IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 8, Number 5, October 2016

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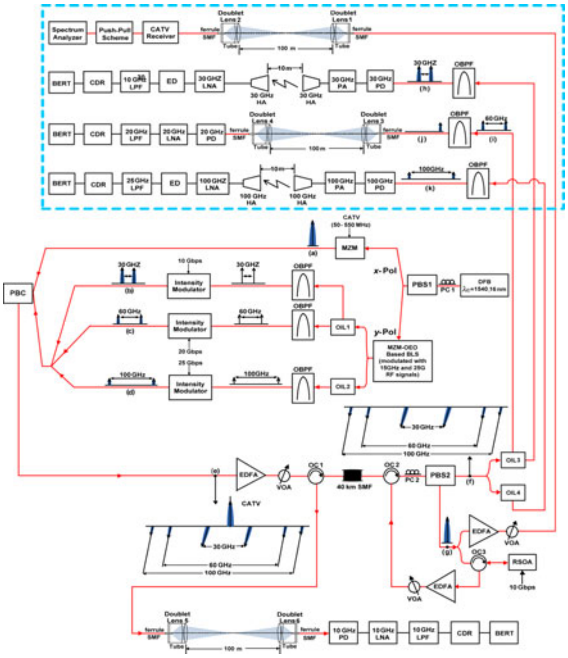

DOI: 10.1109/JPHOT.2016.2603605

A Bidirectional Fiber-Wireless and Fiber-IVLLC Convergence System with a Dual-Polarization Modulation Scheme and an MZM-OEO-Based BLS

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DOI:10.1109/JPHOT.2016.2603605

Manuscript received July 29, 2016; revised August 22, 2016; accepted August 24, 2016. Date of publication August 30, 2016; date of current version September 23, 2016. Corresponding author: H.-H. Lu (hhlu@ntut.edu.tw).

Abstract: A bidirectional fiber-wireless and fiber-invisible laser light communication (IVLLC) convergence system that adopts a dual-polarization modulation scheme and a Mach–Zehnder modulator (MZM)-optoelectronic oscillator (OEO)-based broadband light source (BLS) for hybrid cable television (CATV)/microwave (MW)/millimeter-wave (MMW)/baseband signal transmission is proposed and experimentally demonstrated. The MZM employed in the MZM-OEO is operated at the minimum transmission point, which results in the format of optical carrier suppression for the *y*-axis component of the light. Using a dual-polarization modulation scheme, the optical carrier modulated with CATV signal (*x*-polarization) and the optical sidebands modulated with MW and MMW data signals (*y*-polarization) are separated and polarized orthogonally automatically. Through an in-depth observation, good carrier-to-noise ratio, composite second-order, composite triple-beat, and bit error rate performances are obtained over a 40-km single-mode fiber and a 10-m RF/100-m optical wireless transport. Such a bidirectional fiber-wireless and fiber-IVLLC convergence system is a notable option; it would be attractive for providing broadband heterogeneous services such as CATV, Internet, and big data services.

Index Terms: Dual-polarization modulation, fiber-invisible laser light communication (IVLLC) convergence, fiber-wireless convergence, Mach–Zehnder modulator (MZM)-optoelectronic oscillator (OEO).

