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Bidirectional fiber-wireless and fiber-VLLC transmission system based on an OEO-based BLS and a RSOA

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A bidirectional fiber-wireless and fiber–visible-laser-light-communication (VLLC) transmission system based on an optoelectronic oscillator (OEO)-based broadband light source (BLS) and a reflective semiconductor optical amplifier (RSOA) is proposed and experimentally demonstrated. Through an in-depth observation of such bidirectional fiber-wireless and fiber-VLLC transmission systems, good bit error rate performances are obtained over a 40 km single-mode fiber and a 10 m RF/optical wireless transport. Such a bidirectional fiber-wireless and fiber-VLLC transmission system is an attractive option for providing broadband integrated services.

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Fiber-wireless and fiber–visible-laser-light-communication (VLLC) transmission systems are developed to provide multiple gigabit services by using the enormous bandwidth of fiber and the flexibility of RF/optical wireless transport. The advantages of fiber-wireless and fiber-VLLC transmission systems are that they can utilize the efficacy of both optical and wireless technologies, the inherently large bandwidth of optical fiber, and the unused bandwidth in millimeter-wave (MMW) and microwave (MW) bands. Serving as fiber long-distance and RF/optical wireless short-distance technologies, fiber-wireless and fiber-VLLC transmission systems can cover the service areas with faster speed and lower cost [1–4]. A 60 GHz optical/wireless multi-input multioutput (MIMO) system integrated with optical subcarrier multiplexing and 2×2 wireless communication was demonstrated previously [1]. However, an expensive dual-parallel Mach–Zehnder modulator (DP-MZM) and a complicated Levin–Campello bit-loading algorithm were required. A hybrid lightwave transmission system for cable television (CATV)/MMW/MW signal transmission based on fiber-wireless convergence was illustrated previously [2]. Nevertheless, it has room for improvement. For uplink transmission, the fiber-wireless transmission subsystem can be replaced by a fiber-VLLC one. And, thereby, the costly and sophisticated RF devices are not needed. Furthermore, a hybrid wavelength-division-multiplexing (WDM) lightwave transport system based on fiber-wireless and fiber-VLLC convergences was presented formerly [3]. Nonetheless, such a hybrid WDM lightwave transport system is not flexible due to unidirectional transport. In addition, a radio-over-fiber (RoF) access architecture for integrated broadband wireless services was demonstrated formerly [4]. However, a sophisticated ultra-dense-wavelength-division-multiplexing (UDWD) scheme and an advanced subcarrier multiplexing (SCM) dual-wavelength heterodyne beating technique were required. In this Letter, a bidirectional fiber-wireless and fiber-VLLC transmission system based on an optoelectronic oscillator (OEO)-based broadband light source (BLS) and a reflective semiconductor optical amplifier (RSOA) to transmit downstream 10 Gbps (Gigabits/s)/30 GHz MW, 10 Gbps/45 GHz MMW, and 10 Gbps/60 GHz MMW data signals, as well as an upstream 5 Gbps data stream, is proposed and experimentally demonstrated. To be the first one to employ an OEO-based BLS and a RSOA in such bidirectional fiber-wireless and fiber-VLLC transmission systems, the downstream light is optically promoted from a 10 Gbps/15 GHz MW data signal to 10 Gbps/30 GHz MW and 10 Gbps/60 GHz MMW ones. The downstream light is also optically promoted from a 10 Gbps/22.5 GHz MW data signal to a 10 Gbps/45 GHz MMW one. Furthermore, the downstream light is reused and remodulated for uplink transmission by a RSOA using a 5 Gbps data stream. Through an in-depth observation of such bidirectional fiber-wireless and fiber-VLLC transmission systems, good bit error rate (BER) performances are achieved over a 40 km single-mode fiber (SMF) and a 10 m RF/optical wireless transport.

