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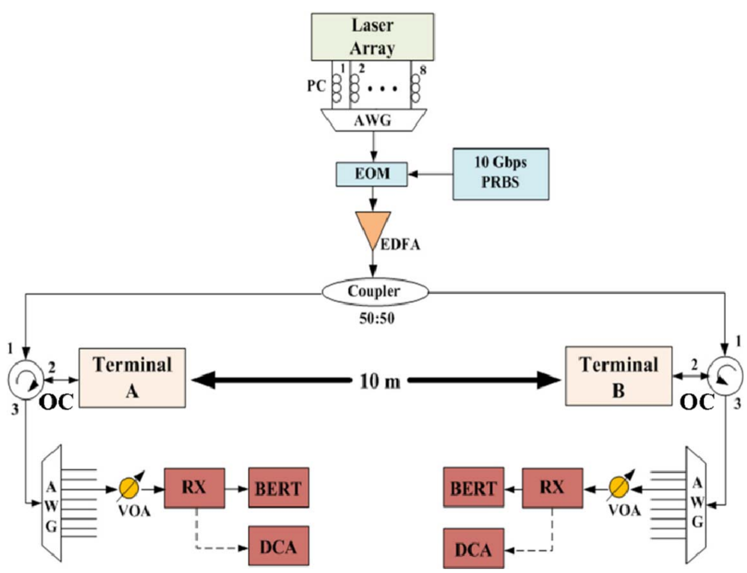

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Abstract: We demonstrate a practical 2 × 80 Gbit/s dense wavelength division multiplexing (DWDM) bidirectional short-range optical wireless link. The measured power penalties for the bidirectional transmission are less than 0.8 and 0.2 dB compared to the back-to-back link and the unidirectional transmission system, respectively. We also practically evaluate the impact of the offset angles between the optical transmission path and the building windows. The result shows that the power penalty is as small as 0.3 dB. This technology offers a great potential for applications in building-to-building inter-transmission as part of local/wide area networks.

Index Terms: Optical wireless, free space optics, bidirectional transmission, wavelength division multiplexing.

1. Introduction

Optical wireless communications (OWC) is an age long technology that has undergone through cycles of technical evolutions mainly due to the remarkable development in light sources, optics, photodetectors (PD) and optical receiver technologies. Nowadays OWC links with Gbit/s data rates have been reported [1] for outdoor and indoor applications. However, there are two key challenges for OWC at the Gbit/s range: (i) the limitation of device availability (sources and PDs) for optical wireless application, since most components are intended for optical fiber based communications system, and (ii) the limited link coverage (range and divergence angle) due to the limit of permissible transmit optical power, which is inversely proportional to the available modulation bandwidth. The availability of optical sources and PDs is however directly dependent on the utilized materials as well as the dimensions of the device active area, which is typically in the range of sub-millimeters in high speed systems. An optical fiber based ultrafast laser together with a fast avalanche PD can be readily employed to provide a cost effective and a reliable OWC link. In addition, high-speed and complex modulation and demodulation techniques currently used in optical communications could be adopted in OWCs. As a result a number of high-speed OWC links have been reported in recent years based on the fiber sub-systems. In [2] a high-speed duplex OWC system for indoor personal area networks is reported offering higher speed compared with the

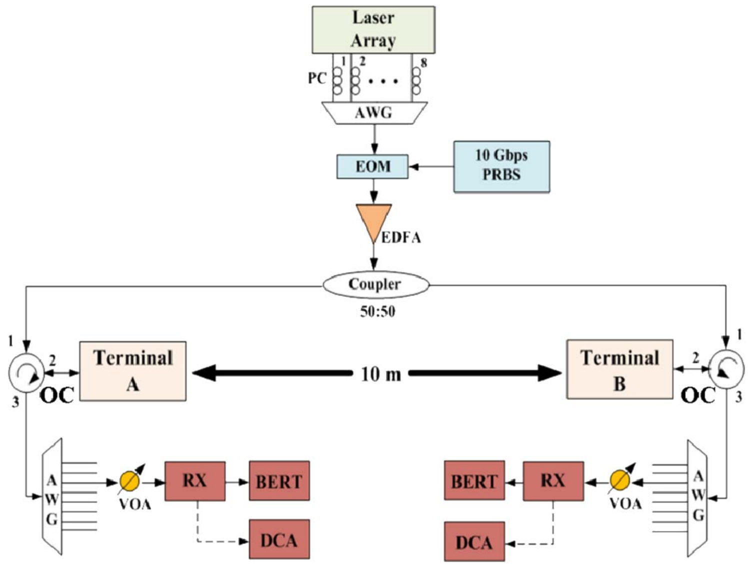


Fig. 1. System setup for a bidirectional 80 Gbit/s optical wireless communications link with multiplexing/demultiplexing capability. (EOM: electro-optical modulator; AWG: array waveguide grating; OC: optical circulator; RX: receiver; BERT: bit error rate test set; DCA: digital communications analyzer).