1. Introduction

Fiber-wireless and fiber-invisible laser light communication (IVLLC) convergence systems are capable of delivering multi-gigabit of data, voice, and video services concurrently through the inherently large bandwidth of optical fiber and the flexibility of RF/optical wireless transmission. Fiber-wireless and fiber-IVLLC convergence systems are advantageous because they can use the efficiency of both optical and wireless technologies, as well as cover service areas with faster speed and lower cost using fiber long-haul and RF/optical wireless short-range characteristics [1]–[3]. A bidirectional fiber-wireless and fiber-IVLLC convergence system based on the Mach-Zehnder modulator (MZM)-optoelectronic oscillator (OEO)-based broadband light source (BLS) was previously illustrated [4]. However, considerable improvement can still be achieved. Developing a configuration with potentially simple characteristics to ensure the real implementation of a bidirectional fiber-wireless and fiber-IVLLC convergence system is essential. Dual-polarization modulation scheme, which can separate the optical carrier (*x*-polarization light) and the optical sidebands (*y*-polarization light) automatically, is expected to simplify the configuration of the bidirectional fiber-wireless and fiber-IVLLC convergence systems [5]–[9]. The scheme proves to be an outstanding one with a simple advantage of separating the optical carrier and optical sidebands. Thus, a traditionally used wavelength-dependent fiber Bragg grating combined with optical circulator (OC) is not required at the transmitter and receiver sides for uplink transmission. In addition, the MZM employed in the MZM-OEO is operated at the minimum transmission point (null-bias point) to suppress the optical carrier and enhance the optical sidebands for the *y*-axis component of the light. Moreover, given that 60-GHz millimeter-wave (MMW) and 100-GHz MMW signals have high atmospheric attenuation (especial for 60-GHz MMW) [10]; fiber-IVLLC convergence is a promising substitution for fiber-wireless convergence in 60-GHz and 100-GHz MMW transmissions. Furthermore, the free-space link of IVLLC subsystem can be extended up to 100 m with the assistance of doublet lens scheme. Accordingly, fiber-IVLLC convergence is a notable option into which fiber backbone and optical wireless feeder networks can be integrated.

In this paper, a bidirectional fiber-wireless and fiber-IVLLC convergence system with a dual-polarization modulation scheme and a MZM-OEO-based BLS to deliver downstream 50–550 MHz cable television (CATV), 10 Gbps/30 GHz microwave (MW), 20 Gbps/60 GHz MMW, and 25 Gbps/100 GHz MMW signals, as well as upstream 10 Gbps baseband (BB) data stream is proposed and experimentally demonstrated. The optical carrier modulated with CATV signal (*x*-polarization light) and the optical sidebands modulated with MW and MMW data signals (*y*-polarization light) are separated and polarized orthogonally automatically. The downstream light is optically promoted from a 15-GHz RF signal to 10 Gbps/30 GHz MW and 20 Gbps/60 GHz MMW data signals, and is also optically promoted from a 25-GHz RF signal to 25 Gbps/100 GHz MMW data signal. Such a bidirectional fiber-wireless and fiber-IVLLC convergence system is practical and flexible due to different transmission rates for downstream MW and MMW data signals. And further, the optical carrier with a downstream 50–550 MHz CATV signal is picked up by a polarization beam splitter (PBS) and reused for uplink transmission by a gain-saturated reflective semiconductor optical amplifier (RSOA) [11] with a 10-Gbps BB data stream. Over a 40-km SMF and a 10-m RF transport/100-m free-space link, carrier-to-noise ratio (CNR), composite second order (CSO), composite triple beat (CTB), and bit error rate (BER) perform well in the proposed bidirectional fiber-wireless and fiber-IVLLC convergence system. This bidirectional fiber-wireless and fiber-IVLLC convergence system for a hybrid CATV/MW/MMW/BB signal transmission is a notable option because it can provide broadband heterogeneous services such as CATV, Internet, and big data services.

2. Experimental Setup

The configuration of the proposed bidirectional fiber-wireless and fiber-IVLLC convergence system with a dual-polarization modulation scheme and a MZM-OEO-based BLS is shown in Fig. 1. The output of distributed feedback (DFB) laser diode (LD), with a central wavelength of 1540.16 nm, is separated into two branches along the two orthogonal polarization states by polarization controller 1 (PC1) and PBS1. The *x*-polarization light is fed into a MZM for 50-550 MHz CATV signal downlink transmission [inset (a) of Fig. 1], and the *y*-polarization light is fed into a MZM-OEO-based BLS for 10 Gbps/30 GHz MW, 20 Gbps/60 GHz MMW, and 25 Gbps/100 GHz MMW data signals downlink transmission. The optical output of the MZM-OEO-based BLS is split using a 1 × 2 optical splitter and fed into optical interleaver 1 (OIL1) and OIL2 to separate the optical signal into odd and even optical sidebands. OIL1 has an input channel spacing of 15-GHz and an output channel spacing of 30-GHz, whereas OIL2 has an input channel spacing of 25-GHz and an output channel spacing of 50-GHz.