The configuration of the proposed bidirectional fiber-wireless and fiber-VLLC transmission systems based on an

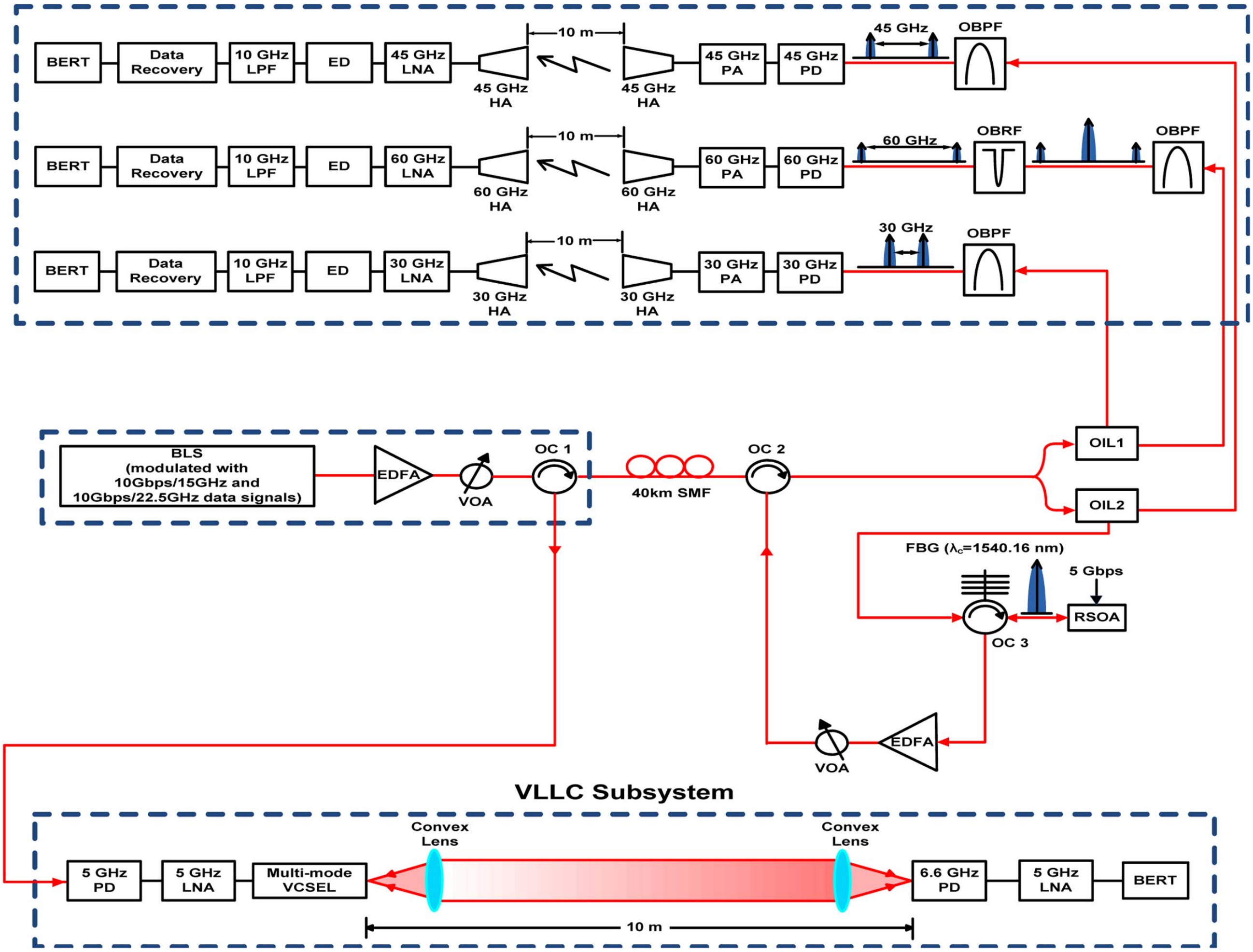

Fig. 1. Configuration of the proposed bidirectional fiber-wireless and fiber-VLLC transmission system based on an OEO-based BLS at the transmitting site and a RSOA at the receiving site.

