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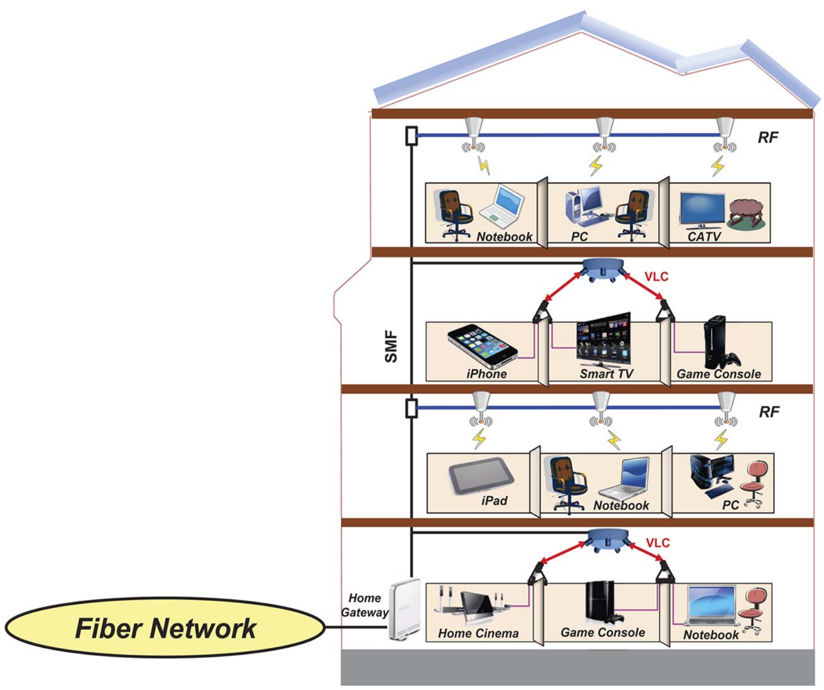

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A Hybrid WDM Lightwave Transport System Based on Fiber-Wireless and Fiber-VLLC Convergences

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Abstract: A hybrid wavelength-division-multiplexing (WDM) lightwave transport system for millimeter-wave (MMW)/microwave (MW)/baseband (BB) signals that are transmission based on fiber-wireless and fiber-visible laser light communication (VLLC) convergences is proposed and demonstrated. A broadband light source with an optical signal-to-noise ratio enhancement scheme in a hybrid lightwave transport system is employed. Light is optically promoted from a 5-Gbps/15-GHz RF data signal to 5-Gbps/60-GHz MMW and 5-Gbps/30-GHz MW data signals in fiber-wireless convergence. Light is also optically demoted from a 5-Gbps/15-GHz RF data signal to a 5-Gbps data stream in fiber-VLLC convergence. Over a 40-km single-mode fiber and a 4-m RF wireless/a 10-m free-space VLLC transmission, bit error rate performs impressively for 60-GHz MMW, 30-GHz MW, and 5-Gbps BB signal transmission. Such a hybrid WDM lightwave transport system could have practical applications for fiber-wireless and fiber-VLLC convergences to provide broadband integrated services.

Index Terms: Fiber-VLLC convergence, fiber-wireless convergence, hybrid lightwave transport systems, wavelength-division multiplexing.