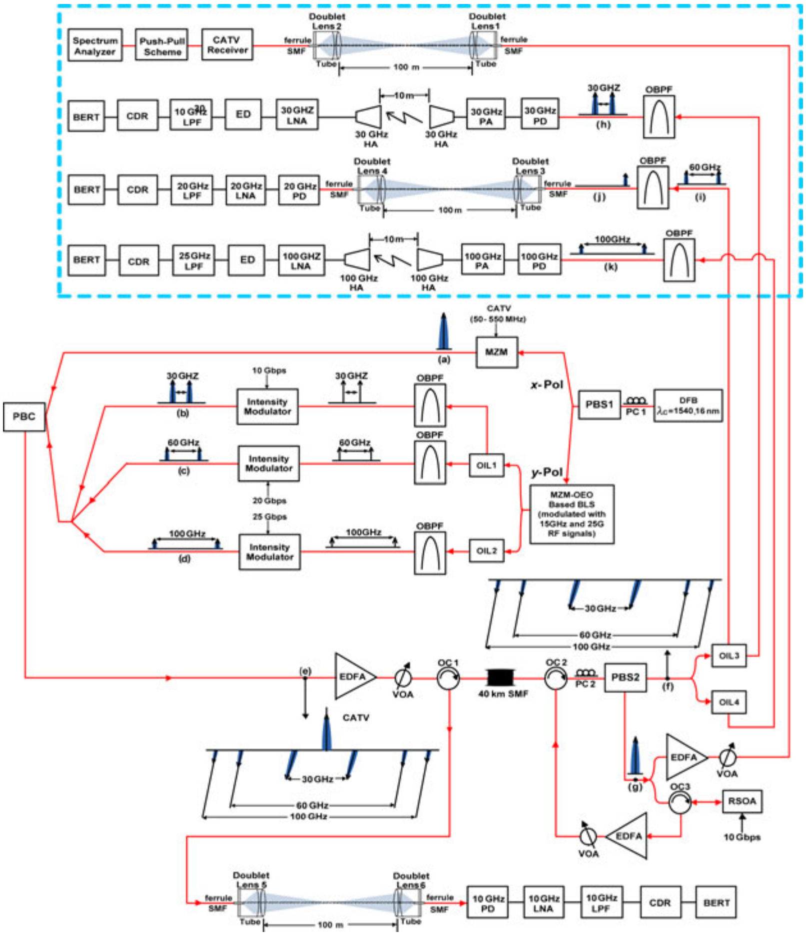


Fig. 1. Configuration of the proposed bidirectional fiber-wireless and fiber-IVLLC convergence system with a dual-polarization modulation scheme and a MZM-OEO-based BLS.