discrete based devices, but with a limited range and coverage area [3], [4] (where the system power link margin is almost zero). In OWCs the data rate can be further increased by employing WDM technique [5], [6] and complex modulation schemes [7]. Arimoto *et al.* [8] demonstrated a 1.25 Gb/s free space optical communications link over 320 m, whereas Kim *et al.* [9] reported simultaneous wired and wireless 1.25-Gb/s bidirectional WDM-RoF transmission scheme. For higher speed, WDM transmission, Chen *et al.* [10] demonstrated a 16-channel 10 Gb/s WDM OWC over 2.16 km in a clear atmosphere using a detector diameter of 6 cm with 12 dB coupling loss (i.e., multimode fiber (MMF) to SMF). Ciaramella *et al.* [11] demonstrated 32 $\times$ 40 Gbit/s WDM OWC over 200 m. The power penalty variation among WDM channels ranges from 0 to 5 dB. Several EDFAs and fast steering mirror were used for signal perception and detection.

In this paper, the aim is to implement an ultra-high speed OWC link using a bidirectional DWDM, and demonstrate the multiple-user access capability by means of wavelength reuse. The advantage of wavelength reuse is to significantly increase the bandwidth efficiency for OWC system. We also present the investigation of the full system performance. Eight channels in either transmission direction, each at 10 Gbit/s, are multiplexed and transmitted over a 10 m free space channel, which could be increased within the available power link budget. To the best of our knowledge, this paper for the first time demonstrates WDM OWC using SMF to SMF with no steering mirrors, bidirectional WDM system in free space with wavelength reuse function at high data rate. In addition the proposed system has the potential of scalability. The proposed scheme could be readily adopted to investigate outdoor OWC links performance under atmospheric conditions within the controlled indoor environment such as the work reported in [12].

2. System Design and Experimental Setup

Fig. 1 depicts the system block diagram of the proposed bidirectional 2 $\times$ 80 Gbit/s link offering the wavelength reuse as well as channel add/drop multiplexing capabilities at both ends (e.g., terminals A and B). The channel between the two terminals is free space of 10 m length. An array waveguide grating (AWG) connected to the laser array is used as a multiplexer, whereas a high-speed electro-optical modulator (EOM) is adopted to modulate WDM signals. To compensate for free space transmission losses an Erbium-doped fiber amplifier (EDFA) is used to boost the WDM signals. To demonstrate the concept of wavelength reuse, a 50/50 coupler is used to split all WDM channels from

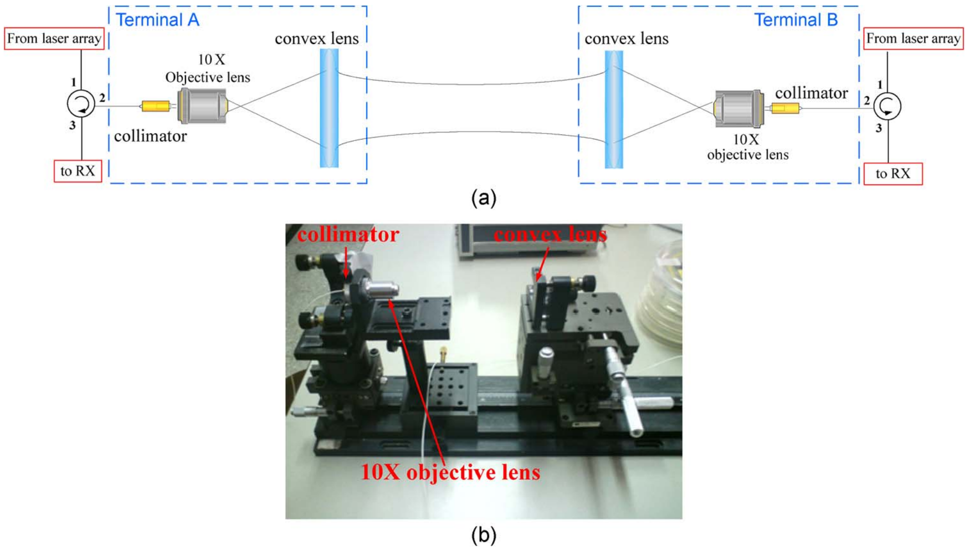


Fig. 2. (a) Two identical terminals A and B. Each terminal acts as a transceiver for bi-directional transmission. (b) A photograph of the five-axis platform based terminal.