1. Introduction

Wavelength-division-multiplexing (WDM) lightwave transport system is a promising candidate for broadband communication systems. An optical network that can provide both wired and wireless communications concurrently has been required due to the increased demands in bandwidth and access data rate for various applications [1], [2]. Transmitting hybrid millimeter-wave (MMW), microwave (MW), and baseband (BB) signals over a WDM lightwave transport system has several advantages, including large bandwidth, high-speed access rate, and wide service area. A hybrid WDM lightwave transport system that carries different optical wavelengths to deliver combined MMW/MW/BB signals would be very useful in providing telecommunication, Internet, and big data services [3], [4]. Nevertheless, transporting MMW/MW/BB signals simultaneously by using one optical fiber in a simple and cost-effective way is difficult. A single-wavelength system multiplexing different signals in the electrical domain may be a solution. However, interactions among MMW, MW, and BB electrical signals are a major concern for systems. Multiplexing these hybrid signals in the electrical domain induces large distortions after beating among the electrical signals. Moreover, multiplexing such hybrid MMW/MW/BB signals in a conventional optical WDM transport system requires multiple distributed feedback laser diodes (DFB LDs) to support different kinds of services [5], [6]. DFB LDs are wavelength-selected for each optical channel, and this process increases the complexity of systems. Thus, developing configurations with potentially easy characteristics to ensure implementation of hybrid MMW/MW/BB WDM lightwave transport systems is necessary. In this paper, a hybrid WDM lightwave transport system for MMW/MW/BB signals transmission based on fiber-wireless and fiber-visible laser light communication (VLLC) convergence is proposed and demonstrated. Light is optically promoted from a 5 Gbps/15 GHz RF data signal to 5 Gbps/60 GHz MMW and 5 Gbps/30 GHz MW data signals in fiber-wireless convergence by employing a broadband light source (BLS) with an optical signal-to-noise ratio (OSNR) enhancement scheme [7], [8]. Further, light is also optically demoted from a 5 Gbps/15 GHz RF data signal to a 5-Gbps data stream in fiber-VLLC convergence [9], [10]. The OSNR enhancement scheme is employed to optimize the optical lightwave generated from the BLS. Some sidebands can be generated when a lightwave is modulated by a phase modulator driven by an RF signal [11], [12]. We apply appropriate RF signal to drive a phase modulator, resulting in multiple optical sidebands after phase modulation (PM). Subsequently, an OSNR enhancement scheme is employed to optimize the optical sidebands. Over a 40-km single-mode fiber (SMF) and a 4-m RF wireless/a 10-m free-space VLLC transmission, bit error rate (BER) performed impressively for 60-GHz MMW, 30-GHz MW, and 5-Gbps BB signals transmission. A 60-GHz MMW signal could be used for high definition multimedia (HDMI) application, a 30-GHz MW signal could be used for local multipoint distribution service (LMDS) application, and a 5-Gbps BB signal could be used for Internet application. Such a hybrid WDM lightwave transport system for MMW/MW/BB signals transmission could have excellent potential for fiber-wireless and fiber-VLLC convergences to provide broadband integrated services.

2. Experimental Setup

The integration of the fiber-wireless and fiber-VLLC convergences is illustrated in Fig. 1. Radiowaves and visible laser lights transmit and receive signals in a wireless form to integrate the fiber and in-building networks for end-user applications. The experimental configuration of the proposed hybrid WDM lightwave transport systems for 60-GHz MMW, 30-GHz MW, and 5-Gbps BB signals transmission based on fiber-wireless and fiber-VLLC convergences is shown in Fig. 2. The transmitting site is composed of a BLS, an erbium-doped fiber amplifier (EDFA), and a variable optical attenuator (VOA). The BLS is modulated at 5 Gbps data stream mixed with 15 GHz RF carrier to generate the 5 Gbps/15 GHz amplitude shift keying (ASK) data signal. The optical output of the BLS is coupled into an EDFA and then passed through a VOA. Over a 40-km SMF link, the optical signal is fed into an optical interleaver (IL) that can separate the optical signal into even and odd channels. The optical spectra measured at optical IL input [see insert (a) of Fig. 2] and output with even sidebands [see insert (b) of Fig. 2] are present in Fig. 3(a) and (b). Following the optical IL output with even sidebands, the optical signal travels through two optical filters [see insert (c) of Fig. 2]. For the 5 Gbps/60 GHz MMW signal, the optical sidebands of mode -2 and $+2$ [as shown in Fig. 3(c)] were picked up through two optical filters. To promote 5 Gbps/15 GHz ASK data signal into 5 Gbps/60 GHz MMW one, two optical sidebands spaced by 60 GHz (-2 and $+2$) were generated by using an optical band-pass filter (OBPF) and an optical band-rejection filter (OBRF). The OBPF, with a 3-dB bandwidth of 0.48 nm, was utilized to remove the outer optical sidebands. The OBRF, which was centered at 1540.16 nm and with a 3-dB bandwidth of 0.28 nm, was utilized to suppress the three central optical sidebands (-1, 0, and $+1$). After it went through two optical filters, the optical signal was separated by a 1×2 optical splitter. One of the optical signals was detected by a photodiode (PD) with a 3-dB bandwidth of 60 GHz, boosted by a 60-GHz power amplifier (PA), and wirelessly transmitted by a 60-GHz horn antenna (HA). Over a 4-m RF wireless transmission, the 5 Gbps/