For OIL1, the −1 and +1 optical sidebands are utilized for the 30-GHz MW downlink transmission, and the −2 and +2 optical sidebands are utilized for the 60-GHz MMW downlink transmission. For OIL2, the −2 and +2 optical sidebands are utilized for the 100-GHz MMW downlink transmission. The 15-GHz RF signal is converted into a 10 Gbps/30 GHz MW data signal by creating two optical sidebands spaced by 30 GHz (−1 and +1 sidebands) using an optical band-pass filter (OBPF) and an intensity modulator [see inset (b) of Fig. 1]. The 15-GHz RF signal is also converted into a 20 Gbps/60 GHz MMW data signal by creating two optical sidebands spaced by 60 GHz (−2 and +2 sidebands) using an OBPF and an intensity modulator [see inset (c) of Fig. 1]. The 25-GHz RF data signal is converted into a 25 Gbps/100 GHz MMW data signal by creating two optical sidebands spaced by 100 GHz (−2 and +2 sidebands) using an OBPF and an intensity modulator [see inset (d) of Fig. 1]. The *x*-polarization light and the *y*-polarization light are combined by a polarization beam combiner (PBC) [see inset (e) of Fig. 1], amplified by an erbium-doped fiber amplifier (EDFA), and attenuated by a variable optical attenuator (VOA). Next to the VOA, the OC1 and OC2 are placed to bridge the downstream and upstream lightwaves. Over a 40-km SMF transport, the lights are separated by PC2 and PBS2. The *y*-polarization light [see inset (f) of Fig. 1] is split by a 1 × 2 optical splitter and then fed into OIL3 and OIL4. The *x*-polarization light [see inset (g) of Fig. 1] is also split by a 1 × 2 optical splitter. One optical signal is sent through an EDFA, attenuated by a VOA, and launched into a 100-m IVLLC subsystem with a doublet lens scheme (doublet lens 1 and doublet lens 2). The IVLLC subsystem implements the free-space link using a pair of doublet lenses

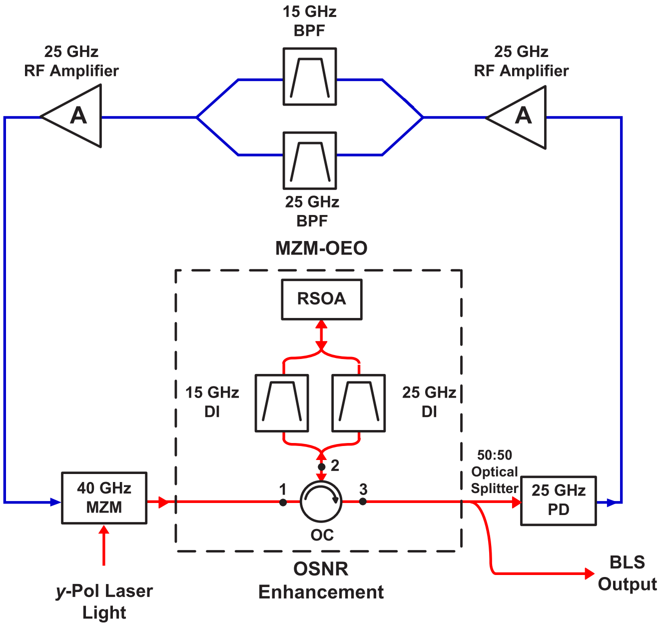


Fig. 2. MZM-OEO-based BLS.

with SMFs. Over a 100-m free-space link, the optical signal is received by a CATV receiver, fed into a push-pull scheme for nonlinear distortion reduction [12], and inputted into a spectrum analyzer for CATV performance (CNR, CSO, and CTB) analysis. The other optical signal is circulated using an OC3, and subsequently reused and remodulated using a gain-saturated RSOA with a 10-Gbps BB data stream for uplink transmission.

Following the OIL3 output with odd sidebands, the optical signal is passed through an OBPF [see inset (h) of Fig. 1], detected by a 30-GHz photodiode (PD), amplified by a power amplifier (PA) with 30-GHz, and wirelessly transmitted by a horn antenna (HA) with 30-GHz. Over a 10-m RF wireless transport, the 10 Gbps/30 GHz MW data signal is received by a 30-GHz HA, boosted by a low-noise amplifier (LNA) with 30-GHz, and down-converted by an envelope detector (ED) with a frequency range of 0.5-10 GHz. After ED detection, the 10 Gbps data stream is filtered by a 10-GHz low-pass filter (LPF), and clock/data are recovered through 10 Gbps clock/data recovery (CDR). Finally, the 10-Gbps data stream is supplied to a BER tester (BERT) for BER performance evaluation. Following the OIL3 output with even sidebands [see inset (i) of Fig. 1], the optical signal is passed through an OBPF to form only one optical sideband [see inset (j) of Fig. 1], and inputted into a 100-m IVLLC subsystem with doublet lens scheme (doublet lens 3 and doublet lens 4). Following the OIL4 output with even sidebands, the optical signal is passed through an OBPF [see inset (k) of Fig. 1], detected by a 100-GHz PD, amplified by a PA at 100-GHz, and wirelessly transmitted by a HA at 100-GHz.