laser array prior to feeding into terminals A and B via optical circulators (OCs). Thus, terminals A and B acting as transceiver are bidirectional and can be used to launch and receive WDM signals via the same free space channel. The downstream signal path is from the 50/50 coupler via terminal A to terminal B. For upstream transmission, signal path is symmetrical to the downstream signal path. In terminals A and B the AWG is used as a demultiplexer followed by an optical attenuator (VOA) in order to adjust the received optical power level when carrying out optical signal-to-noise (OSNR) and bit error rate (BER) measurements. A bit error rate test set (BERT) and a digital communications analyzer (DCA) are used to analyze the system performance. Either terminals A and B can be used to launch and receive signals via the same free space channel.

A discrete lens system is used for beam collimation. The optics system is called the Kepler light beam expander. The link experiences two main losses including beam spreading in free space (i.e., the divergence loss) and fiber coupling. The collimated beam radius can be compressed (reduced) or expanded (magnified) by adjusting the lens and their focal lengths. For the coupling loss when light is incident onto the optical fiber end, the difference in interface refractive index will result in 4% return loss as part of the light is reflected. Instead of using a multimode fiber, we have used a single-mode fiber (SMF) with a core diameter of 9 μm to ensure mono-mode high speed transmission with the reduced insertion loss. In general, the typical insertion loss of SMF is determined by:

$$L = -10 \times \log\left(\frac{d_2}{d_1}\right)^2, \tag{1}$$

where d_2 and d_1 are the fiber diameters of the transmitting side and receiving side, respectively. In the experiment, both collimators are connected to the same SMF with a core diameter of 9 μm. Thus the insertion loss is close to zero (dB).

The laser beam with a divergence angle of 2 mrad is collimated to ensure the achievement of a long free space transmission. Precise optical components are utilized to achieve an accurate alignment between the transceivers in both terminals A and B, which are symmetrical and identical. Fig. 2(a) shows the diagram with two identical terminals A and B. Each terminal acts as a transceiver where the transmitter and receiver are separated by the circulator nearby, thus creating the bi-directional transmission. Each of the terminals is used to launch and receive WDM signals from free space. Inside the terminal, a collimator is used for precise alignment, including a 10$\times$ objective lens and a convex lens, with a diameter of 24 mm and a focal length of 13 cm, is used to

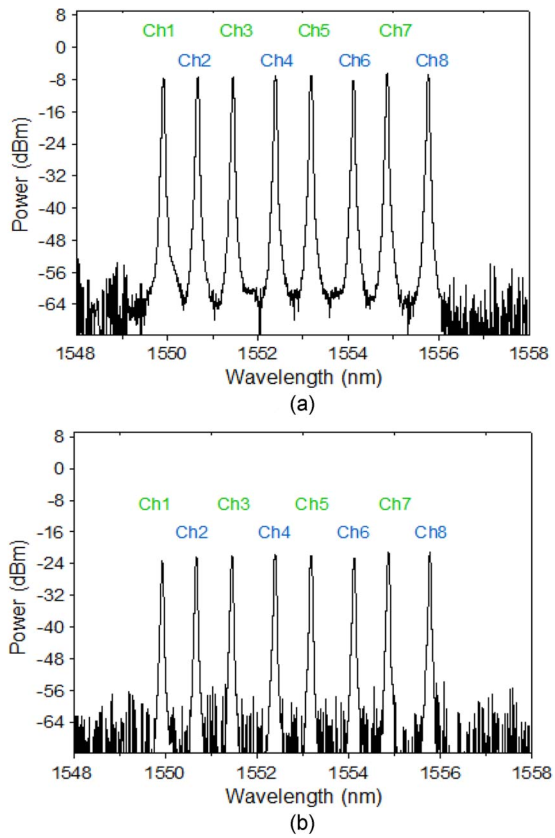


Fig. 3. The measured optical spectra at the (a) transmitter side (average power of −6.5 dBm) and (b) receiver side (average power of −21.15 dBm).

reduce the beam size and power loss. To ensure precise link alignment and stability, terminals A and B, including the fiber and optics, were all mounted on a five-axis platform pair, as depicted in Fig. 2(b), which offers accurate link alignment in the order of 10 μm.

