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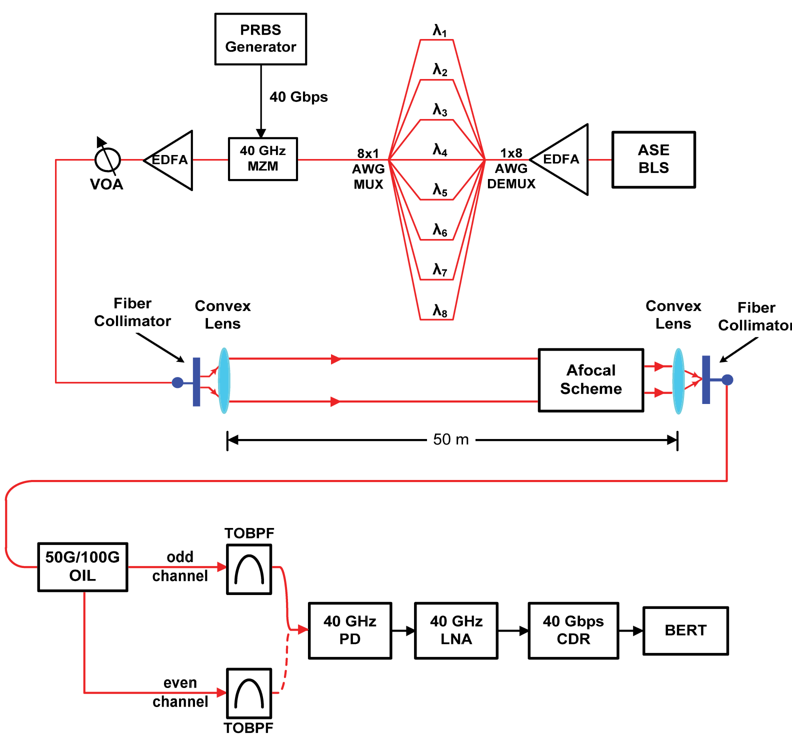

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A 50-m/320-Gb/s DWDM FSO Communication With Afocal Scheme

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Abstract: This paper proposes and presents the experimental demonstration of 320-Gb/s free-space optical (FSO) communication based on dense-wavelength-division-multiplexing (DWDM) technology and afocal scheme. To the best of our knowledge, this is the first one that adopts DWDM technology and afocal scheme to successfully demonstrate 50-m/320-Gb/s FSO communication. Results show that the free-space transmission distance is greatly increased by the afocal scheme and that the free-space transmission rate is significantly enhanced by the DWDM technology. DWDM FSO communication over a 50-m free-space link with a total transmission rate of 320 Gb/s $(40\ \text{Gb/s}/\lambda \times 8\lambda = 320\ \text{Gb/s})$ is achieved. With the aid of a low-noise amplifier and clock/data recovery at the receiving site, good bit-error-rate (BER) performance and clear eye diagram are obtained at a 50-m/320-Gb/s operation. Such 50-m/320-Gb/s DWDM FSO communication provides the advantages of optical wireless communications for long transmission distance and high transmission rate, which is thoroughly useful for long-haul and high-speed light-based WiFi (LiFi) applications.

Index Terms: Afocal scheme, dense-wavelength-division multiplexing, free-space optical communication.

