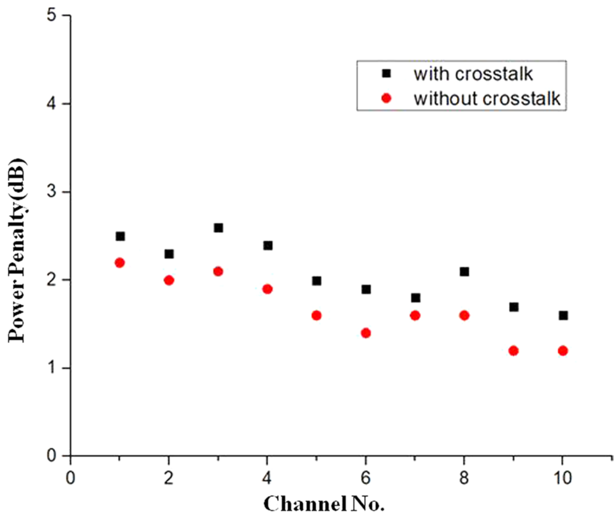



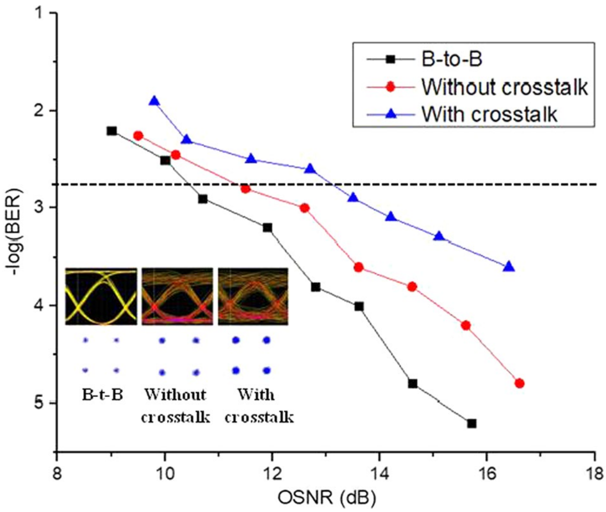

**Fig. 6** Measurement of power penalty for OAM + 9 with and without crosstalk from all other OAM modes

channels and wavelength channels are on. Mathematically BER and OSNR are related as,

$$BER = \frac{1}{2} \times erfc\left(\sqrt{OSNR}\right) \quad (4)$$

where $erfc(x) = \left(\frac{2}{\sqrt{n}}\right) \int_x^\infty e^{-v^2} dv$. Figure 7 is well agreed with Eq. (4). A net power penalty of ~ 2.1 dB at a BER of $2.2 \times 10^{-3}$ has been produced by both the WDM crosstalk and OAM crosstalk. The eye diagrams and the constellation diagrams for channel-1 are also shown in Fig. 7. For all channels, open eye and clear constellation diagrams have validated the efficiency of the proposed system for FSO communication.

**Fig. 7** Plot of BER versus OSNR along with eye and constellation diagrams for channel-1 for B-t-B, without crosstalk, and with crosstalk




## 4 Conclusion

A 10 Tbps free-space data transmission using successive multiplexing of wavelength, OAM, and polarisation of light-wave have been successfully proposed and represented using simulation. Sufficient low power penalty of 2.1 dB at forward error correction (FEC) threshold BER value of $2.2\times10^{-3}$, open eye, and clear constellation diagrams have been achieved, which have affirmed the feasibility of the system. The utilization of self injection-locked QD-LD significantly reduces the cost of the system. The crosstalk is also restricted between − 14.6 and − 23.07 dB due to the different topological charges of OAM beams. The utilization of self-injection locked QD-LD significantly reduces the cost of the system. DOVG has simplified the generation and detection process of OAM beams and may become an emerging technique for the OAM based communication system. Terabit scale data rate transmission is achieved in the proposed system with low crosstalk, power penalty, and BER value, which confirms that our proposed architecture is suitable for terabit scale FSO communication.

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**Data availability** The data that support the findings of this study are available from the corresponding author upon reasonable request.

## Declarations

**Conflict of interests** The authors declare that they have no conflict of interests.

**Ethical approval** The authors declare that this is their original work, and this paper has not been submitted to any other journals.

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