3. Experimental Results and Discussion

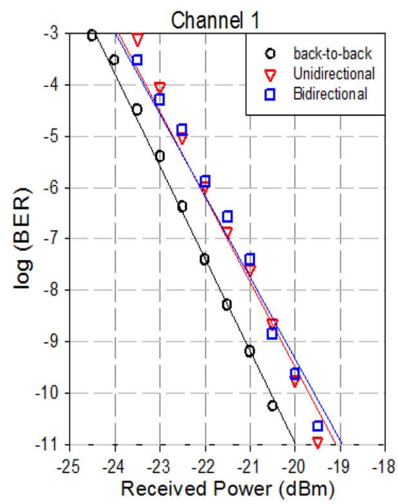
Fig. 3(a) and (b) shows the measured optical spectra for 8 channels at the transmitter and receiver ends, respectively. The power loss is approximately −14.65 dB, which includes the coupling and free space losses. The measured power variation for different channels is relatively small, which is 0.5 dB. The relation between OSNR in Fig. 3 and the BER in Fig. 4 is given by [13]:

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

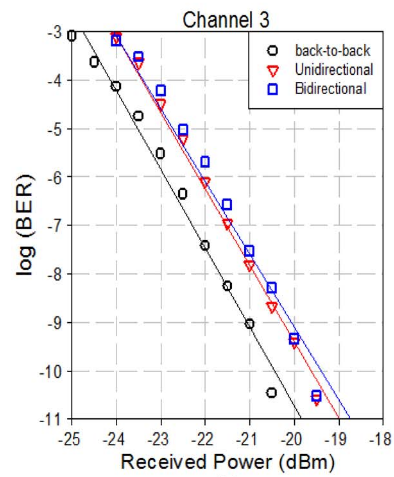
where $erfc(x)$ is the complementary error function, and it is defined by

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_{x}^{\infty} e^{-t^2} dt = 1 - erf(x) = 1 - \frac{2}{\sqrt{\pi}} \int_{0}^{\pi} e^{-t^2} dt \tag{3}$$

where $erf(x)$ is an error function. According to equations (2) and (3) one may predict the relationship between BER and OSNR under 10 Gb/s per channel condition. An OSNR of 17.0 dB corresponds to a BER of 10^{-9} (i.e., a Q factor of 6) according to previous work [14]. Therefore, all



(a)



(b)

Fig. 4. BER vs. the received optical power for (a) channel 1 and (b) channel 3 in 10 m unidirectional and bidirectional transmissions.

channels have more than 45 dB OSNR on the receiver ends, thus ensuring that the minimum BER requirement of 10^{-9} could be achieved.

To investigate the bidirectional DWDM OWC link shown in Fig. 1, the 8-channel DFB laser array is externally modulated by an EOM at 10 Gbit/s/channel. We have used a $2^{31} - 1$ pseudo random bit sequence (PRBS) data stream in the non-return-to-zero (NRZ) format. Fig. 4(a) illustrates the measured BER plots for the channel 1 (1559.08 nm) for the back-to-back, 10 m unidirectional transmission and 10 m bidirectional transmission links with multiple channels. The measured power penalties for the bidirectional transmission are $<$ 0.8 dB and 0.2 dB compared with the back-to-back and the unidirectional transmission links. Fig. 4(b) shows the measured BER for channel 3 (1551.68 nm) for all three cases as in Fig. 4(a), illustrating similar characteristics as in channel 1. Note that there is a very small power penalty incurred when using identical wavelengths (channel 1 $\sim$ channel 8) for the bidirectional transmission. Thus is due to the Rayleigh back scattering at a certain wavelength that induces quite small homodyne (intraband) crosstalk to the identical wavelength, which is transmitted in the opposite direction. The achieved BER results confirm the feasibility of the proposed bidirectional scheme.