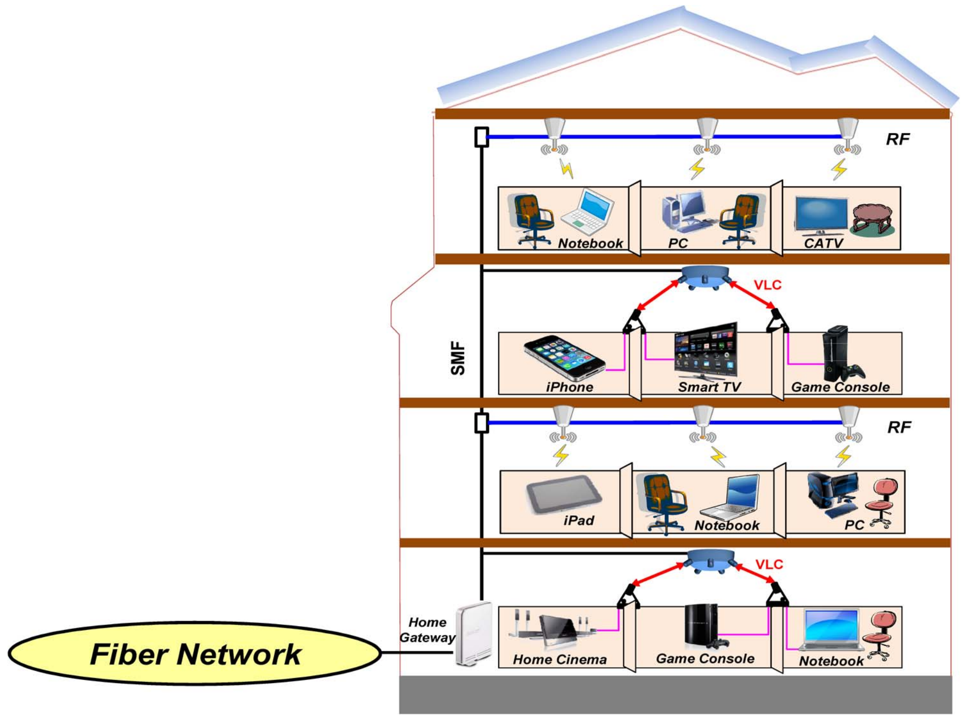

Fig. 1. The integration of the fiber-wireless and fiber-VLLC convergences.

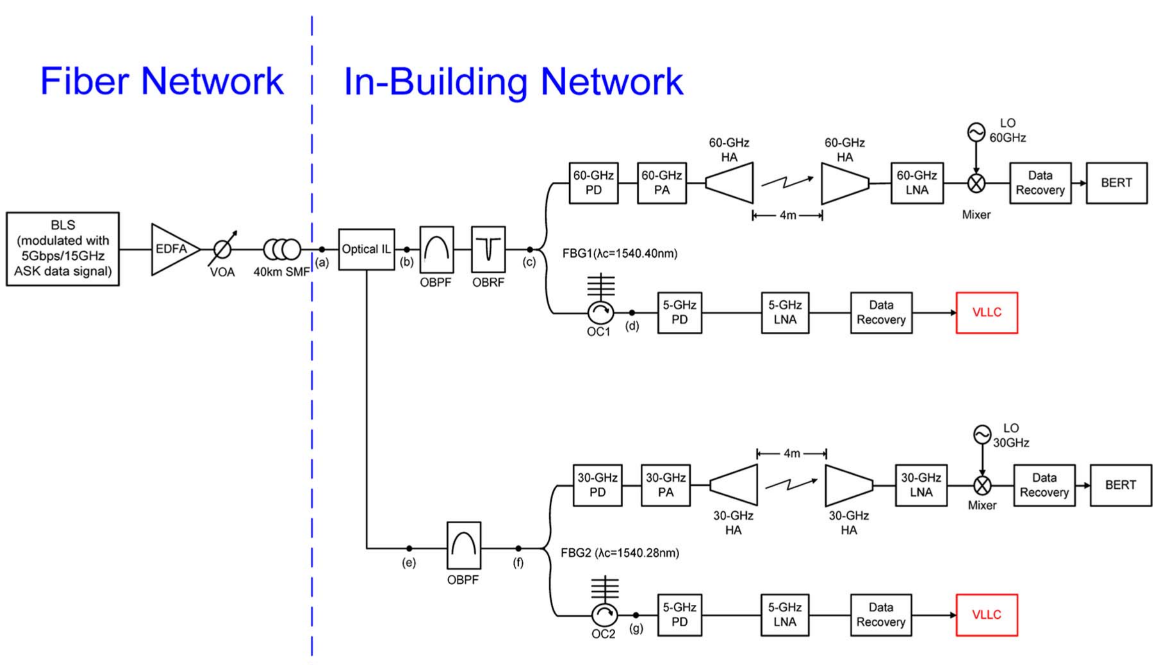

Fig. 2. The experimental configuration of the proposed hybrid WDM lightwave transport systems for 60-GHz MMW, 30-GHz MW, and 5-Gbps BB signal transmission based on fiber-wireless and fiber-VLLC convergences.

