IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 10, Number 4, August 2018

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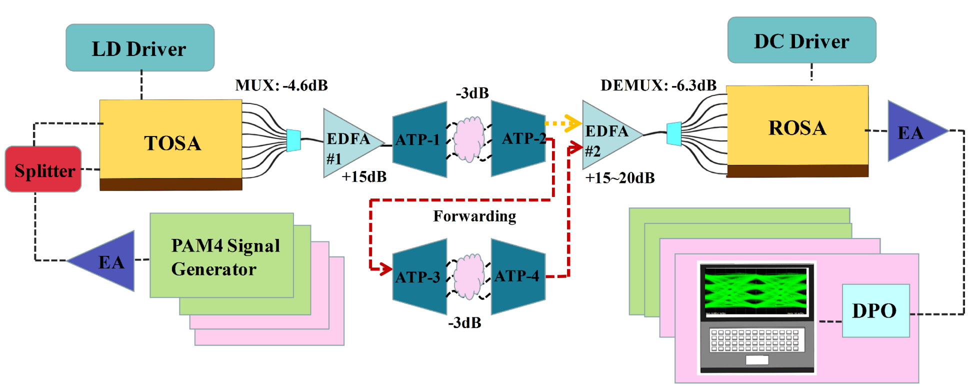

DOI: 10.1109/JPHOT.2018.2851558
1943-0655

200 Gb/s FSO WDM Communication System Empowered by Multiwavelength Directly Modulated TOSA for 5G Wireless Networks

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DOI:10.1109/JPHOT.2018.2851558

Manuscript received May 21, 2018; revised June 21, 2018; accepted June 25, 2018. Date of publication June 29, 2018; date of current version July 16, 2018. Corresponding author: Jianguo Liu (jgliu@semi.ac.cn).

Abstract: In this paper, a 200-Gb/s free-space optical (FSO) wavelength division multiplexing (WDM) transmission architecture based on multiwavelength directly modulated transmitter optical sub-assemblies for 5G wireless networks has been proposed and demonstrated experimentally. Pulse amplitude modulation-4 (PAM-4) modulation format is adopted in our scheme to further improve system capacity. In order to demonstrate the feasibility of our scheme, the outdoor experiments with 25 Gb/s PAM-4 are tested in free space. With 8 $\times$ 25 Gb/s $\sim$50-m outdoor transmission between the two buildings, the eye diagrams and bit error rates (BERs) are tested for one-hop system and forwarding system, respectively. For one-hop system, clear eye diagrams and stable BER performance are demonstrated in all the wavelengths. For the forwarding system, the values of BER with eight channels are measured lasting for 30 min that range from 1E-2 to 1E-3. The experimental results show that the scheme is feasible in FSO transmission system for 5G wireless networks. The advantages of integration, channelization, miniaturization, and low power consumption of the FSO WDM scheme present a promising result on constructing the future fronthaul/backhaul link for wireless cellular networks and optical access network extension.

Index Terms: Free-space optical communication, wavelength division multiplexing, directly modulated TOSA, 5G wireless networks.