OEO-based BLS at the transmitting site and a RSOA at the receiving site is presented in Fig. 1. A BLS modulated with 10 Gbps/15 GHz and 10 Gbps/22.5 GHz data signals is employed to generate multiple optical sidebands. The BLS is firstly amplified by an erbium-doped fiber amplifier (EDFA). A variable optical attenuator (VOA) is introduced after the EDFA to reduce the distortion as the optical power launched into the fiber decreases. Next to the VOA, optical circulator 1 (OC1) and OC2 are placed to bridge the downstream and upstream lightwaves. Two optical interleavers (OIL1 and OIL2) are utilized to separate the even and odd optical sidebands of the optical signal. The 10 Gbps/15 GHz MW data signal is transformed into a 10 Gbps/30 GHz MW one by generating two optical sidebands spaced by 30 GHz (−1 and 1 sidebands) using an optical bandpass filter (OBPF) with a 3 dB bandwidth of 0.24 nm and a 40 dB bandwidth of 0.46 nm. The 10 Gbps/15 GHz MW data signal is also transformed into a 10 Gbps/60 GHz MMW one by generating two optical sidebands spaced by 60 GHz (−2 and 2 sidebands) using an OBPF with a 3 dB bandwidth of 0.44 nm and an optical band-rejection filter (OBRF) with a 3 dB bandwidth of 0.42 nm. And, further, the 10 Gbps/22.5 GHz MW data signal is transformed into a 10 Gbps/45 GHz MMW one by generating two optical sidebands spaced by 45 GHz (−1 and 1 sidebands) using an OBPF with a 3 dB bandwidth of 0.36 nm and a 40 dB bandwidth of 0.58 nm. Over a 40 km SMF and a 10 m RF wireless transport, the data signal is amplified by a low noise amplifier (LNA) and down-converted by an envelope detector (ED). And, then, the 10 Gbps data stream is filtered by a 10 GHz low-pass filter (LPF), recovered by a data recovery scheme, and fed into a BER tester (BERT) for BER performance evaluation. For uplink transmission, the optical signal (central carrier) picked up by a fiber Bragg grating (FBG) with a central wavelength of 1540.16 nm is reused by a RSOA. A 5 Gbps data stream, with a pseudorandom binary sequence (PRBS) length of $2^{15} - 1$, is directly fed into the RSOA. The remodulated upstream lightwave is circulated by 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 detected by a 5 GHz photodiode (PD), boosted by a 5 GHz LNA, and fed into the multimode vertical-cavity surface-emitting laser (VCSEL)-based VLLC subsystem. The multimode VCSEL has a 3 dB bandwidth of 5.2 GHz and a wavelength range of 680.8–682.5 nm. The light emitted from the VCSEL is diverged,

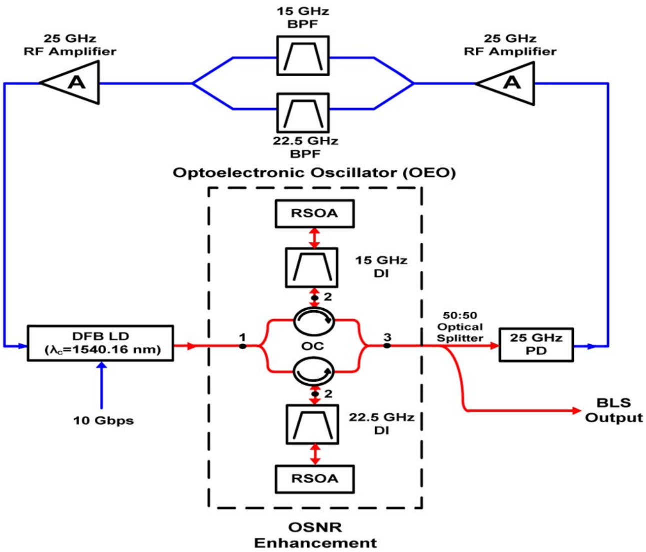

Fig. 2. Configuration of the proposed BLS.

