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Cost-efficient half-duplex 10-Gbit/s all-optical indoor optical wireless communication enabled by a low-cost Fabry-Perot laser/photodetector

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To develop an indoor optical wireless communication (OWC) system, both the system complexity/cost and data rate need to be taken into consideration. In this letter, a cost-efficient half-duplex OWC system for photonic home area network applications is proposed and experimentally demonstrated. A low-cost Fabry-Perot laser diode (FP-LD) is proposed to be employed as both the downlink receiver (Rx) and uplink transmitter (Tx) at the user side. Enabled by the Fabry-Perot transceiver (FP-TRXs), the indoor transmission of 10-Gbit/s 4-level pulse-amplitude-modulation (PAM-4) signal for both down- and uplink is experimentally achieved over 1.7-km SMF and 1.1-m free space. Moreover, the proposed scheme also enables to operate orthogonal frequency division multiplexing (OFDM) signal. The BER levels of multi-gigabit OFDM data for both down- and uplink over 10-hour measurement are all under 7% forward error correction (FEC) limit of 3.8×10⁻³, which indicates the proposed system is robust, thus can provide a promising solution for high-speed low-cost home area OWC networks. © 2018 Optical Society of America

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With rising amount of mobile terminals for indoor consumer products and 4K/8K high-definition video service, the immense growth in the need for more bandwidth results in the data traffic and radio spectrum crisis in in-home networks [1]. Thereby, an unsatisfied appetite of indoor bandwidth appeals for the broadband communication technologies. Recently, some techniques, such as 60-GHz millimeter waves (mm-waves) communication and optical wireless communication (OWC) are released to provide up to 1-Gbit/s wireless connectivity to end-users [2, 3]. Compared with mm-wave systems, OWC systems offer much wider license-free bandwidths ranging from ultraviolet, visible to infrared regions allowing higher data rate. Both visible light and infrared light are employed for OWC systems, namely, visible light communication (VLC) and infrared wireless communication (IWC). The rising of VLC is accompanied with illumination by modulating the transmitted data on the light emitting diode (LED) chips. However, the capacity of VLC system is usually limited because of the restricted modulation bandwidth of LEDs [4]. In contrast, the IWC system can easily provide over 10-Gbit/s data rate per user by employing the well-established C+L band fiber-optic communication technologies [1].

Bidirectional OWC systems with all-optical down- and uplinks exhibit their advantages on symmetric data rates and limited complexity. Although many demonstrations have been studied for indoor OWC downlink to increase the transmission capacity at infrared band, only a few results are reported for OWC uplinks. Wang et al. proposed to use vertical cavity surface emitting laser (VCSEL) with 850-nm wavelength to transmit uplink data. They experimentally implemented the transmission of 500-Mbit/s on-off keying (OOK) signal over 1-m distance [5] and then improved the maximum data rate to 2 Gbit/s using 16-ary carrierless-amplitude phase (CAP) modulation [6]. Full-duplex all-optical indoor OWC scheme with wavelength reuse was demonstrated in [7]. The uplink optical carrier is extracted by using two cascaded
The second technique is using cost-effective half-duplex OWC systems with a common ground: the transmitter (Tx) and receiver (Rx) at the mobile terminals are separated, which further increases the requirement on system complexity and alignment. In this letter, we propose and experimentally demonstrate a cost-effective half-duplex OWC system with all-optical down- and uplink. The balance between cost (complexity) and performance (data rate) is achieved by using a low-cost Fabry-Perot laser diode (FP-LD). Only one FP-LD is employed to fabry-perot transceiver (FP-TRx) to the mobile device (MD) to support both down- and uplink operation. Enabled by the FP-TRx, the bidirectional 10-Gbit/s OWC system is experimentally demonstrated over 1.7-km single-mode fiber (SMF) and 1.1-m free space link.

Figure 1 illustrates our proposed cost-effective half-duplex OWC system based on the FP-TRx. The beam steering (BS) system mounted on the room ceiling can be realized by MEMS mirrors [6] or 2D arrayed waveguide grating router [8]. A communication control center (CCC) connects the high-speed fiber distribution access network with the BS system via an optical cross connector (OXC). For the downlink, the modulated optical beams are distributed to indoor free-space through BS system. Each steered beam serves one user independently. In the uplink, we also use infrared beam to load data, which is passed through the BS system and then transmitted back to the CCC through the distributed fiber for further detection and data processing. Three key techniques are adopted to realize the high-speed half-duplex OWC system for downstream and downstream data transmission. The first one is based on the reversibility principle of optical beam path [7], which simply means that the light can return in the same direction as it comes. The second technique is using cost-efficient 4-level pulse-amplitude-modulation (PAM-4) modulation format combined with simple electronic signal processing (DSP) to enable spectrum-efficient high-speed data transmission. The third technique is the bidirectional characteristic of FP-LD used as optical TRx for MD. Many previous demonstrations have shown that FP-LD can be employed as a cost-efficient direct modulated transmitter for high-speed passive optical networks (PON) [9, 10]. But few works are done to explore the potential of FP-LD as an optical Rx [11]. The FP-LD used in this work is designed and fabricated based on a buried hetero-structure with the front-facet reflectivity less than 1.2% benefiting from the gain spectral broadening from 13 to 32 nm. The employed thermally stabilized FP-TRx is packaged in a TO-56-can pig-tailed with a SMF as in the inset of Fig. 1.