In order to evaluate the effect of building windows on the link performance when the light beam is propagating through them, two pieces of glasses (with the thickness of 5 mm) were placed very

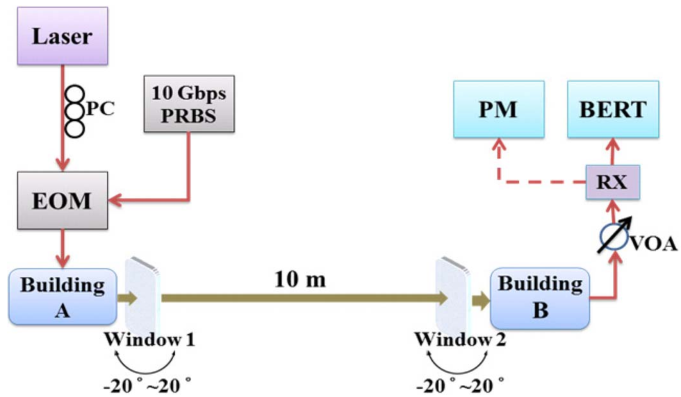


Fig. 5. System setup for 10 m window angle offset measurement. (PM: power meter; EOM: electro-optical modulator).

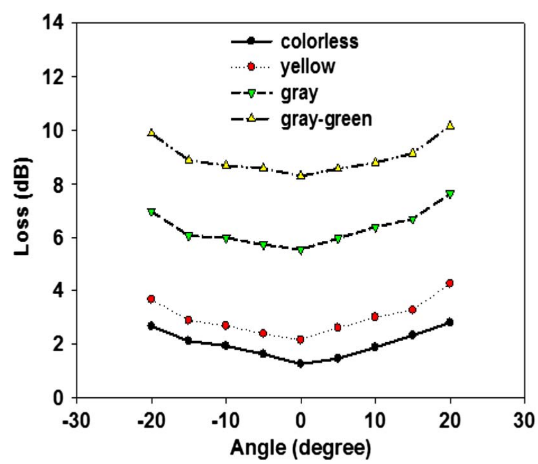


Fig. 6. The optical loss against the offset angle between TX/RX path for a range of glasses at different colors.

close to the laser source and the receiver, as shown in Fig. 5. Glasses with different colors are used to test the glass effects on the transmission performance.

In general the optical path from the laser source (TX) to the receiver (RX) may not be precisely orthogonal with the two building windows. Fig. 6 shows the measured optical loss against the offset angle between the TX/RX optical path and the two glasses with different colors. Note that the power loss increases with the offset angle. It is observed that the colorless and gray-green glasses introduce the lowest and highest power loss, respectively. Fig. 7 illustrates the measured BER performance against the received power for the back to back link (1559.08 nm) with colorless glasses, and the free space link with glasses within a range of offset angles. Note that the measured power penalty is as small as 0.3 dB, thus indicating that although the offset angle between glasses (i.e., windows) and the optical path may induce power losses, very little degradation in the BER performance is observed. Therefore, the proposed scheme would be attractive for future building to building, and indoor OWC communications.

4. Conclusion

A symmetrical bidirectional wavelength reused methodology was proposed and demonstrated for a 2×80 Gbit/s high capacity DWDM OWC link. The measured power penalties for the bidirectional

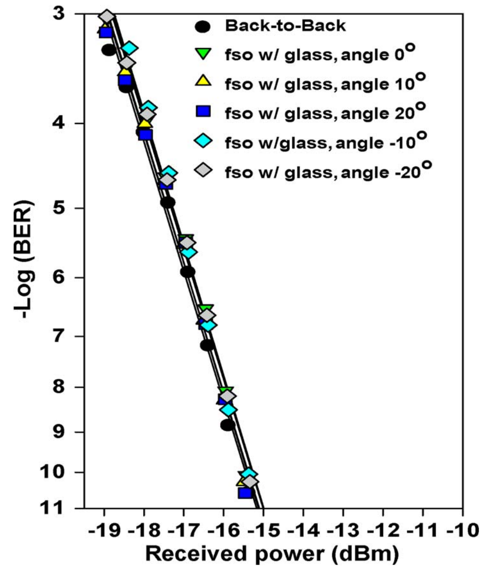


Fig. 7. The measured BER performance for colorless windows (at 1559.08 nm) in back to back as well as angle offset conditions.

transmission were lower than 0.8 dB and 0.2 dB compared with the back-to-back and the unidirectional transmission links, respectively. We have also practically evaluated the impact of the offset angle between the optical transmission path and the building windows with different types of glasses. The achieved results have also showed that the induced power loss had very little impact on the proposed OWC system BER performance. The proposed link would be very useful for further characterization of the outdoor OWCs under atmospheric conditions in an indoor controlled laboratory environment. Further work is currently in progress to investigate beam steering in order to increase the system angular coverage range.