For uplink transmission, the optical carrier circulated by the OC3 is reused and remodulated by a gain-saturated RSOA. A 10-Gbps data stream, with a pseudorandom binary sequence length of $2^{15}-1$, is directly fed into the RSOA. The remodulated upstream lightwave is circulated by the OC3, amplified by an EDFA, attenuated by a VOA, and launched into the same 40 km SMF link. Over a 40-km SMF transport, the optical signal is inputted into a 100-m IVLLC subsystem with a doublet lens scheme (doublet lens 5 and doublet lens 6). Over a 100-m free-space link, the optical signal is detected by a PD with 10-GHz. After PD detection, the detected 10 Gbps data stream is boosted by a LNA with 10-GHz and filtered by a 10-GHz LPF. Clock/data are recovered through 10 Gbps CDR and fed into a BERT to evaluate the BER performance.

As shown in Fig. 2, the MZM-OEO-based BLS comprises MZM-OEO and optical signal-to-noise ratio (OSNR) enhancement scheme. Since the MZM is operated at the minimum transmission

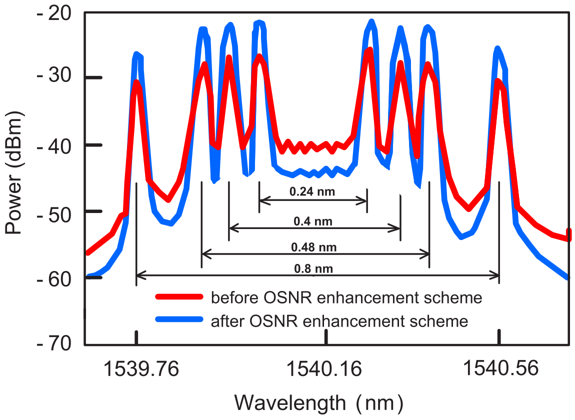


Fig. 3. Optical spectra of the MZM–OEO–based BLS before and after OSNR enhancement.

point, yet the *y*-axis component of the light is modulated in the format of optical carrier suppression. Half of the laser output is utilized as the BLS, while the other half of the laser output is utilized for feedback through an optoelectronic feedback loop. The MZM is modulated by 15-GHz and 25-GHz RF signals, which causes the generation of multiple optical sidebands with channel spacing of 15-GHz and 25-GHz. Using OILs and OBPFs at the transmitter side, the multiples of the 15-GHz and 25-GHz RF signals such as 30-GHz MW (0.24 nm), 60-GHz MMW (0.48 nm), and 100-GHz MMW (0.8 nm) signals are generated. These generated optical sidebands are then fed into the OSNR enhancement scheme to improve the OSNR values. The OSNR enhancement scheme is composed of two optical splitters/combiners, one OC, two delay interferometers (DIs) with free spectral ranges (FSRs) of 15 GHz and 25 GHz, and one RSOA. The optical spectra of the MZM-OEO-based BLS before and after OSNR enhancement are shown in Fig. 3. Clearly, around 5 dB to 8 dB OSNR value improvements is obtained for the optical sidebands as the OSNR enhancement scheme is employed. The OC is used to route the optical sidebands into the DIs, and the DIs are used as optical comb filters. By taking the FSR characteristic of the DI, if we carefully shift the DI working wavelength range to align with the modulated RF frequency (15 and 25 GHz), then the valleys of the optical sidebands will locate in the stop-band of the DI. As a result, the noise between each two optical sidebands is reduced. Following that, a RSOA is used to amplify and reflect the optical sidebands. As the optical signal goes through the RSOA, the optical sidebands will be amplified. In result, the OSNR values of the optical sidebands are greatly improved.

