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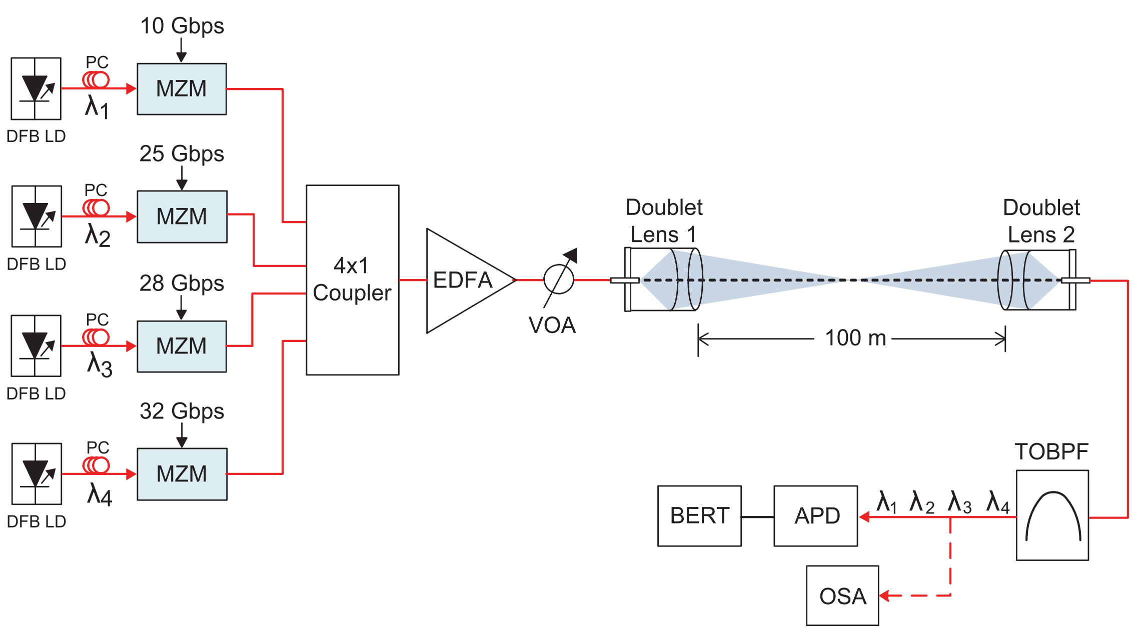

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WDM Free-Space Optical Communication System of High-Speed Hybrid Signals

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Abstract: A wavelength-division-multiplexing (WDM) free-space optical (FSO) communication system of a high-speed hybrid signal is proposed and demonstrated in this study. This study is the first to transmit a high-speed hybrid signal mixed with four wavelengths that are modulated with different signals, namely 10, 25, 28, and 32 Gb/s, using a single beam. Favourable bit error rate (BER) and clear eye maps are achieved by adopting parameters after investigating the bandwidth of tuneable optical bandpass filter, channel spacing, and number of mixed light channel effects on system performance. The WDM-FSO communication system of a high-speed hybrid signal has a simple configuration, low cost, and low BER.

Index Terms: Distributed feedback laser, wavelength division multiplexing, free-space optical communication, visible light.

1. Introduction

The issue of limited frequency spectrum of a traditional RF system becomes increasingly critical because of the rapid development and deployment of wireless networks. However, such a problem can be relieved by the implementation of free-space optical (FSO) communication technology. This system is suitable for circumstances where fibre optic cables cannot be laid [1]–[5]. The FSO communication system has the advantages of unrestricted spectrum and high-speed transmission over other wireless communication systems. This system is likely to replace other wireless communication systems in many fields and become the solution for last-mile communication. Communication is currently required to provide rich bandwidths, and a wavelength division multiplexing (WDM) technology can be used to solve this problem. This technology is widely used in optical fibre networks and is slightly mature. The use of the WDM technology in the FSO communication system is a new research field. The WDM-FSO has been attempted several times [6]–[9]. The FSO transmissions use single or multiple beams. For the single-beam system, the WDM channels are modulated with the same signal. In addition, the WDM channels that are modulated with different