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References

[1] E. Ciaramella, Y. Arimoto, G. Contestabile, M. Presi, A. D'Errico, V. Guarino, and M. Matsumoto, "1.28-Tb/s (32 40 Gb/s) free-space optical WDM transmission system," *IEEE Photon. Technol. Lett.*, vol. 21, no. 16, pp. 1121–1123, Aug. 2009.

[2] K. Wang, A. Nirmalathas, C. Lim, and E. Skafidas, "High-speed duplex optical wireless communication system for indoor personal area networks," *Opt. Exp.*, vol. 18, no. 24, pp. 25 199–25 216, Nov. 2010.

[3] H. L. Minh, D. O'Brien, G. Faulkner, O. Bouchet, M. Wolf, L. Grobe, and L. Jianhui, "A 1.25-Gb/s indoor cellular optical wireless communications demonstrator," *IEEE Photon. Technol. Lett.*, vol. 22, no. 21, pp. 1598–1600, Nov. 2010.

[4] D. O'Brien, R. Turnbull, H. Le Minh, G. Faulkner, O. Bouchet, P. Porcon, M. El Tabach, E. Gueutier, M. Wolf, L. Grobe, and J. Li, "High-speed optical wireless demonstrators: Conclusions and future directions," *J. Lightw. Technol.*, vol. 30, no. 13, pp. 2181–2187, Jul. 2012.

[5] K. Wang, A. Nirmalathas, C. Lim, and E. Skafidas, "4 $\times$ 12.5 Gb/s WDM optical wireless communication system for indoor applications," *J. Lightw. Technol.*, vol. 29, no. 13, pp. 1988–1996, Jul. 2011.

[6] H.-S. Chen, H. P. A. van den Boom, E. Tangdiongga, and A. M. J. Koonen, "30 Gbit/s Bi-directional transparent optical transmission with an MMF access and an indoor optical wireless link," *IEEE Photon. Technol. Lett.*, vol. 24, no. 7, pp. 572–574, Apr. 2012.

[7] K. Wang, A. Nirmalathas, C. Lim, and E. Skafidas, "High-speed optical wireless communication system for indoor applications," *IEEE Photon. Technol. Lett.*, vol. 23, no. 8, pp. 519–521, Apr. 2011.

[8] Y. Arimoto, A. Chiuchiarelli, R. Corsini, M. Presi, and E. Ciaramella, "Carrier class availability in a transparent 1.25 Gb/s free space optical communication link over 320 m," in *Proc. IWOW*, Pisa, Italy, 2012, pp. 1–3.

[9] H. S. Kim, T. T. Pham, Y. Y. Won, and S. K. Han, "Simultaneous wired and wireless 1.25-Gb/s bidirectional WDM-RoF transmission using multiple optical carrier suppression in FP LD," *J. Lightw. Technol.*, vol. 27, no. 14, pp. 2744–2750, Jul. 2009.

[10] P. L. Chen, S. T. Chang, S. T. Ji, and S. C. Lin, "Demonstration of 16 channels 10 Gb/s WDM free space transmission over 2.16 km," in *Proc. IEEE/LEOS Summer Topical Meeting*, Taipei, Taiwan, 2008, pp. 235–236.
[11] E. Ciaramella, Y. Arimoto, G. Contestabile, M. Presi, A. D'Errico, V. Guarino, and M. Matsumoto, "1.28 Terabit/s (32 $\times$ 40 Gbit/s) WDM transmission system for free space optical communications," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 9, pp. 1639–1645, Dec. 2009.
[12] Z. Ghassemlooy, H. Le Minh, S. Rajbhandari, J. Perez, and M. Ijaz, "Performance analysis of Ethernet/fast-Ethernet free space optical communications in a controlled weak turbulence condition," *J. Lightw. Technol.*, vol. 30, no. 13, pp. 2188–2194, Jul. 2012.
[13] Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, *Optical Wireless Communications: System and Channel Modelling with MATLAB*. Boca Raton, FL, USA: CRC, Jul. 2012.
[14] J. M. Senior, *Optical Fiber Communications: Principle and Practice,* 3rd ed. Hertfordshire, U.K.: Prentice-Hall, 2009.
[15] S. K. Liaw, P. S. Tasi, K. Y. Hsu, and S. J. Lin, "Power-compensated 3 $\times$ 3 reconfigurable bidirectional multiwavelength cross-connect device based on strain tunable fiber Bragg gratings," in *Proc. Eur. Conf. Netw. Opt. Commun.*, New Castle, U.K., 2011, pp. 103–106.