1. Introduction

The free-space optical (FSO) communication have recently attracted extraordinary attention within the research community because of their advantages such as high capacity, free license optical spectrum bands, network flexibility, etc. [1]–[3]. It have been considered as a promising field and can be applied for many scenarios like spatial optical communication, back-haul for wireless cellular networks, and optical access network extension [4]. In recent time, the rapid evolution of 5G wireless systems necessitate quantum jump of data rate, system capacity and spectral efficiency for front-haul and back-haul networks [5], [6], while the one of main challenges of the 5G wireless systems is to transmit massive heterogeneous data which from different network planes into the core network. This indicates that 5G wireless systems need adoption of spatial multiplexing, efficient modulation formats and integration with core optical backbone transmission route. Considered the advantages of FSO communication systems, a combination of FSO and wavelength-division multiplexing (WDM) is necessary for 5G for forming complementary the strengths. Many studies have been carried out for analyzing the performance of WDM FSO systems. Pei-Lin Chen etc. present a 16×10 Gb/s WDM transmission in a terrestrial FSO link using sixteen distributed feedback (DFB) lasers with on/off keying (OOK) modulation [7]. In [8], a 60 cm FSO card-to-card WDM transmission architecture using OFDM modulation is demonstrated and the net data rate is up to 106.9 Gb/s. E. Ciaramella etc. verify a record 8×40 Gb/s WDM transmission between the roofs of two buildings [9], and next year their group support a record high capacity FSO WDM transmission (32×40 Gbit/s) with OOK modulation [10]. While the devices adopted in the above systems are discrete that make the system complex and cost a lot. In [11], Mbah *et al.* derived simplified expressions of the probability of outage in the presence of turbulence-accentuated interchannel crosstalk. In 2017, Madhusudan Singh etc. theoretically analyzed the transmission performance of WDM FSO link in the presence of optical and wireless nonlinearities [12]. To our best of knowledge, most of the related FSO WDM researches have mainly focused on theory or model simulation. What's more, most of the existing FSO WDM transmission experiments use the OOK modulation format. In addition, WDM transmission based on optical frequency comb (OFC) for FSO communication also has been investigated [13], [14], but it cannot meet the requirements of integration and high capacity at the same time. Therefore, a 200 Gb/s FSO WDM communication system empowered by a integrated transmitter module instead of discrete devices has been proposed. PAM-4 high-order modulation format has also been verified to further improve the system capacity. Compared with the WDM FSO systems mentioned above, the proposed system can simultaneously meet system simplicity and high speed transmission.

In despite of the major advantages of FSO communication, its widespread use has been hampered by weather conditions like fog, rain, haze, atmospheric turbulence, pointing error and misalignment etc. Some of these impairments are avoidable by adopting different kind of solutions. One method is to employ spatial multiplexing technique with multiple transmitters and receivers. Multiple-input multiple-output (MIMO) optical channel technology has been recently studied both theoretically and experimentally [15], [16]. Another method to improve the reliability of FSO system is setting up multi-hop relaying transmission system, it can mitigate the effects of fading and extend coverage in FSO communication systems [17], [18]. However, the limitation of both the MIMO and multi-hop relaying transmission techniques increases the deployment cost and complexity of the system. For 5G wireless networks, the efficient fronthaul/backhaul of small cell base stations (SBSs) is still a significant challenge. Therefore, it is necessary to explore a novel radio access network (RAN) architecture to realize a dense small cell deployment. In this paper, the proposed scheme can be well integrated with 5G wireless networks mentioned by [19]. Fig. 1 shows the graphical illustration of the proposed system integrated with vertical backhaul/ fronthaul framework for 5G wireless networks. The networked flying platforms (NFPs) that can carry heavy payloads (FSO transceivers) are adopted for providing communications services and they would move based on weather conditions and coverage requirements. The NFPs to core network connectivity and the communication between the NFPs are all based on FSO links. Each SBS with a clear line-of-sight (LOS) link communicate with intended NFP via an point to point FSO link. On the other hand, SBSs with no LOS with a NFP can be served by a nearby SBS which has a clear LOS with a NFP. The scheme we proposed not only enables a super high rate data communication between NFPs, but also distributes data to various base stations at the same time.

In this paper, a FSO WDM transmission architecture based on multi-wavelength directly modulated TOSA has been demonstrated experimentally. Given the limitations of experimental conditions, only outdoor experiments between the two buildings with 25 Gb/s PAM-4 are tested in free space. With 8×25 Gb/s $\sim$ 50 m outdoor transmission, the eye diagrams and BERs are tested for