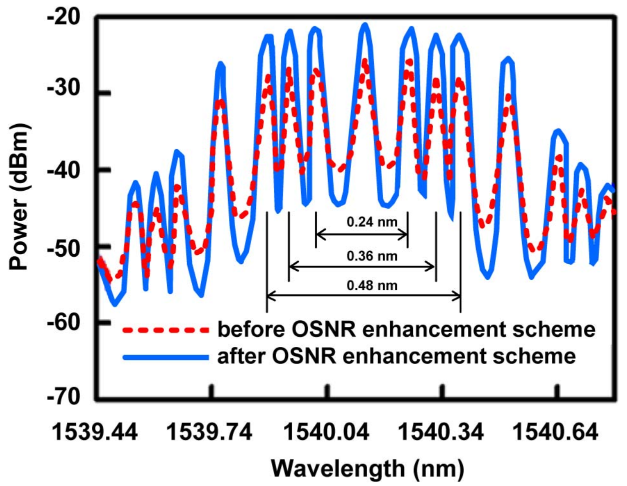

Fig. 3. Optical spectra of the BLS before and after the OSNR enhancement scheme.

launched into the first-stage convex lens, delivered into free space, input into the second-stage convex lens, and focused on the PD. The PD has a 3 dB bandwidth of 6.6 GHz and a responsivity of 0.43 mA/mW (at 680 nm). The distance between the VCSEL and the PD is 10 m. After PD detection, the detected 5 Gbps data stream is boosted by a 5 GHz LNA and supplied to a BERT for BER performance analysis.

As shown in Fig. 2, the BLS comprises OEO and optical signal-to-noise ratio (OSNR) enhancement schemes [3,5]. The OEO scheme is composed of one distributed feedback (DFB) laser diode (LD) with a central wavelength of 1540.16 nm, one 50:50 optical splitter, one 25 GHz PD, two 25 GHz RF amplifiers, and two separate 15 GHz and 22.5 GHz RF BPFs. The OSNR enhancement scheme is composed of one optical splitter, two OCs, two delay interferometers (DIs) with free spectral ranges (FSRs) of 15 GHz and 22.5 GHz, two RSOAs, and one optical combiner. The output of the DFB LD is coupled into port 1 of the OC, and port 3 of the OC is separated off by a 1×2 optical splitter. Half of the laser output is used as the BLS, while the other half of the laser output is used for feedback through an optoelectronic feedback loop. The detected RF signals are amplified by the first RF amplifier, picked up by two separate BPFs, amplified by the second RF amplifier, and fed into the DFB LD. And, thereby, the DFB LD is modulated by 15 GHz and 22.5 GHz RF signals, resulting in the generation of multiple optical sidebands with channel spacings of 15 GHz and 22.5 GHz. These generated optical sidebands are supplied to the OSNR enhancement scheme to improve the OSNR values. In addition, a 10 Gbps data stream is fed into the DFB LD to generate 10 Gbps/15 GHz and 10 Gbps/22.5 GHz data signals.

For the BLS, the number of optical sidebands depends on the amplitude of the RF signal produced by the OEO scheme. To utilize this characteristic, we adjust the proper RF signal to drive the DFB LD. The OEO scheme is based on converting the laser light to RF signals. The oscillation of an OEO starts from the noise transient, which is then built up and sustained with feedback at the level of the oscillator output signal. As to the value of the channel spacing, it is determined by the central frequency of the RF BPF employed in the OEO scheme. In this study, the generated RF signals modulate the DFB LD directly, and multiple optical sidebands (as shown in Fig. 3) are generated with channel spacings of 15 GHz and 22.5 GHz. For the limitation on the transmission rate, the value of the transmission rate cannot exceed the value of the RF carrier frequency. This means that the maximum transmission rate cannot exceed 15 Gbps at a RF carrier frequency of 15 GHz. However, the higher the delivered transmission rate, the worse the transmission performance will be. To have a trade-off between transmission rate and transmission performance, the transmission rate in the proposed systems is set at 10 Gbps.