1. Introduction

At present, free-space optical (FSO) communications are being developed to create high-speed, high security, and friendly communications employing high bandwidth and a high capacity light signal instead of traditional radio-frequency (RF) communications. FSO communications have many attractive characteristics, such as worldwide available and license-free bandwidth, non-interference with radio bands, and the promotion of multi-Gigabit optical wireless applications by facilitating flexibility through free-space transmissions [1]–[5]. Therefore, the development of FSO communications is expected to overcome the wireless connection issues. For a real and practical implementation of FSO communication, long transmission distance and high transmission rate are the major interests of system designers. In this paper, a 320-Gbps FSO communication with afocal scheme and dense-wavelength-division-multiplexing (DWDM) technology is proposed. The free-space transmission distance is greatly increased by the afocal scheme, and the free-space transmission rate is significantly enhanced by the DWDM technology. Afocal scheme, which can reduce the beam size of laser beam, is expected to provide a long free-space transmission distance in an FSO communication [6]. DWDM technology, which can fully utilize the free-space bandwidth, is expected to enhance the transmission rate of an FSO communication [7]. A DWDM FSO communication that utilizes different optical wavelengths to deliver the combined data streams would be quite useful for providing higher transmission rate. This study demonstrates a DWDM FSO communication by using an 8-wavelength system as an example, with each wavelength carrying a data stream of 40 Gbps. A DWDM FSO communication over a 50-m free-space link with a total transmission rate of 320 Gbps $(40\ \text{Gbps}/\lambda \times 8\lambda = 320\ \text{Gbps})$ is obtained. As far as we know, it is the first time to successfully establish a 50 m/320 Gbps FSO communication that employs afocal scheme and DWDM technology. With the help of low noise amplifier (LNA) and clock/data recovery (CDR) at the receiving site, good bit error rate (BER) performance and clear eye diagram are achieved at a 50 m/320 Gbps operation. This proposed 50 m/320 Gbps DWDM FSO communication is shown to be a prominent one and not only provides the advantages of optical wireless communications for long transmission distance and high transmission rate but reveals its feasibility for long-haul and high-speed light-based WiFi (LiFi) applications [8] as well.

2. Experimental Setup

Fig. 1 depicts the experimental configuration of the proposed 50 m/320 Gbps DWDM FSO communications that employs afocal scheme and DWDM technology. The output of the amplified spontaneous emission (ASE) broadband light source (BLS) is amplified by an erbium-doped fiber amplifier (EDFA) and efficiently split into eight optical channels by a 1 $\times$ 8 arrayed waveguide grating (AWG) demultiplexer (DEMUX) with a channel spacing of 0.4 nm (50 GHz). Eight wavelengths of λ_1 to λ_8 from the AWG DEMUX output are multiplexed into a 40-GHz Mach–Zehnder modulator (MZM) by a 8 $\times$ 1 AWG multiplexer (MUX). The MZM is modulated by a 40-Gbps pseudorandom binary sequence (PRBS) of $2^{15} - 1$ generated by a PRBS generator. It means that the same PRBS sequence is transmitted over all eight channels. A variable optical attenuator (VOA) is positioned at the start of the second-stage EDFA so that the optical power launched into the free-space can be optimized to obtain the best transmission performances. Given that EDFA can only amplify optical signals in the 1550 nm region, thereby, such DWDM FSO communications are enhanced by the introduction of 1550 nm technology. A pair of fiber collimators is used to collimate light from a fiber to form a collimated optical beam and to guide a collimated optical beam from the free-space into an optical fiber. The fiber collimators connected to single-mode fibers (SMFs) play an important role in forming an optical beam to transport optical signal through the free-space between the two sides. This fiber collimator has an operating wavelength range of 1050–1620 nm, a fiber-to-lens distance of 7.5 mm, and a focal length of 7.5 mm. The light emitted from the first-stage fiber collimator is launched into the first-stage convex lens, delivered in the free-space, inputted into an afocal scheme, and fed into the second-stage convex lens to concentrate on the second-stage fiber collimator. The function of the first-stage convex lens is to transform the divergent beam into the parallel beam, the function of the afocal scheme is to reduce the beam size of the collimated optical beam, and the function of the second-stage convex lens focusses the reduced parallel beam into a point.

Over a 50-m free-space link, the eight laser lights with a total data stream of 320 Gbps $(40\ \text{Gbps}/\lambda \times 8\lambda)$ is reached to a 50G/100G optical interleaver (OIL). An OIL is deployed at the receiving site to separate odd and even optical sidebands of the optical signal. The OIL has two output ports; one output port provides the optical signal only with the odd optical sidebands, and the other output port provides the optical signal only with the even optical sidebands. The OIL used in this experiment has an input channel spacing of 50 GHz and an output channel spacing of 100 GHz. Following the OIL output with odd (even) optical sidebands, the optical sidebands are separated by a spacing of 100 GHz and fed into a tunable optical band-pass filter (TOBPF),