3. Experimental Results and Discussion

The measured CNR/CSO/CTB values over a 40-km SMF transport and over a 40-km SMF transport as well as a 100-m free-space link are shown in Fig. 4. Over a 40-km SMF transport, the measured CNR/CSO/CTB values (≥50.5/61/61.6 dB) satisfy the fiber optical CATV CNR/CSO/CTB requirements at the optical node (≥50/60/60 dB) [13]. Further transmission over a 100-m free-space link is conducive to lower received optical power and leads to lower CNR/CSO/CTB values. However, over a 40-km SMF transport and a 100-m free-space link, the measured CNR/CSO/CTB values (≥43.1/53.8/54.2 dB) still meet the fiber optical CATV CNR/CSO/CTB demands at the subscriber (≥43/53/53 dB) [13].

The measured BER curves of the 10 Gbps/30 GHz MW data signal for back-to-back (BTB) and over a 40-km SMF as well as a 10-m RF wireless transport scenarios are shown in Fig. 5(a). At a 10^{-9} BER operation, a 4.4-dB power penalty exists between BTB and 40 km SMF as well as 10 m RF wireless transport scenarios. The measured BER curves of the 20 Gbps/60 GHz MMW data signal for BTB and over a 40-km SMF transport as well as a 100-m free-space link scenarios are shown in Fig. 5(b). At a 10^{-9} BER operation, a large 6.4-dB power penalty is observed between BTB

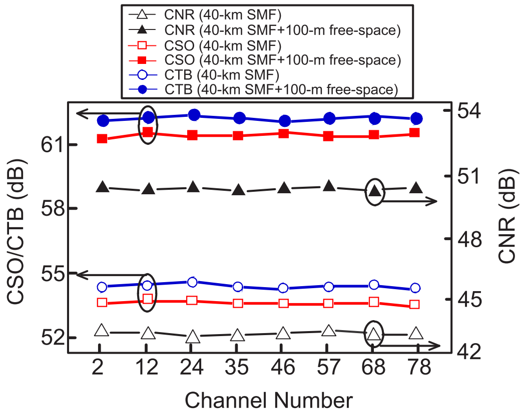
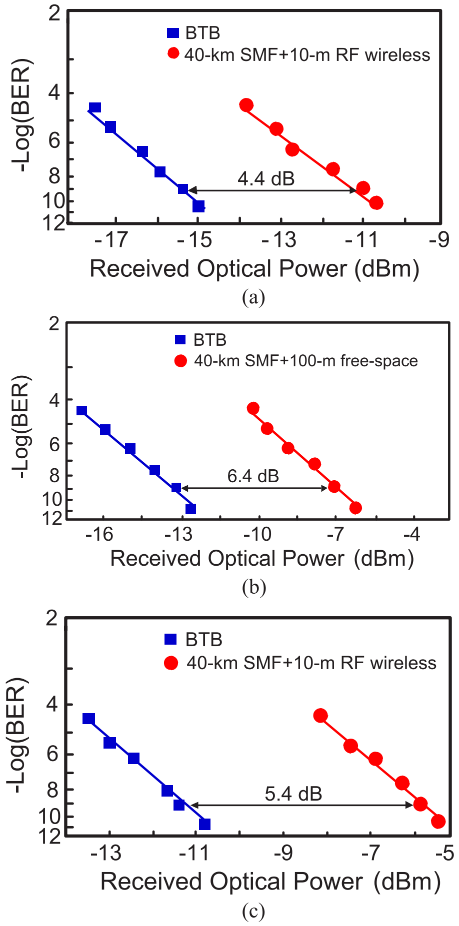


Fig. 4. Measured CNR/CSO/CTB values over a 40-km SMF transport and over a 40-km SMF transport, as well as a 100-m free-space link.