The optical spectra of the BLS before and after the OSNR enhancement scheme are shown in Fig. 3. As the OSNR enhancement scheme is employed, around 7–10 dB of OSNR value enhancement is obtained for the optical sidebands. The OC is used to circuit the optical sidebands into the DI, and the DI is used as an optical comb filter. As the optical signal passes through the DI, the noise level between each of the two optical sidebands will be suppressed. And, further, the RSOA is used to amplify and reflect the optical sidebands. As a result, the OSNR values of the optical sidebands are improved significantly.

The measured BER curves of the 10 Gbps/30 GHz MW data signal for the back-to-back (BTB) transmission scenario and the 40 km SMF plus 10 m RF wireless transport transmission scenario are shown in Fig. 4(a). A power penalty of 4.2 dB existed between the BTB transmission scenario and the 40 km SMF plus 10 m RF wireless transport transmission scenario, at a BER of 10^{-9}. The measured BER curves of the 10 Gbps/45 GHz MMW data signal for the BTB scenario and the 40 km SMF plus 10 m RF wireless transport scenario are shown in Fig. 4(b). At a BER of 10^{-9}, a power penalty of 4.4 dB is observed between the BTB transmission scenario and the 40 km SMF plus 10 m RF wireless transport transmission scenario. The measured BER curves of the 10 Gbps/60 GHz MMW data signal for both transmission scenarios are shown in Fig. 4(c). A power penalty of 4.7 dB existed between the BTB transmission scenario and the 40 km SMF plus 10 m RF wireless transmission scenario, at a BER of 10^{-9}. These power penalties of 4.2, 4.4, and 4.7 dB could have resulted from fiber

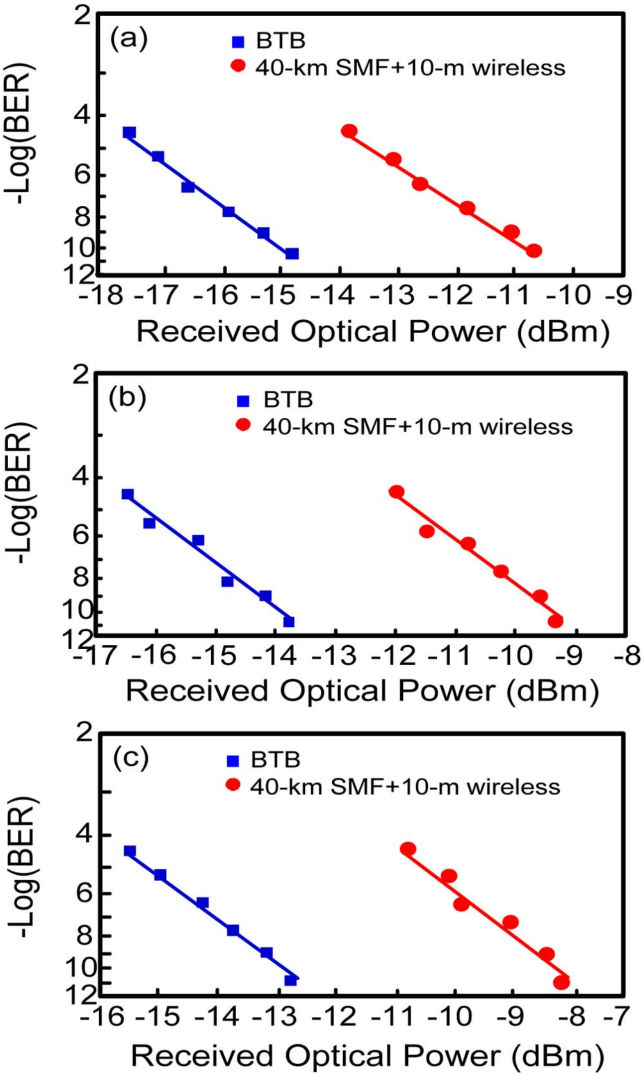

Fig. 4. Measured BER curves of (a) 10 Gbps/30 GHz MW data signal, (b) 10 Gbps/45 GHz MMW data signal, and (c) 10 Gbps/60 GHz MMW data signal.

dispersion over a 40 km SMF transmission and a fading effect over a 10 m RF wireless transmission.