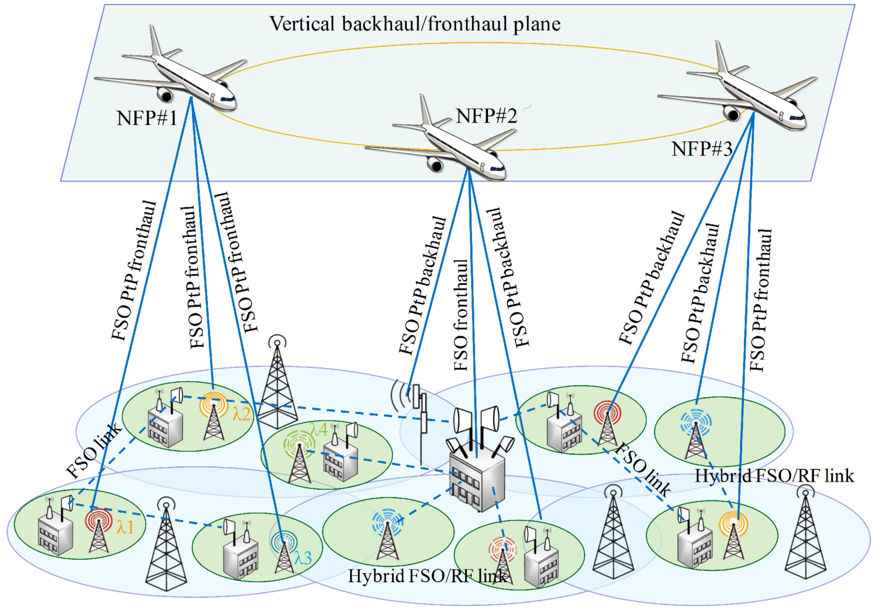

Fig. 1. The graphical illustration of the proposed system integrated with vertical backhaul/ fronthaul framework for 5G wireless networks.

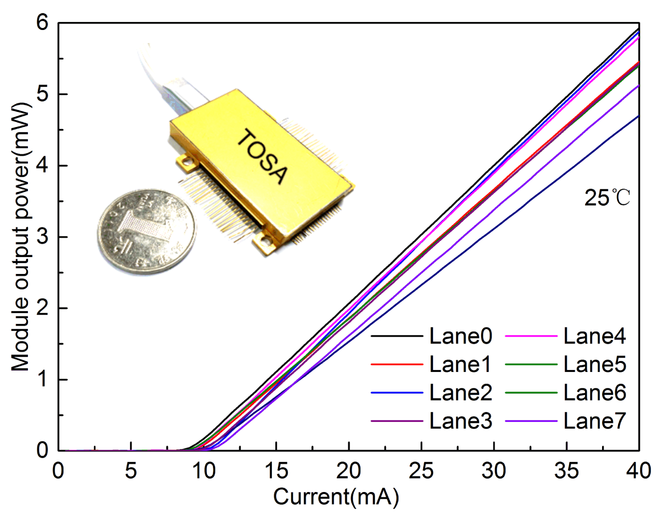

Fig. 2. The P-I characteristic and the photograph of TOSA.

one-hop system and forwarding system, respectively. The experimental results preliminarily prove the feasibility of the scheme.

2. Transmitter Optical Sub-Assembly

The TOSA whose the photograph shown in Fig. 2 is fabricated in our laboratory and it consists of three parts that are eight independent laser chips array, a ceramic board and double-lens array with isolators [20]. The laser chips adopt the InGaAsAl multiple quantum well (MQW) as active region structure and its wavelength is well controlled by phase shifts based on the reconstruction-equivalent-chirp. DMLs array, double lens and isolators array share a common thermoelectric cooler