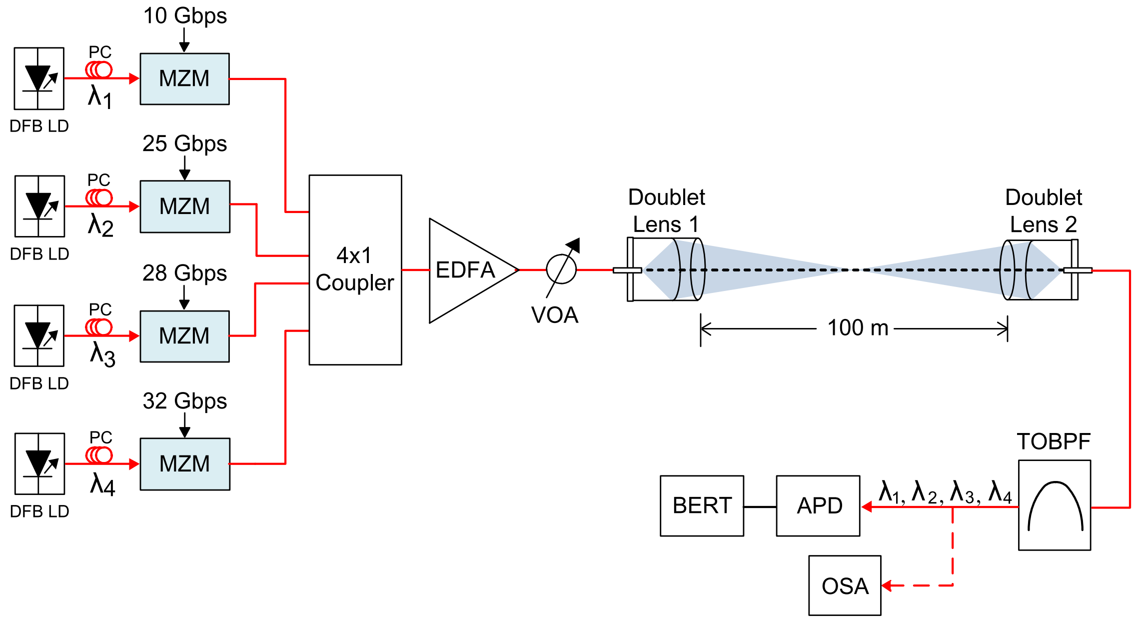

Fig. 1. Configuration of the proposed WDM-FSO communication system that transmits hybrid signals through a doublet lens scheme.

signals are proposed by using only simulated results [10]–[14]. The optical lens for the multi-beam WDM-FSO increase with the number of WDM channels, thereby considerably increasing the cost of the network [6]–[9], [15]–[17]. This study demonstrates a WDM-FSO communication system that transmits hybrid signals, wherein four wavelengths are modulated with various high-speed signals using a single beam. This study is the first successful implementation of a WDM-FSO communication system of high-speed hybrid signals using a single-beam transmission. A favourable bit error rate (BER) performance and a clear eye map over a 100 m free-space optical can be achieved through appropriate channel spacing. The proposed WDM-FSO communication system of high-speed hybrid signals is a promising scheme to obtain a high-speed and long-distance FSO transmission.

2. Experimental Setup

The experimental configuration of the proposed WDM-FSO communication system that transmits hybrid signals through a doublet lens scheme is plotted in Fig. 1. The system is built indoors. In this figure, four signals, namely, 10, 25, 28 and 32 Gbps, are transmitted concurrently. The transmitter side has four distributed feedback lasers (DFBs) with different wavelengths. The outputs of these DFBs are fed into four Mach–Zehnder modulators, which are modulated by 10, 25, 28 and 32 Gbps data streams mixed by a 4×1 coupler and directed to an erbium-doped fibre amplifier (EDFA) for light signal amplification. The light signal is sent through a variable optical attenuator (VOA) after being amplified. The VOA is used to optimise the light power output into the free space and obtain the optimum transmission performance.

A pair of doublet lenses (doublet lenses 1 and 2) is introduced to transmit light signals from an optical fibre to the free space and couple light signals from the free space to the optical fibre. A pair of doublet lenses is configured to direct four light signals from an optical fibre onto the free space and couple four light signals from the free space to the optical fibre. The 100 m free-space transmission is accomplished by the system by designing doublet lenses (doublet lenses 1 and 2). The doublet lenses consist of biconvex and biconcave lenses. The back focal length (FL) is 87.8 mm, the radius is 15 mm and the FL is 100 mm. The laser beam is emitted to doublet lens 1 through a single-mode fibre (SMF) whose numerical aperture is 0.14. The beam focalises firstly