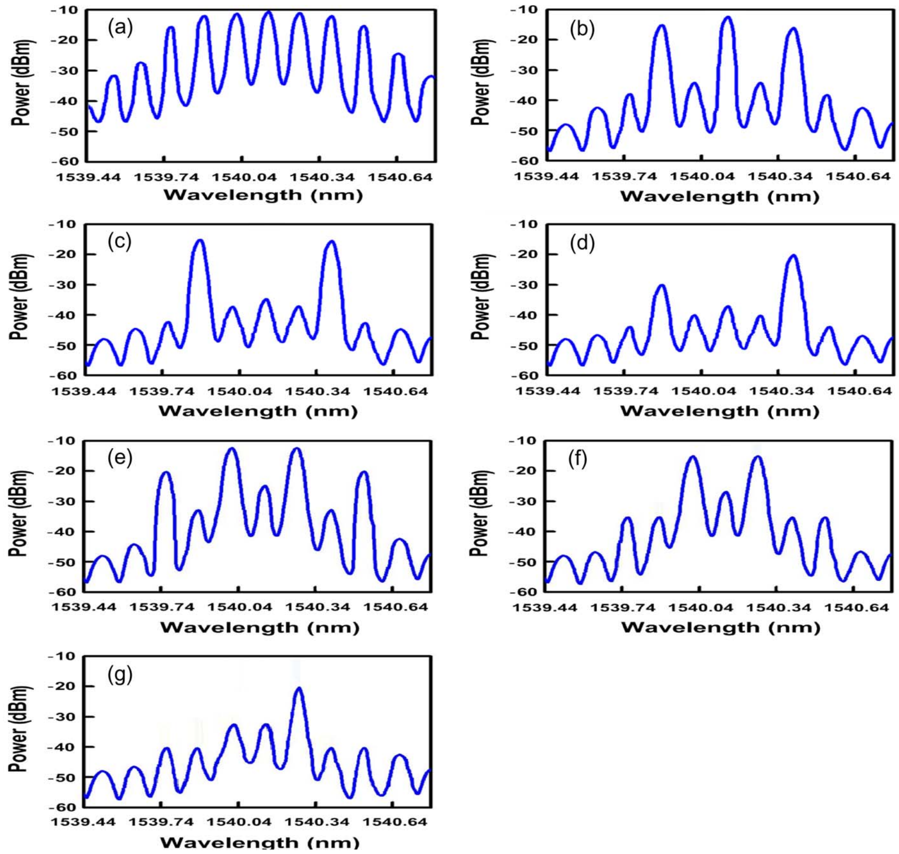

Fig. 3. (a)–(g) The optical spectra of the different signals at several interesting points in the optical path [see insert (a)–(g) of Fig. 2].

60 GHz MMW signal was received by a 60-GHz HA, amplified by a 60-GHz low-noise amplifier (LNA) with a noise figure of around 4.5 dB, down-converted by a 60-GHz local oscillator (LO) and mixer (60-GHz GaAs MMIC mixer with integrated LO buffer), data regenerated by a data recovery scheme, and fed into a BER tester (BERT) for BER performance evaluation. For data recovery scheme, the receiving site generates a clock from an approximate frequency reference, phase-aligns to the transitions in the data stream, and thus regenerates the data stream. Another optical signal was selected by an optical circulator (OC1) combined with a fiber Bragg grating (FBG1) ($\lambda_c = 1540.40$ nm) and directly detected by a 5-GHz PD to obtain the 5-Gbps data stream. The optical spectrum measured in front of PD [see insert (d) of Fig. 2] is present in Fig. 3(d). Subsequently, the 5-Gbps data stream was amplified by an LNA, data regenerated by a data recovery scheme, and supplied to the vertical cavity surface emitting laser (VCSEL)-based VLLC subsystems.

The optical spectrum measured at the optical IL output with odd sidebands [see insert (e) of Fig. 2] is shown in Fig. 3(e). Following the optical IL output with odd sidebands, the optical signal travels through another OBPF [see insert (f) of Fig. 2]. For the 5 Gbps/30 GHz MW signal, the optical sidebands of mode -1 and $+1$ [see Fig. 3(f)] were picked up via one optical filter. The 5 Gbps/15 GHz ASK data signal was promoted into 5 Gbps/30 GHz MW one by generating two optical sidebands spaced by 30 GHz (-1 and 1) using one OBPF. The OBPF with a 3-dB bandwidth of 0.26 nm was utilized to remove the outer optical sidebands. The optical signal is separated off by a 1×2 optical splitter after passing through the OBPF. One of the optical signals was detected using a PD with a 3-dB bandwidth of 30-GHz, boosted by a 30-GHz PA, and wirelessly transmitted by a 30-GHz HA. Over a 4-m RF wireless transmission, the 5 Gbps/30 GHz MW signal was received by a 30-GHz HA, amplified by a 30-GHz LNA with a noise figure of about 3.2 dB, down-converted by a 30-GHz LO and mixer, data regenerated by a