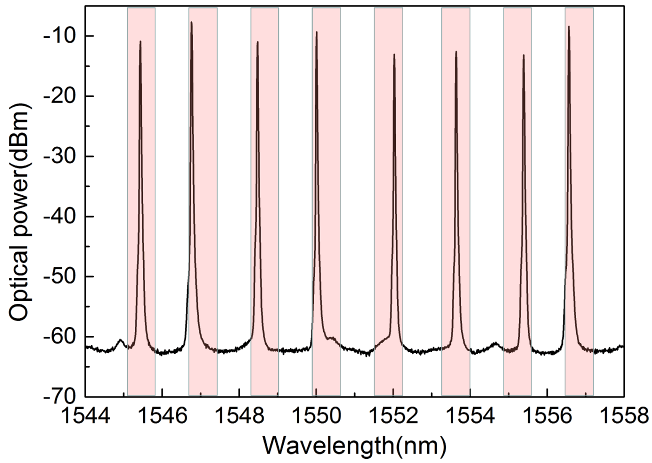

Fig. 3. The lasing spectrum of TOSA.

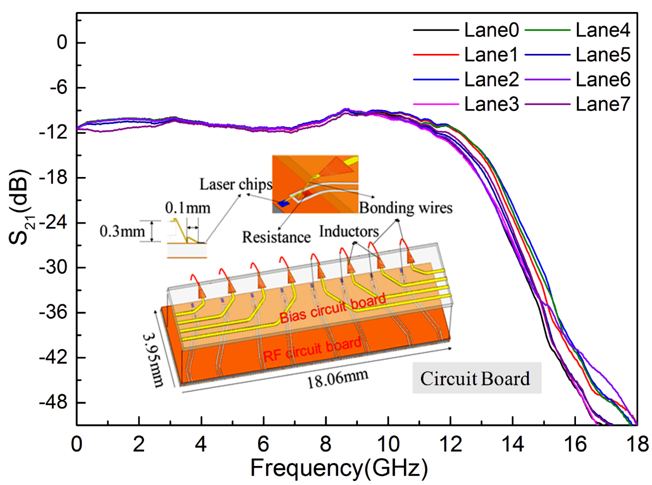

Fig. 4. The measured transmission response of TOSA and schematic structure of the two-layer circuit board.

(TEC) for thermal stabilization. Microwave design is very important to obtain good performance for TOSA. For RF circuit board design, electrical crosstalk which seriously deteriorates transmission performance should be mainly considered. Two technologies are proposed into the TOSA to suppress the electrical crosstalk. One of the technical keys is achieving the side metallization of transmission lines. The other is widening the width of pitch between the RF signal lines. Therefore, three-dimensional microwave package circuit is specially designed, namely the direct-current (DC) lines and signal lines are placed on two different inner circuit boards, so the radio frequency (RF) signals and bias currents can be injected separately.

The schematic structure of the two-layer circuit board is shown in Fig. 4. The width between the RF signal lines is 2 mm and electrical crosstalk between adjacent channels is less than -60 dB which can be ignored. Termination resistances on the signal line end are set at 45 ohm to realize 50-ohm independence matching and inductors are fabricated on the top layer to prevent RF signals. The TOSA is packaged in butterfly housing shown in Fig. 2 which two sides are DC pins providing bias current for lasers. High frequency RF pins of the front end of the body are specially designed to input or output frequency signal.

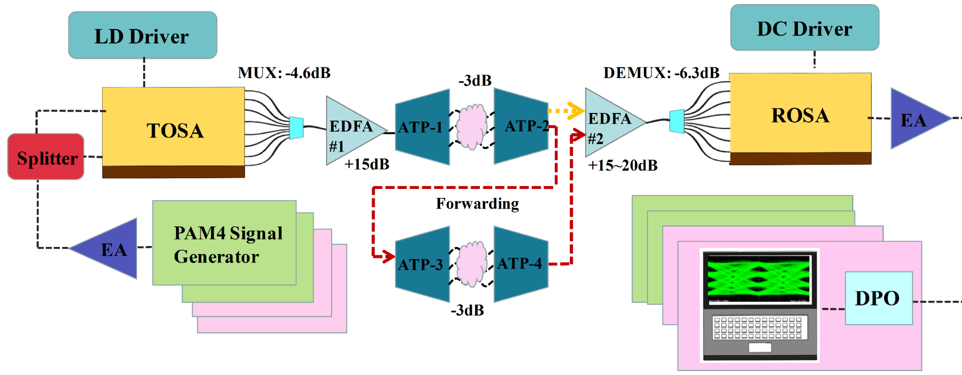

Fig. 5. The experimental system diagram. TOSA: transmitter optical sub-assembly, ROSA: receiver optical sub-assembly, AWG: arrayed waveguide grating, EA: electrical amplifier, EDFA: erbium-doped fiber amplifier, ATP: acquisition, pointing and tracking, DPO: digital phosphor oscilloscope.