For uplink transmission, the measured BER curves of the 5 Gbps data stream for the BTB transmission scenario and the 40 km SMF plus 10 m free-space transmission scenario are shown in Fig. 5. At a BER of 10^{-9}, a power penalty of 4.5 dB is observed between the two transmission scenarios. Such a 4.5 dB power penalty could have resulted from fiber dispersion after the 40 km SMF transmission and modal noise caused by the multimode VCSEL. The optical spectrum of the VCSEL is presented in Fig. 6. It can be seen that the VCSEL has a multimode output characteristic. Multimode VCSELs often give rise to modal noise, leading to transmission performance degradation. The transmission performance could be improved by replacing the multimode VCSEL with a single-mode VCSEL to remove the modal noise. As far as we know, however, the maximum modulation bandwidth of a 680 nm VCSEL is 5.2 GHz, which is a multimode VCSEL instead of a single-mode VCSEL. Thereby, a multimode VCSEL is employed to implement the VLLC subsystem.

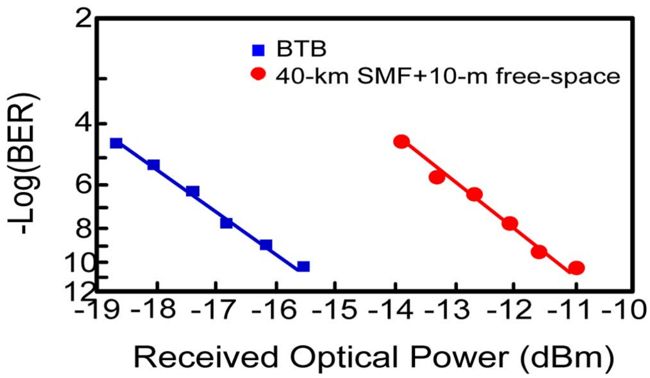

Fig. 5. Measured BER curves of 5 Gbps data stream.

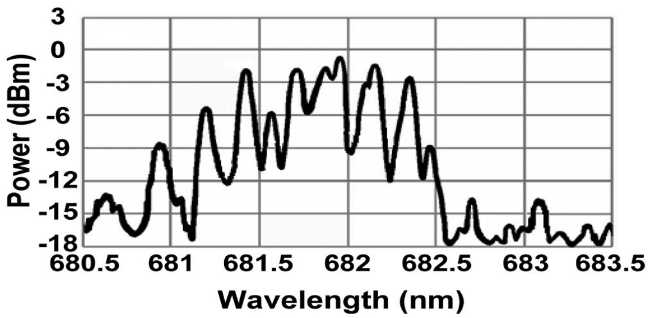

Fig. 6. Optical spectrum of VCSEL.

A bidirectional fiber-wireless and fiber-VLLC transmission system in MW, MMW, and baseband (BB) bands is developed to provide multigigabit mobile/free-space applications by making use of the huge bandwidth of fiber and the flexibility of RF/optical wireless delivery. Serving as fiber long-haul and RF/optical wireless short-distance technologies, bidirectional fiber-wireless and fiber-VLLC transmission systems would be attractive for fiber backbone and RF/optical wireless feeder applications to provide broadband integrated services. The downstream 10 Gbps/30 GHz MW and 10 Gbps/45 GHz MMW data signals could be used for fifth generation (5G) mobile service and local multipoint distribution service (LMDS), and the downstream 10 Gbps/60 GHz MMW data signal could be used for high definition multimedia (HDMI) service. Meanwhile, the upstream 5 Gbps BB data stream could be used for supporting different kinds of downlink services. As fiber deployment extends to buildings and premises, a bidirectional fiber-wireless and fiber-VLLC transmission system will take off.

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