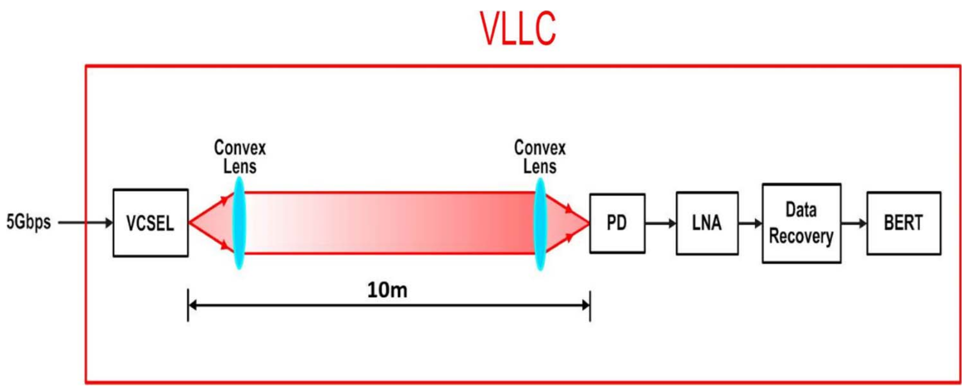

Fig. 4. The schematic configuration of the VCSEL-based VLLC subsystems over a 10-m free-space transmission.

data recovery scheme, and fed into a BERT for BER performance analysis. Another optical signal was selected by using OC2 combined with FBG2 ($\lambda_c = 1540.28$ nm), and directly detected by a 5-GHz PD to obtain the 5-Gbps data stream. The optical spectrum measured in front of PD [see insert (g) of Fig. 2] is present in Fig. 3(g). The 5-Gbps data stream is then amplified by a LNA, data regenerated by a data recovery scheme, and supplied to the VCSEL-based VLLC subsystems.

The schematic configuration of VCSEL-based VLLC subsystems over a 10-m free-space transmission is shown in Fig. 4. The VCSEL, which has a 3-dB modulation bandwidth/wavelength range/color of 5.2 GHz/678–680 nm/red, was directly modulated by a 5-Gbps data stream. After being emitted by the VCSEL, the light became diverged, launched into the first convex lens, delivered in the free-space, launched into the second convex lens, and focused on the PD. The PD has a detection wavelength range of 320–1000 nm, an active area diameter of 0.08 mm, and a responsivity of 0.44 mA/mW (at 680 nm). The received data signal was then boosted by a LNA and recovered by a data recovery scheme. Eventually, the data signal was supplied to a BERT for BER performance evaluation.

3. Experimental Results and Discussion

Simplification of the light source is a key issue that should be addressed in the development of a suitable network topology and in the implementation of a successful hybrid WDM lightwave transport system. Few techniques, such as utilizing phase-modulated light source, have been developed to overcome the light source problem. PM is a feasible technique that can generate multiple optical sidebands and avoid the need for multiple DFB LDs, making it simpler and more economical. The configuration of the proposed BLS with OSNR enhancement scheme can be found in Fig. 5, which shows that BLS is composed of a DFB LD, a phase modulator, and an OSNR enhancement scheme. The DFB LD, which has a central wavelength of 1540.16 nm, is phase-modulated with a 5 Gbps/15 GHz ASK data signal via a phase modulator. Multiple optical sidebands are generated with a channel spacing of 15 GHz (0.12 nm) when a proper driving ASK data signal is used on the phase modulator. Subsequently, the generated multiple optical sidebands are fed into an OSNR enhancement scheme to improve OSNR values. An OC, a delay interferometer (DI), and a reflective semiconductor optical amplifier (RSOA) compose the OSNR enhancement scheme. The OC is employed to route the optical sidebands into the DI, which is utilized as an optical comb filter. The use of free spectral range (FSR) characteristics of the DI and the cautious shifting of the DI work wavelength range to align with the modulated RF frequency (15 GHz) will result in every inserted optical carrier locating in the pass-band of the DI. The valleys of those carriers will locate in the stop band of the DI. As a result, the noise levels for every two optical sidebands can be attenuated to lower values. A RSOA is then used to amplify and reflect the optical sidebands. The optical spectrum of the generated BLS before