With the special consideration for microwave circuits and coupling structures, the TOSA shows a good performance in terms of output power, lasing spectrum and −3 dB bandwidth. In the experiment, a receiver optical sub-assemblies (ROSA) with eight channels which also packaged in butterfly housing is used. The optical powers of all channels are around 5 mW at bias current of 40 mA, and the threshold current is approximately10 mA which shows the threshold current is nearly independent of the wavelengths. In Fig. 3, we report the output spectrum of the eight channels obtained by operating eight lanes simultaneously with a bias current of 30 mA. The eight wavelengths are 1545.43, 1546.76, 1548.48, 1550.01, 1552.03, 1553.64, 1555.26, and1556.57 nm, respectively which following the standard ITU-T recommendation. The -3 dB bandwidth of eight channels reach up to ∼12.5 GHz with the 30 mA bias currents as shown in Fig. 4.

3. Experimental Setup and Results

The experimental configuration of the 200 Gb/s FSO WDM communication system is shown in Fig. 5. The system is established with TOSA, ROSA and acquisition, pointing and tracking (ATP) systems. The TOSA is driven by multi-channel current source simultaneously whose each lane is set at 40 mA, and the temperature controller is adopted to keep thermal stabilization. PAM-4 modulation format generated by arbitrary waveform generator is adopted to further improve spectral efficiency and capacity of communication system. To reduce the number of signal sources and simplify the complexity of WDM system, electrical power splitters are applied to generate multiple signals. However, the electrical power splitter causes half the power loss at least, thus electrical amplifiers are employed to enhance the output electrical power to ∼20 dBm and then achieve a higher signal to noise ratio (SNR). We used two arrayed waveguide gratings (AWGs) with 50 GHz channel interval as multiplexer (MUX) and demultiplexer (DEMUX). The eight output light are combined by the MUX. Then they are amplified by the first erbium-doped fiber amplifier (EDFA, output power: 17 dBm) whose the model number is CEFA-C-HG-SM-40-B201-FA-FA and then they are directly plugged to the connector of ATP-1 by means of a single mode fiber. After ∼50 m outdoor free-space transmission between the two buildings, the optical signals were received by ATP-2. If the optical signals were amplified by the second EDFA (output power: 18 dBm) by the next step like yellow dotted line marked, the transmission system would be defined as one-hop transmission system in this paper. The second EDFA used here aims to compensate the power consumption caused by ATP-2 system. If optical signals are transmitted to ATP-3 by the next step labeled by red dotted line, the transmission system would be defined as forwarding transmission system. The ATP systems allow transparent and direct optical connection to single mode fibers and they include a electronic control unit which effectively tracks the signal beam wandering on account of mechanical vibrations and atmospheric turbulence. The pigtail of the ATP is multi-mode fiber, hence