(a)

(b)

(c)

Fig. 5. Measured BER curves of the (a) 10 Gbps/30 GHz MW, (b) 20 Gbps/60 GHz MMW, and (c) 25 Gbps/100 GHz MMW data signals.

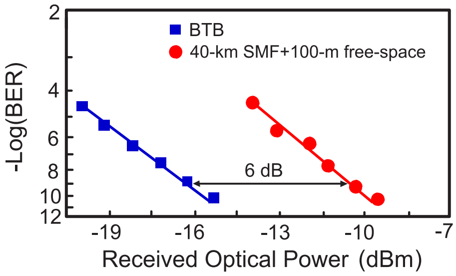


Fig. 6. Measured BER curves of the 10-Gbps data stream for BTB and over a 40-km SMF transport, as well as a 100-m free-space link.

and 40 km SMF as well as 100 m free-space transport scenarios. The measured BER curves of 25 Gbps/100 GHz MMW data signal for BTB and over a 40-km SMF, as well as a 10-m RF wireless transport scenarios are shown in Fig. 5(c). At a 10^{-9} BER operation, a 5.4-dB power penalty exists between BTB and 40 km SMF, as well as 10 m RF wireless transport scenarios. These power penalties of 4.4, 6.4, and 5.4 dB can be attributed to fiber dispersion over a 40-km SMF transport, fading effect over a 10-m RF wireless transport, and optical power transmission loss due to a 100-m free-space link.

The IVLLC subsystem is to implement the free-space link using a pair of doublet lenses with SMFs [14], [15]. Delivering a laser light through the free-space between the doublet lenses enacts the IVLLC subsystem to work as if the SMFs were connected seamlessly. A pair of doublet lenses is deployed to emit laser light from an optical fiber to the free-space and to guide laser light from the free-space into an optical fiber. The function of the doublet lenses is to extend the free-space link greatly. The doublet lenses connected to SMFs play crucial roles for delivering laser light through the free-space between the two sides. Given that the diameter of the laser light is smaller than the diameter of the doublet lens at the transmitter/receiver side; thereby, a pair of doublet lenses is workable for a 100-m free-space link. For an IVLLC subsystem, a reduction setup should be realized at the receiver side to reduce the laser light size for guiding into the ferrule of SMF. The function of the doublet lens at the receiver side is to reduce the laser light size for guiding into the ferrule of SMF.

For uplink transmission, the measured BER curves of the 10-Gbps data stream for BTB and over a 40-km SMF transport as well as a 100-m free-space link are presented inFig. 6. At a 10^{-9} BER operation, a large 6-dB power penalty exists between BTB and 40 km SMF, as well as 100 m free-space transport scenarios. The 6 dB power penalty is the result of the fiber dispersion over a 40-km SMF transport and optical power transmission loss over a 100-m free-space link. Further transmission over a 100-m free-space link leads to a lower received optical power and OSNR value, which results in the degradation of BER performance.

4. Conclusion

A bidirectional fiber-wireless and fiber-IVLLC convergence system with a dual-polarization modulation scheme and a MZM-OEO-based BLS to transport downstream CATV/MW/MMW signal and upstream BB data stream is proposed and demonstrated. Using a dual-polarization modulation scheme, the optical carrier and the optical sidebands are separated and polarization-orthogonal automatically. It reveals a promising alternate with simpler advantage to separate the optical carrier and the optical sidebands. The MZM employed in the MZM-OEO is operated at the minimum transmission point to obtain the format of optical carrier suppression and optical sidebands enhancement for the *y*-axis component of the light. The results show that CNR, CSO, CTB, and BER perform excellently over 40-km SMF and 10-m RF/100-m optical wireless transport. This proposed bidirectional fiber-wireless and fiber-IVLLC convergence system is notable for the integration of a fiber backbone and RF/optical wireless feeder.

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