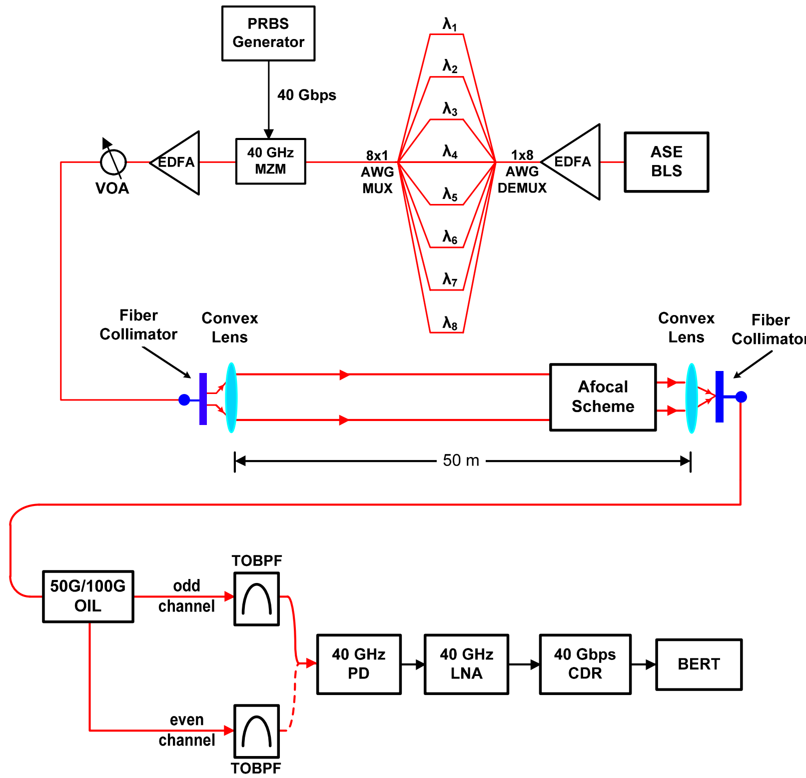

Fig. 1. Experimental configuration of the proposed 50-m/320-Gb/s DWDM FSO communication that employs afocal scheme and DWDM technology.

with a 3-dB bandwidth of 0.32 nm, to select the desired wavelength. The selected optical wavelength is then detected by a 40-GHz photodiode (PD) with a responsivity of 0.55 mA/mW (at 1550 nm) and amplified by a 40-GHz LNA with a small signal gain of 20 dB (measured at 40 GHz) and a noise figure of around 2 dB. It is necessary for an LNA to amplify the data stream while adding as little noise and distortion as possible. After LNA amplification, the data stream is recovered and regenerated by a 40-Gbps CDR and fed into a bit error rate tester (BERT) for BER performance analysis. The function of the CDR is to recover and regenerate the data stream from the distorted data stream. Considering that BER will increase as the receiver cannot discriminate between noise and transmitted data, a CDR is necessary at the receiving site.

3. Experimental Results and Discussion

The simplification of the BLS is a key issue that should be addressed in the development of DWDM FSO communications. A BLS, comprising optoelectronic oscillator (OEO) and optical signal-to-noise ratio (OSNR) enhancement schemes, has been demonstrated previously [9]. However, sophisticated OEO and OSNR enhancement schemes are required. And further, high power superluminescent diodes (SLDs)-based BLS has been illustrated previously [10]. Nonetheless, it is not flexible due to a narrow optical 3-dB bandwidth. Spectrum slicing is a feasible technique by which narrow wavelengths are filtered from a BLS and externally modulated to deliver optical signals. It is attractive because it avoids the need of multiple distributed feedback (DFB) laser diodes (LDs) with selected wavelengths [11]. Fig. 2 shows the configuration of the ASE BLS, which is composed of a bidirectional pumped EDFA with LDs at 980 nm. Two 980 nm pumping LDs with 180 mW pumping power are coupled into a 3-m Er/Yb doped fiber by two 980/1550 nm WDM couplers. Two optical isolators are used to prevent reflections which can degrade ASE BLS performance. Part of the laser output is utilized for optoelectronic feedback to enhance the performance of ASE BLS, and another part of the laser output is used for ASE BLS. A PD converts laser light into the electronic