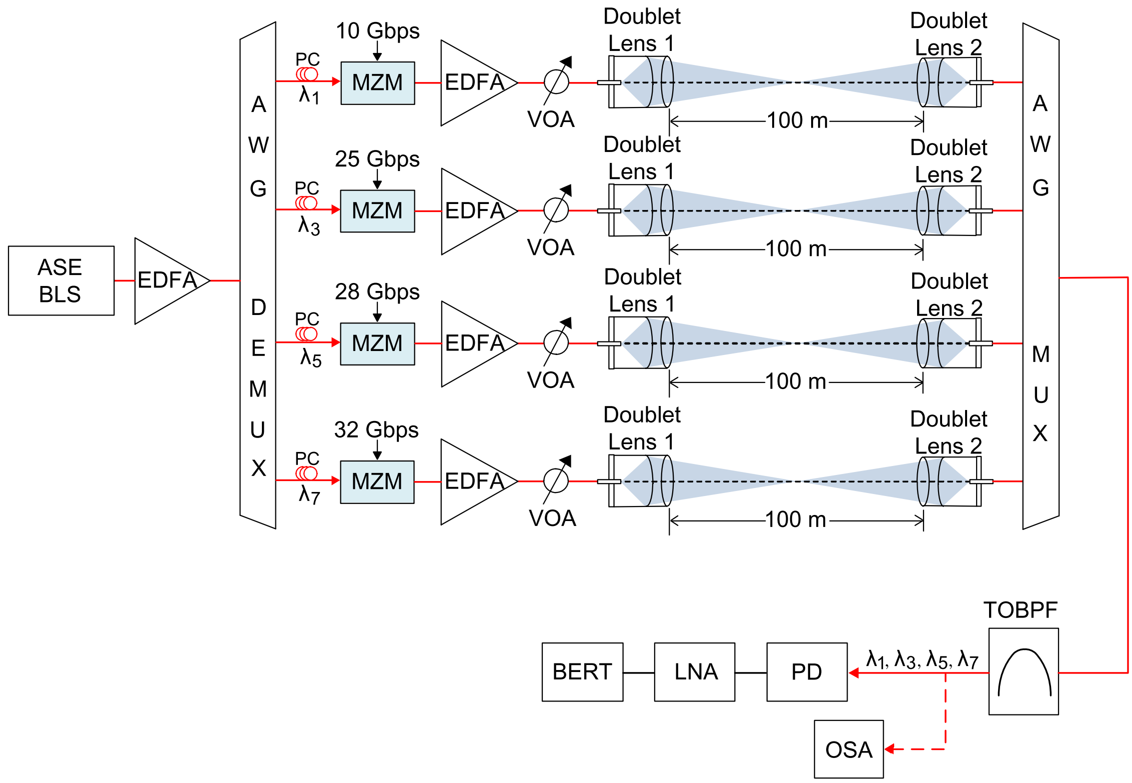

Fig. 2. Configuration of a DWDM FSO communication system through the SDM technique.

through doublet lens 1 and then diverges in free space. It is finally coupled to the SMF by doublet lens 2.

The light signal over a 100 m free-space link is fed into a tuneable optical band-pass filter (TOBPF) to obtain the required optical wavelength. The selected optical signal is detected by an avalanche photodiode to gain 10, 25, 28 or 32 Gbps data streams. The high-speed data stream is fed into a BER tester (Anritsu MU183040B - 32 G High-sensitivity ED) for BER performance evaluation.

3. Experimental Results and Discussion

A DWDM-FSO communication system that uses a multi-beam with the space division multiplexing (SDM) technique [15] can be a succedaneum for the proposed WDM-FSO communication system, which transmits hybrid signals through the doublet lens scheme (Fig. 2). The output of the amplified spontaneous emission broadband light source is amplified by an EDFA and separated into four odd channels (λ1, λ3, λ5 and λ7) by a 1 $\times$ 8 arrayed waveguide grating (AWG) de-multiplexer with a channel of 0.8 nm. Each wavelength light is independently transmitted with the SDM technique. A four-channel FSO link lead is required to increase the cost of a system compared with the proposed WDM-FSO communication system of high-speed hybrid signals.