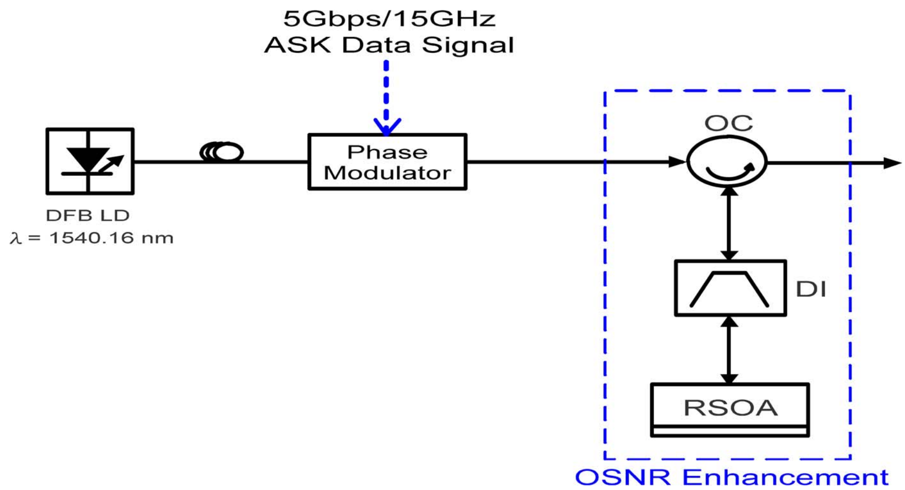

Fig. 5. The configuration of the proposed BLS with OSNR enhancement scheme.

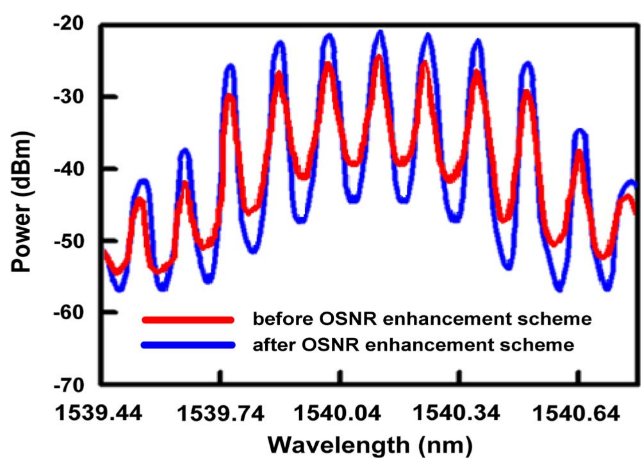

Fig. 6. The optical spectrum of the generated BLS before and after OSNR enhancement scheme.

and after the OSNR enhancement scheme is shown in Fig. 6. As the OSNR enhancement scheme is applied, around 8–10 dB OSNR value improvement could be obtained for the optical sideband.

The measured BER curves of 5 Gbps/60 GHz MMW signal for back-to-back (BTB) and over 40-km SMF as well as 4-m RF wireless transmission scenarios are shown in Fig. 7(a). A large power penalty of 4.8 dB (measured at point (a) of Fig. 2) is observed between BTB and 40-km SMF as well as 4-m RF wireless transmission scenarios at BER of 10^{-9}. Since the BLS is generated by phase-modulating an optical carrier with a 5 Gbps/15 GHz ASK data signal, yet the generated optical sidebands remains coherent with each other and the channel spacing between the adjacent sidebands is fixed at 15 GHz. The -2 and $+2$ sidebands are obtained from the BLS, and thus, the 5 Gbps/15 GHz ASK data signal can be optically promoted to the 5 Gbps/60 GHz MMW one. However, the RF power degradation induced by fiber dispersion will be generated. Over a 40-km SMF transmission, fiber dispersion degrades the transmission performance because of the nature characteristics of the two optical sidebands. And further, over a 4-m RF wireless transmission, fading effect results in amplitude and phase fluctuations in the received signal, thereby leading to performance degradation. Meanwhile, the measured BER curves of VCSEL channel, in which obtaining 5-Gbps data stream from 5 Gbps/60 GHz MMW

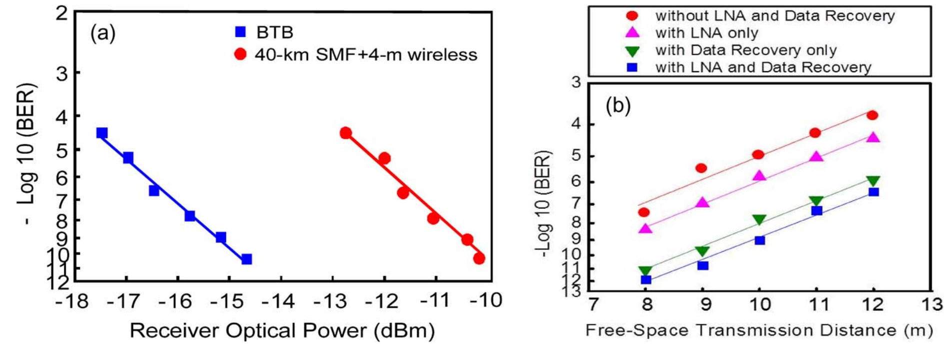

Fig. 7. (a) The measured BER curves of 5 Gbps/60 GHz MMW signal for BTB and over 40-km SMF, as well as 4-m RF wireless transmission scenarios. (b) The measured BER curves of the VCSEL channel, obtaining a 5-Gbps data stream from a 5 Gbps/60 GHz MMW signal, over a 40-km SMF and a 10-m free-space VLLC transmission.