The operation principle of the FP-TRx is relatively simple. The FP-LD presents to be an optical transmitter when pumping a positive current +U, while becomes a Rx when injecting a negative voltage -U. We measured the characteristics of FP-TRx as shown in Fig. 2. For Rx, two important parameters are responsivity \( R (A/W) \) and modulation bandwidth \( B_r (GHz) \). \( R \) is related to the driving voltage. As shown in Fig. 2 (a), the injected optical power is 2 dBm (1.58 mW) at wavelength of 1560 nm. At -1, -1.5 and -2 V, the measured output currents are 0.38, 0.62 and 0.88 mA, corresponding to the sensitivities of 0.24, 0.39 and 0.55 A/W, respectively. The measured output current is proportional to the driving voltage -U. Thus, as increasing the driving voltage, the responsivity will become larger. Fig. 2 (b) shows the measured frequency response of FP-Rx under different driving voltages. The -3 and -8-dB bandwidths are about 0.4 and 1.4 GHz for \( U = 2V \). Since the FP-LD is fabricated commercially at 200 µm length [10], the carrier transit time is large, which narrows the modulation bandwidth. In this paper, we successfully used this FP-Rx to detect 5.3-Gbit/s orthogonal frequency division multiplexing (OFDM) and 10-Gbit/s PAM-4 signals with bit error rate (BER) levels under 7% forward error correction (FEC) limit. Fig. 2 (c) and (d) displays the measured P-I curve and frequency response of FP-Tx. After
the threshold bias current ($I_B=16 \text{ mA}$), the output optical power $P_{out}$ has a linear relationship with the bias current $I$ (the red dashed line in Fig. 2 (c) is the fitting curve), where $a$ and $b$ are the constants and their values are about 0.09 and -1.63 based on the measured results in Fig. 2 (c). The measured 3-dB bandwidths under bias currents of $1.25 I_B$ (20 mA), $1.87 I_B$ (30 mA) and $2.5 I_B$ (40 mA) are about 3.7, 6.8 and 7.9 GHz, respectively, as shown in Fig. 2 (d). Thus, it's feasible to obtain high data rate for uplink.

To verify the feasibility of the proposed architecture, a proof-of-concept experimental setup is built as in Fig. 3. For the downstream, the optical carrier is generated in the CCC with 10-dBm output optical power by a tunable laser source (TLS) for 1530 to 1630 nm and then modulated by a 10-GHz MZM. The electrical data is generated by an arbitrary waveform generator (AWG) to drive the MZM. The modulated optical signal is amplified by an optical amplifier (OA) and then launched into 1.7 km SMF after routing through an optical circulator (OC). The optical beam is launched into free-space via a collimator (Thorlabs, TC18APC-1550) with focal length of 18.36 mm and the beam waist diameter of 3.33 mm. The transmitted optical power is measured to be 9.8 dBm, which is below the eye safety requirement. After 1.1-m free-space transmission, the beam is coupled into SMF by another collimator. It should be noted here that the free-space length is limited by the size of our lab table, hence longer lengths using collimated light such as 10 m are feasible [12]. The received optical power (ROP) of 7.3 dBm is detected by the proposed FP-TRx. The output electrical signal is amplified and then acquired by a digital phosphor oscilloscope (DPO) for further signal processing. A post-amplifier (SHF, 100 APP) with a bandwidth of 12 GHz, a power gain of 19 dB is added behind the scope. The uplink electrical data is generated at MD from an AWG with a voltage of 0.5 $V_{pp}$, then amplified by another RF amplifier (SHF, 100 AP). Before modulated onto the proposed FP-TRx with positive current driving, a 6 dB electrical attenuator is added between RF amplifier and bias-T. As a result, the amplitudes of the electrical 10-Gbit/s data streams are set at 1.9 $V_{pp}$ (PAM-4) and 2.4 $V_{pp}$ (OFDM). Thus, the uplink data is also transmitted through optical beam. In the experiment the driving current is set to be 30 mA, achieving the output optical power of 0.6 dBm (0.87 mW) as illustrated in Fig. 2 (c). The modulated uplink optical signal traverses the same path as the downlink signal and is separated by an OC to another optical path for detection and processing by an avalanche photodiode (APD) and DPO in CCC. The measured ROP in front of APD is -5.3 dBm, which is far above the achieved receiver sensitivity of around -15 dBm at 7% FEC limit as depicted in Fig. 6.