ITU-TG694.1 defines the interval between each wavelength of the DWDM communication system and is set to 0.8 nm or integer multiples of 1.6 or 0.4 nm (1/2 multiple of 0.8 nm). The channel spacing of 1.6 nm/0.8 nm/0.4 nm is utilised for a conventional DWDM fibre optic communication system. FSO, as an extension of the optical fibre communication, is suitable for use in these intervals. The TOBPF, as the actual device, cannot filter the influence of adjacent channels completely because the proposed DWDM-FSO communication system is the actual system. The spectrum of the signal from the TOBPF over a 100 m FSO channel is displayed in Fig. 3. The signals of adjacent channels traverse the TOBPF with minimal residues. The bandwidth and channel spacing of the TOBPF

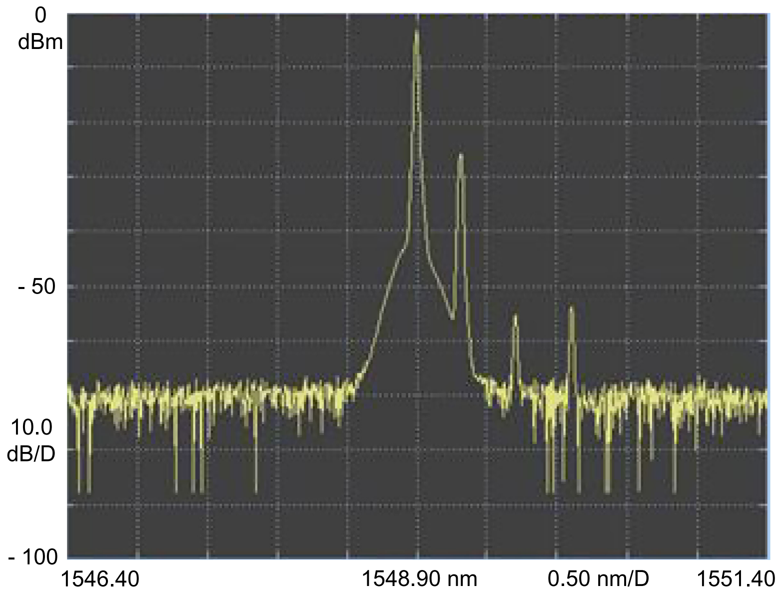

Fig. 3. Spectrum of one signal from the TOBPF (filter bandwidth is 0.25 nm, and channel spacing is 0.4 nm) over a 100 m FSO channel.

TABLE 1
Measured BER of the DWDM-FSO Communication system at a Data Stream of λ_4 for Different Channel Spacing Over a 50 m FSO Channel

Channel spacing (nm)	Bandwidth of TOBPF	
	0.25 nm	**0.4 nm**
0.4	0×10^{-14}	8.4612×10^{-11}
0.8	0×10^{-15}	0×10^{-14}
1.2	0×10^{-15}	0×10^{-15}
1.6	0×10^{-15}	0×10^{-15}

TABLE 2
Measured BER of the DWDM-FSO Communication System at a Data Stream of λ_4 for Different Channel Spacing Over a 100 m FSO Channel

Channel spacing (nm)	Bandwidth of TOBPF	
	0.25 nm	**0.4 nm**
0.4	1.5426×10^{-11}	3.7528×10^{-10}
0.8	0×10^{-14}	1.1523×10^{-11}
1.2	0×10^{-15}	0×10^{-14}
1.6	0×10^{-15}	0×10^{-15}

affect the BER. The measured BER of the DWDM-FSO communication system at a data stream of $\lambda4$ for different channel spacing are summarised in Tables 1 and 2. The minimum BER can be measured at 0×10^{-15} because of the limitation of the instrument. This table indicates that the BER decreases with the increase in channel spacing. The BER is less than 0×10^{-15} (accumulative time was around 521 minutes) when the channel spacing is greater than 1.2 nm. Similarly, with $\lambda4$ as an example, Fig. 4 shows that the channel spacing is at 0.4 nm. The deterioration of BER occurs