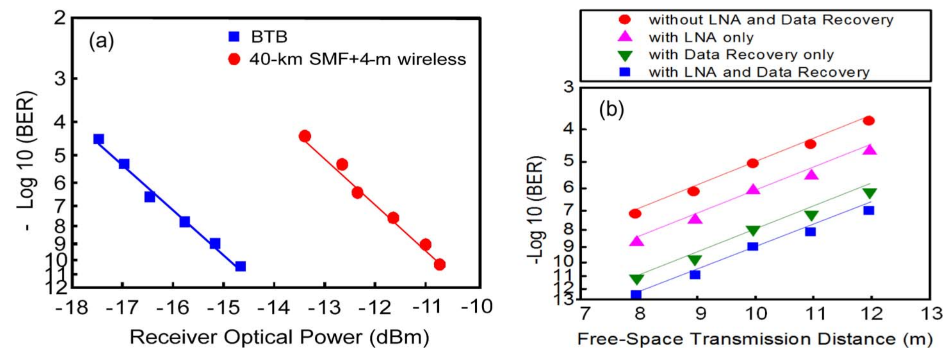

Fig. 8. (a) The measured BER curves of 5 Gbps/30 GHz MW signal for BTB and over 40-km SMF, as well as 4-m RF wireless transmission scenarios. (b) The measured BER curves of VCSEL channel, obtaining 5-Gbps data stream from 5 Gbps/30 GHz MW signal over 40-km SMF and 10-m free-space VLLC transmission.

signal, over 40-km SMF and 10-m free-space VLLC transmission are present in Fig. 7(b). At a free-space transmission distance of 10 m and a received optical power level of around 0.3 dBm (measured in front of PD in Fig. 4); BER is approximately 10^{-5} without employing LNA and data recovery, whereas BER reaches 10^{-9} when LNA and data recovery are employed simultaneously. Given that LNA and data recovery are employed concurrently, error-free transmission is achieved to demonstrate the feasibility of establishing a hybrid WDM lightwave transport system based on fiber-VLLC convergence.

The measured BER curves of 5 Gbps/30 GHz MW signal for BTB and over 40-km SMF as well as 4-m RF wireless transmission scenarios are shown in Fig. 8(a). A large power penalty of 4.1 dB (measured at point (a) of Fig. 2) is observed between BTB and 40-km SMF, as well as 4-m RF wireless transmission scenarios at a BER of 10^{-9}. Such transmission performance degradation can be attributed to fiber dispersion and RF wireless fading effects. Furthermore, the measured BER curves of VCSEL channel, in which obtaining 5-Gbps data stream from 5 Gbps/30 GHz MW signal, over 40-km SMF and 10-m free-space VLLC transmission are present in Fig. 8(b). At a free-space transmission distance of 10 m and a received optical power level of around 0 dBm (measured in front of PD in Fig. 4); BER is about 10^{-5} without employing LNA and data recovery, whereas BER reaches 10^{-9} when LNA and data recovery are employed concurrently. We remove one of the schemes and measure the BER values to illustrate the direct association between LNA and data recovery. The results indicate that BER performance improvement is limited as only one improvement scheme is employed. When only LNA is employed, BER is approximately 10^{-6}, whereas when

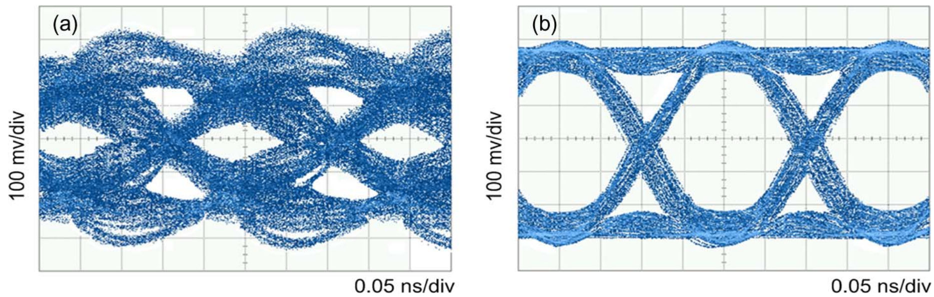

Fig. 9. The eye diagrams of a 5-Gbps data channel at a received optical power level of around −10.4 dBm, obtaining a 5-Gbps data stream from a 5 Gbps/60 GHz MMW signal, over 40-km SMF and 4-m RF wireless transmission (a) without data recovery and (b) with data recovery.