To evaluate the down- and uplink system performance, both OFDM and PAM modulations are employed. In the experiment, the transmitted OFDM and PAM signals are generated offline by MATLAB program. The parameters of one OFDM-16QAM symbol are as follows: IFFT size is 512, signal subcarriers are assigned from 9 to 180, and the first eight subcarriers near zero frequency are not filled with data. 300 symbols are contained in each OFDM frame. For the downstream, the OFDM RF signal is produced by an AWG running at 4 GSa/s. Thus, the bandwidth of the baseband signal is 180/512 = 0.34 GHz, which is the effective signal bandwidth of 1.34 GHz. With 16-QAM modulation, we achieve the data rate of 5.3 Gb/s. While for the upstream, the AWG runs at 8 GSa/s, producing 2.8 GHz baseband signal of OFDM-16QAM. For PAM-4 signal, the sampling rate of AWG is set to 5 GSa/s for both downstream and upstream, thus the achieved data rate is 10 Gb/s. The received electrical PAM signal is oversampled by the DPO running at 12.5 GSa/s. We use least mean square (LMS) channel estimation algorithm with 217 taps to recover the PAM-4 data.

Figure 4 illustrates the downlink BER performance of 5.3-Gbit/s OFDM-16QAM and 10-Gbit/s PAM-4 as a function of ROP using a variable optical attenuator (VOA) placed at the front of FP-TRx, which is just for measurement. At this moment the proposed FP-TRx is used as Rx, thus a negative voltage source is added to the bias-T. In the experiment, the values of the driving voltage for OFDM signal are set to -1, -1.5 and -2 V. As shown in Fig. 4, the BER performance of OFDM-16QAM signal becomes better for larger driving voltages. At the 7% FEC limit of 3.8×10^-3, the corresponding values of ROP are 0.9, 1.3 and 1.9 dBm for -2, -1.5 and -1 V, respectively. When using the 20% FEC limit at the BER level of 2×10^-5, the ROP becomes -1 dBm. The
measured ROP for downstream 10-Gbit/s PAM-4 signal is 2.1 dBm (20% FEC limit) and 4 dBm (7% FEC limit) at the driving voltage of -2 V as shown in Fig. 4 with red dashed curve. The insets in Fig. 4 also show the recovered 16-QAM and PAM-4 constellations respectively, which corresponds to the BER levels of $1.8 \times 10^{-3}$ and $2.1 \times 10^{-2}$. We also investigated the downlink BER performance of 10-Gbit/s PAM-4 signal at different optical wavelengths tuned in C/Cl. The wavelengths are adjusted from 1530 to 1600 nm and the BERs are tested at ROP=4.5 dBm. As illustrated in Fig. 5, the measured BER performance gets better at first and then worsens as increasing the wavelength. When the wavelengths are from 1530 to 1535 nm and 1580 to 1600 nm, the BER levels are all under 20% FEC limit [13]. While 7% FEC limit can be utilized when wavelengths are ranged from 1535 to 1580 nm. In short, our proposed FP-Rx is capable of detecting optical signals within wavelength range of 70 nm.

Uplink BER performance of 10.7-Gbit/s OFDM-16QAM and 10-Gbit/s PAM-4 signals as a function of ROP are investigated in Fig. 6. We also measured the uplink BER performance when the downlink TLS in C/Cl is on. For OFDM-16QAM signal as shown in Fig. 6 with circular marked dashed line, the measured ROP is about -17 dBm at the 7% FEC limit when the downlink TLS is off. While the value of ROP becomes -17.9 dBm when turning on the downlink TLS, which means 0.9 dB improvement is achieved. The same results are successfully obtained for 10-Gbit/s PAM-4 signal. The measured ROPs are about -16.2 dBm (TLS off) and -17.5 dBm (TLS on) at the 7% FEC limit, achieving 1.3 dB improvement. That’s because when turning on the downlink laser source, the uplink FP-Tx is under injection-locked operation, which helps to improve the uplink system performance [14]. We observed that the optimal BER value is reduced to $3 \times 10^{-4}$ at injection locked power of 6 dBm and ROP of -15 dBm. Moreover, we observed no significant change in BER values when the polarization state of TLS varies. Finally, we measured the BER performance of OFDM-16QAM signal for both downlink (5.3-Gbit/s) and uplink (10.7-Gbit/s) under 10-hour measurement at the room temperature of 20 °C. It can be seen in Fig. 7 that the measured BER values are all below 7% FEC limit, which suggests that our concept has a good long term stability for deploying in building scenarios.

In conclusion, we have proposed a cost-efficient half-duplex all-optical OWC system based on a low-cost FP-TRx to break the tradeoff between the system complexity/cost and data rate. Different from the traditional bidirectional system with separated Tx and Rx at user side, our proposed system only utilizes one FP-LD to operate optical signal for both down- and uplink. The proposed FP-LD can therefore be used as a high-speed optical Tx and Rx under time-interleaved operation for half-duplex links. Enabled by the FP-TRx, we have experimentally achieved the indoor transmissions of 10-Gbit/s PAM-4 data for both down- and uplink over 1.7-km SMF and 1.1-m free space. In addition, the FP-Rx detects the PAM-4 signal over a wide wavelength range of 70 nm. Moreover, the proposed FP-TRx can also support the operation of multi-gigabit OFDM-16QAM signal over 10-hour measurement with BER levels under 7% FEC limit, which indicates that the concept is experimentally robust and deployable to support multi-level multi-carrier modulation formats, thus can provide a promising solution for high-speed low-cost home area optical wireless networks.

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