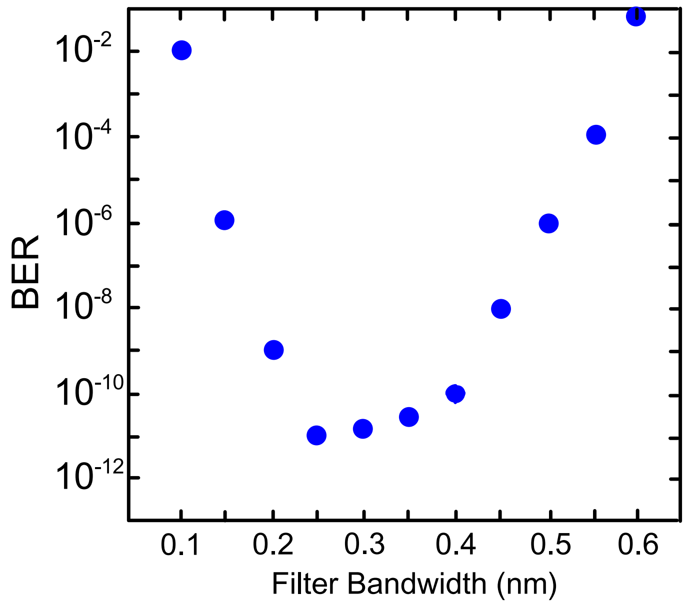

Fig. 4. Trend of BER relative to the filter bandwidth.

TABLE 3
Measured BER of the DWDM-FSO Communication System at a Data Stream of 32 Gbps (λ4) for Different Numbers of Hybrid Light Channels Over a 50 and 100 m FSO Channel When the Bandwidth of the TOBPF is 0.25 nm

Number of hybrid light channels	Communication distance	
	50 m	100 m
1 (λ_4)	0×10^{-15}	0×10^{-15}
2 ($\lambda_1+\lambda_4$)	0×10^{-15}	0×10^{-14}
2 ($\lambda_2+\lambda_4$)	0×10^{-15}	0×10^{-14}
2 ($\lambda_3+\lambda_4$)	0×10^{-14}	1.5421×10^{-11}
3 ($\lambda_1+\lambda_2+\lambda_4$)	0×10^{-15}	0×10^{-14}
3 ($\lambda_2+\lambda_3+\lambda_4$)	0×10^{-14}	1.5860×10^{-11}
3 ($\lambda_1+\lambda_3+\lambda_4$)	0×10^{-14}	1.5298×10^{-11}
4 ($\lambda_1+\lambda_2+\lambda_3+\lambda_4$)	0×10^{-14}	1.5333×10^{-11}

when the filter bandwidth of TOBPF exceeds 0.4 nm, which is mainly caused by the interference between adjacent channels. On the contrary, the BER is optimised because the filter bandwidth of TOBPF is smaller than 0.4 nm. The BER deteriorates when the filter bandwidth of TOBPF is lower than 0.25 nm because the bandwidth and light power of the light signal are affected. The results show that the best BER value (1.5×10^{-11}) is obtained when the filter bandwidth of TOBPF is equal to 0.25 nm.

The measured BERs of the DWDM-FSO communication system at a data stream of λ4 for different numbers of hybrid light channels are presented in Tables 3 and 4. This system adopts the single FSO channel (Fig. 1) that contains many light signals within in contrast to an SDM-FSO system (Fig. 2) with a single light signal in a single FSO channel. Therefore, the BER of λ4 (32 Gbps) is measured when the system transmits different amounts and wavelengths of light signals [10 (λ1), 25 (λ2), 28 (λ3) and 32 Gbps (λ4)] with a channel spacing of 0.4 nm and TOBPF bandwidths of 0.25 and 0.4 nm. In addition, whether interference exists between signals in transmitting many

TABLE 4
Measured BER of the DWDM FSO Communication System at a Data Stream of 32 Gbps (λ4) for Different Numbers of Hybrid Light Channels Over a 50 and 100 m FSO Channel When the Bandwidth of the TOBPF is 0.4 nm

Number of hybrid light channels	Communication distance	
	50 m	100 m
1 (λ_4)	0×10^{-15}	0×10^{-14}
2 ($\lambda_1+\lambda_4$)	0×10^{-15}	0×10^{-14}
2 ($\lambda_2+\lambda_4$)	0×10^{-15}	0×10^{-14}
2 ($\lambda_3+\lambda_4$)	8.8612×10^{-11}	2.9971×10^{-10}
3 ($\lambda_1+\lambda_2+\lambda_4$)	0×10^{-14}	0×10^{-14}
3 ($\lambda_2+\lambda_3+\lambda_4$)	8.3112×10^{-11}	3.5428×10^{-10}
3 ($\lambda_1+\lambda_3+\lambda_4$)	8.4298×10^{-11}	3.7298×10^{-10}
4 ($\lambda_1+\lambda_2+\lambda_3+\lambda_4$)	8.4612×10^{-11}	3.7528×10^{-10}