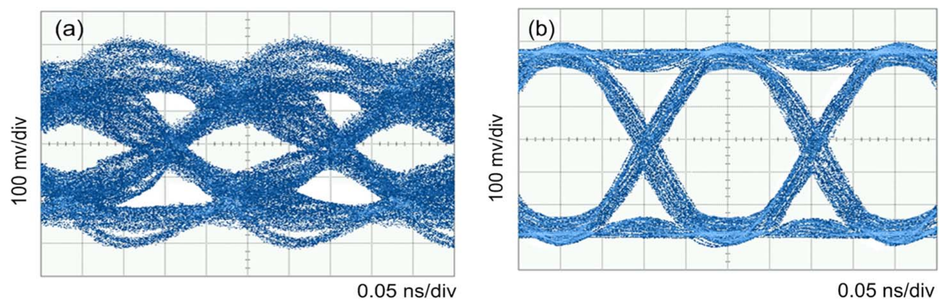

Fig. 10. The eye diagrams of a 5-Gbps data channel at a received optical power level of around 0.3 dBm, obtaining a 5-Gbps data stream from a 5 Gbps/60 GHz MMW signal, over 40-km SMF and 10-m free-space transmission (a) without LNA and data recovery and (b) with LNA and data recovery.

only data recovery is employed, BER is approximately 10^{-8}. These results indicate that LNA and data recovery play important roles for errors correction on BER performance improvements.

Fig. 9(a) and (b) display the eye diagrams of 5-Gbps data channel at a received optical power level of around −10.4 dBm, obtaining 5-Gbps data stream from 5 Gbps/60 GHz MMW signal, over 40-km SMF and 4-m RF wireless transmission without and with data recovery, respectively. At a received optical level of −10.4 dBm, BER reaches 10^{-9} when data recovery is employed. And thereby, only the eye diagrams at a received optical level of −10.4 dBm are presented. In Fig. 9(a), the corresponding jitter, SNR, and rise/fall time are 15.8 ps (rms), 17.7 dB, and 139 ps, respectively. In Fig. 9(b), the corresponding jitter, SNR, and rise/fall time are 4.4 ps (rms), 28.2 dB, and 50 ps, respectively. The amplitude and phase fluctuations in the signal are observed clearly in the case wherein data recovery is not employed. Somewhat clear eye diagram is obtained because of amplitude and phase fluctuations suppression by the data recovery scheme.

Fig. 10(a) and (b) display the eye diagrams of 5 Gbps data channel at a received optical power level of around 0.3 dBm, obtaining 5-Gbps data stream from 5 Gbps/60 GHz MMW signal, over 40-km SMF and 10-m free-space transmission without and with LNA and data recovery, respectively. At a received optical level of 0.3 dBm, BER reaches 10^{-9} when LNA and data recovery are employed simultaneously. And thereby, only the eye diagrams at a received optical level of 0.3 dBm are presented. In Fig. 10(a), the corresponding jitter, SNR, and rise/fall time are 12.6 ps (rms), 21.4 dB, and 122 ps, respectively. In Fig. 10(b), the corresponding jitter, SNR, and rise/fall time are 3.5 ps (rms), 30.5 dB, and 39.5 ps, respectively. The amplitude and phase fluctuations in the signal are observed in the case wherein LNA and data recovery are not employed. A clear eye diagram is obtained due to the use of LNA to amplify the 5-Gbps data stream while adding as little noise and distortion as possible and the use of the data recovery scheme to suppress the amplitude and phase fluctuations.

4. Conclusion

A hybrid WDM lightwave transport system for 60-GHz MMW, 30-GHz MW, and 5-Gbps BB signals transmission based on fiber-wireless and fiber-VLLC convergences is proposed and demonstrated. Light is optically promoted from 5 Gbps/15 GHz ASK data signal to 5 Gbps/60 GHz MMW and 5 Gbps/30 GHz MW data signals in fiber-wireless convergence; whereas light is also optically demoted from 5 Gbps/15 GHz ASK data signal to 5-Gbps data stream in fiber-VLLC convergence. Such a hybrid WDM lightwave transport system for MMW/MW/BB signals transmission has potential for use in fiber-wireless and fiber-VLLC convergences and can serve as an excellent alternative to satisfy the requirements of broadband integrated services.

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