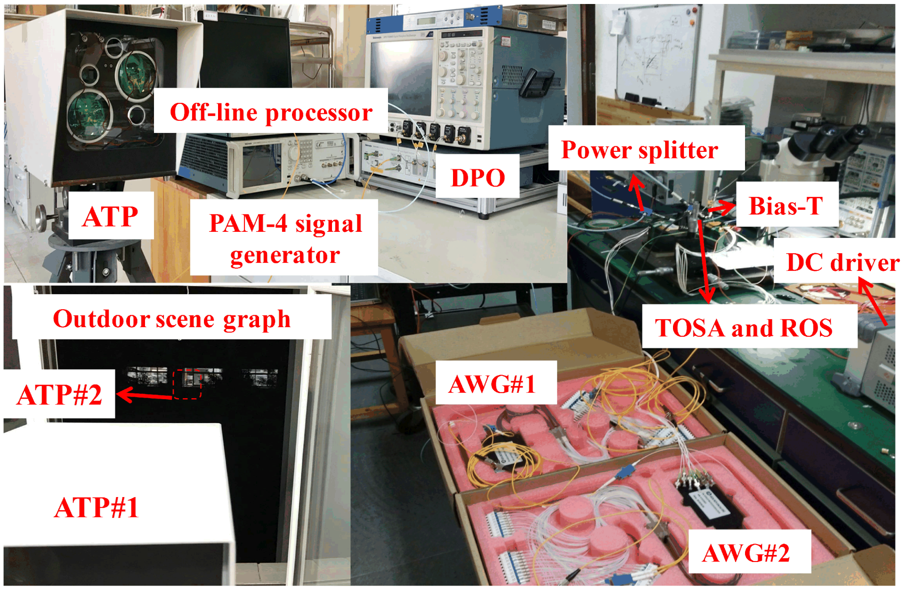

Fig. 6. The photograph of the experiment between the two buildings.

the interfaces between the multimode and signel mode fibers (including incident connection and outgoing connection loss) are up to 10 dB. Optical signals then are divided by DEMUX and detected by ROSA, respectively. The total optical power budgets for one-hop and forwarding transmissions are about 24.7 dBm and 30 dBm, respectively. It mainly caused by AWG (MUX: 4.6 dB, DEMUX: 6.3 dB), space optical transmission (one-hop system: ∼3 dB, forwarding system: ∼6 dB), the interfaces between the multimode and signel mode fibers: 10 dB) and some fiber jumpers (1∼2 dB). Another electrical amplifier is adopted to increase signal amplitude and further improve the SNR of the FSO system. Finally, the electrical signal of each channel is displayed in digital phosphor oscilloscope (DPO) for data acquisition and then be processed offline. The collected data was processed by the Tektronix OM1106 Optical Modulation Analysis Software and then the BER and eye diagrams were obtained at the same time. In the off-line DSP process the FFE-DFE equalizer is used to obtain a better results. The photograph of the experiment between the two buildings is shown in Fig. 6.

To demonstrate the feasibility of 200 Gb/s FSO WDM communication system, the TOSA with eight channels is used as light source and each channel has been carried out a detailed test respectively. We perform two experiments that are transmissions with one-hop and forwarding. As shown in Fig. 5, the first experiment which is marked with yellow dotted line only including one pair ATP systems. For the first experiment, clear eye diagrams and the low BER of all eight channels are achieved with directly detecting 25 Gb/s PAM-4 modulation format signals and each channel performs a good consistency. As shown in Fig. 7, clear eye openings are obtained without any distortion. For example, 4-levels not equally spaced and skew between the eye diagram of each layer do not exist. The results indicate that the communication system exhibits a well linearity characteristic. When an ideal PAM-4 signal is modulated on a laser with poor linearity, the larger amplitude signal will be compressed, and thus cause the height of the upper eye significantly less than the lower eye. Therefore, the linearity of the device is particularly important for the transmission of PAM-4 signals. The values of BER without attenuated incident light power for eight channels range from 1E-4 to 1E-5. As the incident light power decreases, the bit error rate gradually increases and the sharpness of the eye diagram get worse shown in Fig. 7.