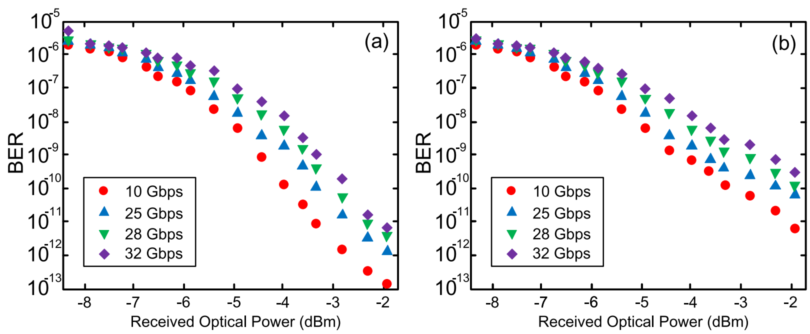

Fig. 5. Measured BER curves for the proposed WDM-FSO communication system at 10, 25, 28 and 32 Gbps data streams over (a) a 50 and (b) 100 m FSO channel.

light signals in a single FSO channel is determined. The result indicates that the change in BER is not related to the increase in wavelength but is affected by the incomplete filtering out of adjacent wavelengths through the TOBPF and the different light powers received after transmitting different distances.

The measured BER curves of the proposed WDM-FSO communication system at a data stream of λ1–λ4 over a 50 and 100 m FSO channel are illustrated in Fig. 5. The adopted bandwidth of the TOBPF and channel spacing is 0.4 nm, considering the future possible AWG applications at the transmitter side. Fig. 5(a) shows that the BER value for transmitting 10, 25, 28 and 32 Gbps data streams in a 50 m FSO channel is higher than 10^{-9} when the received optical power is less than −3 dBm. Fig. 5(b) shows that the BER for transmitting 10, 25, 28 and 32 Gbps data streams in a 100 m FSO channel can also reach 10^{-9} under the receiving light power of −3 dBm. The corresponding eye diagram is illustrated in Fig. 6. Fig. 6(a) depicts the eye diagram measured at the receiving light power of −3.4 dBm for a 50 m FSO channel with 32 Gbps data stream. Fig. 6(b) demonstrates the eye diagram measured at the receiving light power of −3 dBm for a 100 m FSO channel with 32 Gbps data stream. The proposed WDM-FSO communication system of high-speed hybrid signals has a favourable BER value and clear eye maps in the transmission through a 50 and 100 m FSO channel whilst greatly reducing system complexity.

4. Conclusion

A WDM-FSO communication system of high-speed hybrid signals is proposed and demonstrated experimentally. The appropriate bandwidths of the TOBPF and channel spacing are selected, and

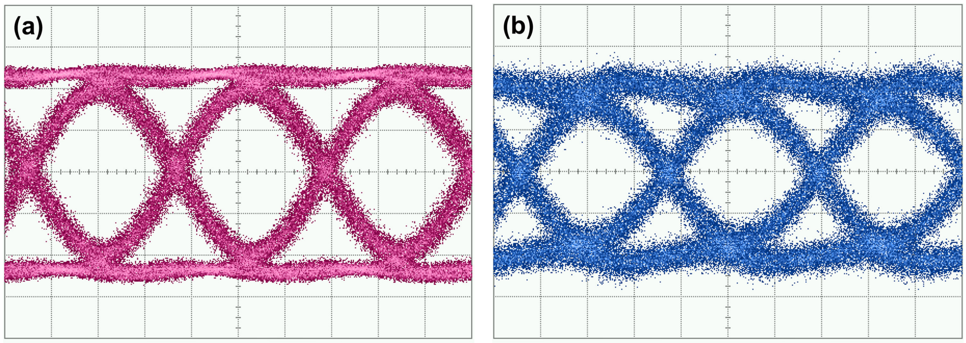

Fig. 6. Eye diagrams of the 32 Gbps (λ4) signal over (a) a 50 and (b) 100 m FSO channel.

a doublet lens scheme that is suitable for high-speed hybrid signal transmissions is designed. The WDM-FSO communication system is the first to use the WDM-FSO technique to transmit high-speed hybrid signals, in which four signals, namely, 10, 25, 28 and 32 Gbps, are mixed using a single-beam transmission communication. The performance of the proposed communication system with over 100 m free-space link is evaluated by using BER and eye diagram maps. The evaluation results indicate that the WDM-FSO communication system of high-speed hybrid signals demonstrates simple configuration, low cost and low BER. The proposed communication system is an eminent alternative to a high transmission rate for high-speed light-based Wi-Fi applications.

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