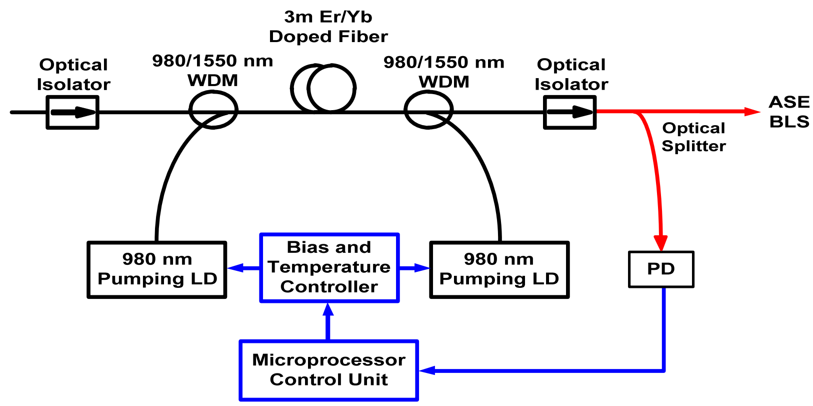

Fig. 2. Configuration of the ASE BLS.

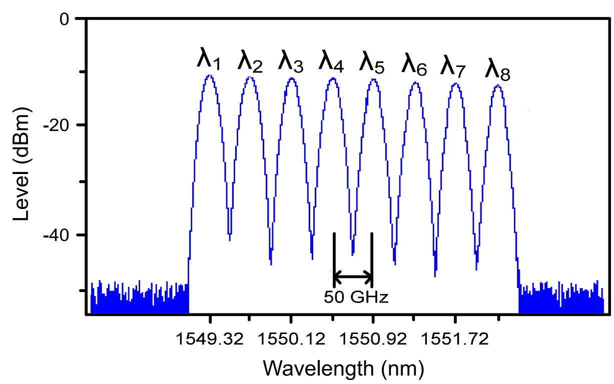

Fig. 3. Optical spectrum of the spectrum-sliced eight wavelengths.

signal to control the microprocessor control unit and the bias and temperature controller. The high power ASE cascaded with EDFA can be efficiently split into many optical channels by using a $1 \times N$ AWG DEMUX. The optical spectrum of the spectrum-sliced eight wavelengths is presented in Fig. 3. The spectrum-sliced eight wavelengths of λ_1, λ_2, λ_3, λ_4, λ_5, λ_6, λ_7, and λ_8 are 1549.32, 1549.72, 1550.12, 1550.52, 1550.92, 1551.32, 1551.72, and 1552.12 nm, respectively, with a channel spacing of 50 GHz (compliant with the ITU standard) and a 3-dB spectral width of about 0.12 nm for each wavelength. To guarantee a successful implementation of a DWDM FSO communication, the wavelengths of λ_1, λ_3, λ_5, and λ_7 (λ_2, λ_4, λ_6, and λ_8) are selected from the odd (even) channel output of the OIL to prevent the crosstalk that arises from the incomplete isolation of the adjacent channels. If only a TOBPF is employed for the demultiplexing (without employing OIL at the receiving site), then the crosstalk that arises from the incomplete isolation of the adjacent channels will obviously increase due to a close channel spacing of 50 GHz. And such crosstalk increment will result in the degradation of BER performance. The function of the demultiplexing scheme is to distinguish each optical wavelength without crosstalk and channel interference. It is a great challenge in closely spaced optical wavelengths.