Further we carry out the second experiment with forwarding transmission which is marked with red dotted line. Due to the optical power loss introduced by the second pair of ATP systems, the quality of eye diagrams are deteriorated seriously and the FSO communication link is less stability than

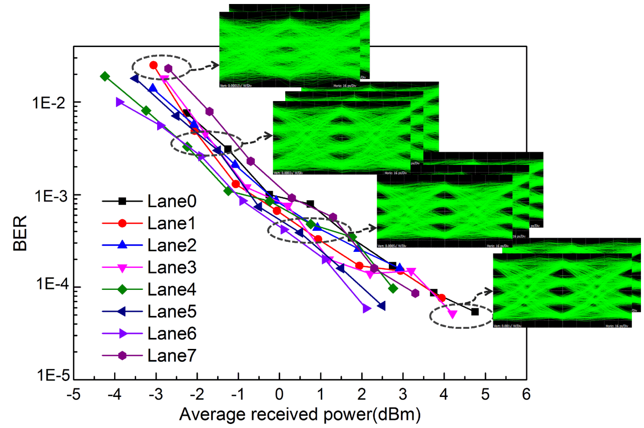

Fig. 7. The BERs of eight channels versus with average received power at 25 Gb/s for one-hop transmission and several representative eye diagrams.

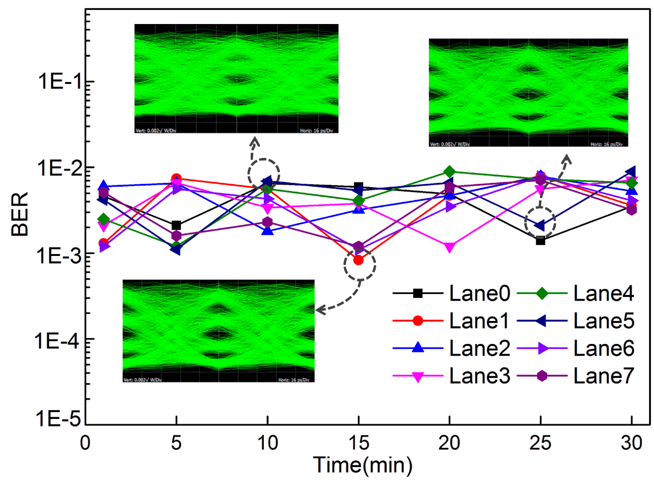

Fig. 8. The BERs of eight channels with forwarding transmission at 25 Gb/s for 30 min and several representative eye diagrams.

the first experiment. Owing to the inaccuracy of instantaneous BER to evaluate the performance of the transmission system, we measure each channel lasting for 30 min with 5 min interval to obtain the BERs for 25 Gb/s PAM4 FSO transmission given in Fig. 8. The values of BER with eight lanes fluctuate between 1E-3 and 1E-2, and the jitters are caused by unstable FSO channels. As shown in Fig. 8, the results indicate that the scheme is feasible for FSO transmission links.

4. Conclusion

In summary, we proposed a FSO WDM system empowered by a hybrid integrated multi-channel directly modulated TOSA whose aggregated data rate is up to 200 Gb/s. The TOSA with -3 dB bandwidth of $\sim$12.5 GHz is assembled by our laboratory. The output power of each channel exceeds 5 mw. To demonstrate the feasible of 200 Gb/s FSO WDM communication in the free space for 5G wireless network, the $\sim$50 m outdoor experiment between two buildings with 8×25 Gb/s PAM-4 modulation format is established. The eye diagrams and BERs are tested for one-hop system and forwarding system, respectively. For one-hop system, clear eye diagrams and stable BER performances are demonstrated in all the wavelengths. For forwarding system, the values of BER range from 1E-2 to 1E-3 lasting for 30 minutes measurement for eight channels. These results indicate that WDM FSO system based on multi-wavelength TOSA has significant potential for 5G radio access network. In addition, the FSO WDM system based on multi-wavelength TOSA can also applied for broadcasting transmission in free-space. Therefore, it may become a more widely used reliable technology than previously expected. Significant issues are still to be investigated in spite of these results indicate promising potential. Among these, the most important are probably the effect of atmospheric turbulence and fog/rain as well as any possible means to further enhance the link reliability.

Acknowledgments

This work has been supported by the National Basic Research Program of China (2014CB340102) and the National Natural Science Foundation of China (NSFC) (61625504, 61727815).

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