Fig. 4 presents the afocal scheme, comprising two convex lenses with different focal lengths of 10 cm (f_1) and 5 cm (f_2). For an afocal scheme, the separation distance (d) of two convex lenses is equal to the sum of the focal lengths ($d = f_1 + f_2$). The function of the afocal scheme is to transform a collimated optical beam with a large diameter of 4.4 mm (d_1) into another collimated optical beam with a small diameter of 2.2 mm (d_2)

$$d_2 = d_1 \frac{f_2}{f_1}. \tag{1}$$

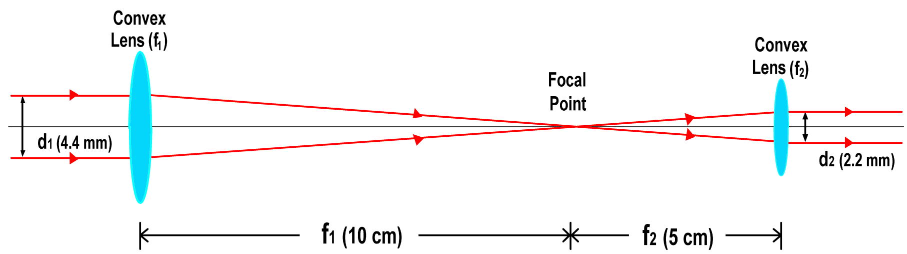

Fig. 4. Afocal scheme, comprising two convex lenses with different focal lengths of f_1 and f_2.

By means of afocal scheme, the diameter of the collimated optical beam was reduced $(d_2 = 0.5d_1)$, producing net convergence to the optical beam and leading to further extension of free-space transmission distance between two convex lenses (the second-stage convex lens of afocal scheme and the second-stage convex lens of FSO communications). Lower focal length ratio (f_2/f_1) leads to smaller collimated optical beam diameter (d_2), resulting in longer free-space transmission distance between the afocal scheme and the second-stage convex lens of FSO communications. If the afocal scheme is operated nearby the receiving site, then the afocal scheme is the pre-afocal scheme. While if the afocal scheme is operated nearby the middle position, then the afocal scheme is the in-line afocal scheme. As the free-space transmission distance increases, however, the received OSNR decreases because other lights form the environment are also received by the PD. Noise is generated when other lights form the environment are received by the PD. As the free-space transmission distance increases the noise increases as well, by which resulting in the decrement of OSNR value and the degradation of BER performance. Thereby, there is a trade-off between the free-space transmission distance (the focal length ratio) and the BER performance. To guarantee a successful design of FSO communication, system designers will have to address the optimization of the afocal scheme (the optimum focal length ratio of the afocal scheme).

The FSO communication is to realize the free-space transmission using a pair of fiber collimators with SMFs. Propagating an optical beam through the free-space between the fiber collimators enacts the FSO communication to work as if the fibers were connected seamlessly. Optical beam alignment and focal spot size between convex lens and fiber collimator are critical for the transmission performance of an FSO communication. An FSO communication with optical beam misalignment and divergent focal spot size (the focal spot size $>$ the mode field size of the fiber) between convex lens and fiber collimator will degrade the transmission performance.

The measured BER curves of DWDM FSO communications at a data stream of 40 Gbps (λ_1) are presented in Fig. 5. At a free-space transmission distance of 50 m, as LNA and CDR are not employed, the BER is approximately 10^{-5}. However, as LNA and CDR are employed simultaneously, the BER reaches around 10^{-9}. A great BER performance improvement is obtained. Excellent BER performance is obtained to demonstrate the possibility of establishing a 50 m/320 Gbps DWDM FSO communication. To better show the relation with LNA, CDR, and BER performance, we remove one of the BER performance improvement schemes. Clearly, when only one BER performance improvement scheme is employed, the BER performance improvement is restricted. Both of the LNA and CDR play important roles for BER improvement. They can improve the error vector magnitude (EVM) and signal-to-noise ratio (SNR) values of FSO communications, leading to BER performance improvement. Fig. 5 also shows the eye diagrams of the 40 Gbps data stream (λ_1) over a 50-m free-space link with/without employing LNA and CDR. Amplitude and phase fluctuations are obviously observed when LNA and CDR are not employed. As LNA and CDR are employed simultaneously, however, a clear eye diagram is observed due to the suppression of amplitude and phase fluctuations. To show a direct association with the demultiplexing scheme and the BER performance, we remove the demultiplexing scheme (without employing OIL and TOBPF at the receiving site) and evaluate the BER performance, as LNA and CDR are employed concurrently. It can be seen that a serious BER

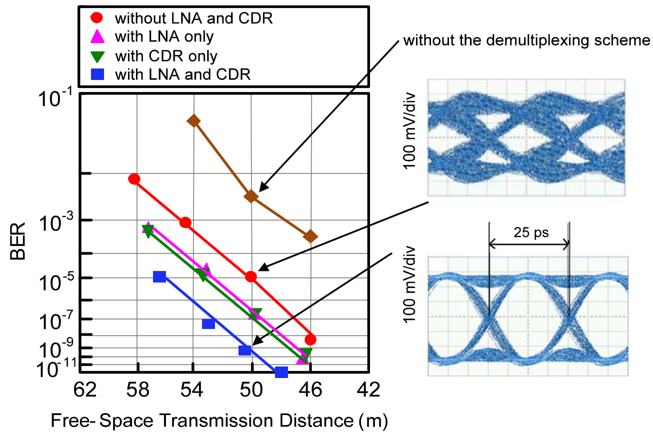

Fig. 5. Measured BER curves of DWDM FSO communication at a data stream of 40 Gb/s (λ_1).

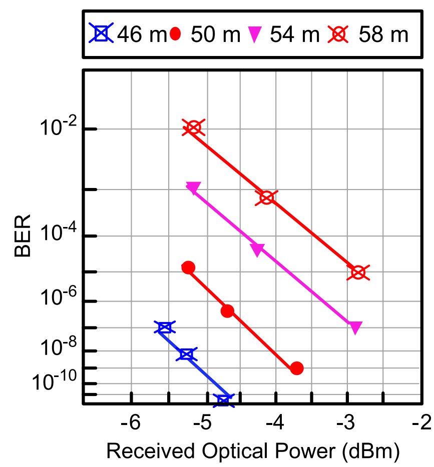

Fig. 6. Measured BER curves of DWDM FSO communication at a data stream of 40 Gb/s (λ_8) over 46-m/50-m/54-m/58-m free-space transmission distances as LNA and CDR are employed concurrently.

performance degradation exists due to crosstalk and interference from other wavelengths. The demultiplexing scheme must reject the adjacent channels so that they do not interfere. If there is no demultiplexing scheme at the receiving site, then the crosstalk and channel interference that arise from other wavelengths will increase significantly. These crosstalk and channel interference increases will lead to a serious BER performance degradation.

Fig. 6 shows the measured BER curves of DWDM FSO communications at a data stream of 40 Gbps (λ_8) over 46 m/50 m/54 m/58 m free-space transmission distances, as LNA and CDR are employed concurrently. As shown, as the free-space transmission distance increases the BER value increases as well. As the free-space transmission distance is larger than 50 m, the BER value is higher than 10^{-9}. Longer free-space transmission distance results in lower received optical power, by which leading to the deterioration of BER performance. The free-space transmission distance can be extended not only by the optimization of the afocal scheme, but also by the employment of an EDFA with higher optical output power. By employing an EDFA with higher optical output power, higher optical power can be launched into the free-space to compensate for the loss of the link. A trade-off occurs between the transmission distance and the transmission rate. Error-free operation can be achieved under different transmission distances with different transmission rates. In Fig. 6, when the received optical power for each curve is the same as that of others, the BER performances differ. The reason is that the received light also includes other lights form the environment. As the free-space transmission distance increases, the received OSNR decreases and leads to worse BER performance.

4. Conclusion

A DWDM FSO communication that adopts afocal scheme and DWDM technology is proposed. The free-space transmission distance and transmission rate are greatly increased by afocal scheme and DWDM technology. A total transmission rate of 320 Gbps is successfully delivered over a 50-m free-space link. The proposed DWDM FSO communications are experimentally demonstrated with low BER operation and clear eye diagram. The findings demonstrated that such a DWDM FSO communication can provide the advantages of optical wireless links for long transmission distance and high transmission rate.

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