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Low-Crosstalk Full-Duplex All-Optical Indoor Wireless Transmission With Carrier Recovery

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Abstract—We propose and demonstrate a novel bi-directional free-space (FS) optical wireless communication system for indoor wireless networks. A 2-D infrared beam-steered system supporting full-duplex communication of at least 10 Gb/s capacity per wireless terminal with simple NRZ-OOK modulation format is experimentally demonstrated. The uplink (UL) is implemented using the optical carrier recovery technique, in which the downlink (DL) OOK modulation is erased by means of two cascaded SOAs operating in the saturation region. We experimentally demonstrate the system with asymmetric speeds (10 Gb/s DL/2.5 Gb/s UL) and symmetric speeds (10 Gb/s) duplex communication over an FS transmission distance of 3 m. We also report the crosstalk in such a system.

Index Terms—Optical wireless communication, infrared, diffraction grating, optical beam steering.

I. INTRODUCTION

The exponential growth of radio wireless traffic is posing a bandwidth is increasing in conjunction with the booming numbers of interconnected devices and applications. Already today, serious signal interference is occurring among radio wireless devices due to traffic congestion. In an unlicensed approach, optical wireless communication offers a promising solution by its inherently large bandwidth. Under line-of-sight conditions, ultra-dense small cells of tens of centimeters providing ultra-high capacity can be achieved.

At present, much attention is seen in improving the downlink (DL) communication in terms of technique, capacity and coverage. However, few progressive works are seen for the uplink (UL) optical communication. Oftentimes, the UL communication in an optical wireless duplex communication requires a separate channel, i.e. by using a radio wireless technique, light emitting diode (LED) or laser. However, by using the radio technique, the UL typically offers a lower channel capacity than the optical DL channel. The broad beam profile of LEDs necessitates a compromise on the link budget and bandwidth of the channel. As for laser communication, the need for UL beam steering leads to latency and complicated receiver hardware. In this letter, we propose a novel solution based on optical pencil beams and carrier recovery method to provide a high capacity UL with simultaneous alignment. It builds on the 2D pencil beam-steered concepts we introduced earlier [1]. Our novel concept eases channel management since the same wavelength is used for both UL and DL, and the actual wavelength provides crucial information on the location of the mobile terminal.

The idea is based on two principles. Firstly, we use the reversibility principle of optics whereby light follows the same path that it traversed when the beam is reversed, as illustrated in Fig. 1. The major advantage here is that the receiver module does not need an additional beam-steering device while maintaining a narrow beam. Secondly, we employ the data erasure and rewrite technique using semiconductor

Fig. 1. Bi-directional propagation path in a two-dimensional steering system.

Fig. 2. SOA output power versus input power curve. SOA is operated at saturation region for data erasure.

Fig. 3. Bi-directional indoor all-optical wireless network with pencil beams. Central Communication Controller (CCC), Optical Cross Connect (OXC).

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optical amplifier (SOA). The concept of data erase in a low extinction ratio (ER) signal by means of an SOA has been proposed before for a passive optical network (PON) [2]. Wavelength rewrite is implemented by first erasing the DL data by operating the SOA in its saturation region (as shown in Fig. 2), and then, rewriting the carrier with the UL data. This method enables mass production of identical and therefore, potentially low-cost receivers. In a preliminary work [3], the feasibility of a symmetric 10 Gbit/s system has been presented. In this Letter, we report evaluations on the system in terms of crosstalk, the effect of the pseudorandom binary sequence (PRBS) pattern length and the impact of the downstream extinction ratio. We further demonstrate the transmission performance of a symmetric 10 Gbit/s system and an asymmetric system (10 Gbit/s DL / 2.5 Gbit/s UL). To the best of authors’ knowledge, this is the first full-duplex all-optical indoor wireless system employing wavelength re-use.

II. ALL-OPTICAL DUAL-DIRECTIONAL WIRELESS SYSTEM

Fig. 3 shows an all-optical bi-directional wireless system concept for indoors. The access network is interfaced to the indoor network via the central communication controller (CCC), which executes the routing algorithms. Data signals are routed to different rooms using an optical cross-connect (OXC) and a fiber-backbone network. 2D beam-steering modules known as pencil radiating antennas (PRAs), which consist of diffractive optics to steer the narrow beams a.k.a. pencil beams, are installed in the access points per room to provide coverage according to the room size and to guarantee line-of-sight. Installation of multiple access points can provide a backup link when a beam from one access point is blocked. Adaptive optics to diverge or narrow a beam can be further employed to increase or decrease the beam coverage to ease tracking of the mobile device. Also, in view of a future heterogeneous network (HetNet) concept, parallel radio links can be used to maintain connectivity. Tunable lasers, stationed at the CCC, will be employed to provide different wavelengths to the selected rooms whereby wavelength is used to steer the beam to the position of a different wireless device on demand. In this way, high capacity channels can be provided to each user individually, simultaneously and dynamically. Optical localization techniques such as angle of arrival detection can be used to locate the mobile device. On the user side, fixed and mobile devices are equipped with an optical transceiver (TRx) that supports data erasure, SOAs for carrier recovery and a modulator for data rewrite on the same wavelength. This eliminates the need for a laser source which has its own wavelength offset and phase noise.

III. EXPERIMENTAL SETUP

We first report the crosstalk evaluation on symmetric 10 Gbit/s and asymmetric (10 Gbit/s DL/2.5 Gbit/s UL) duplex communication channels using a wavelength of 1550 nm in our free space (FS) 2D beam-steered system without carrier recovery. Then, the transmission performance of the 2D-steered FS duplex communication system with carrier recovery is evaluated using symmetric and asymmetric bitrates in order to compare both systems, with different PRBS pattern lengths and downstream extinction ratios.

A. Crosstalk Evaluation

Fig. 4 illustrates the testbed for the crosstalk evaluation of an all-optical wireless system with 2D beam steering over 2 m FS [4]. A laser source of 1550 nm is distributed 50:50 to provide identical optical input power and wavelength for the DL and UL transmission. The DL Mach-Zehnder modulator (MZM) modulates the beam with an NRZ-OOK signal with PRBS $2^7 - 1$ bits. An Erbium-doped fiber amplifier (EDFA) is used to amplify the optical signal up to 8.9 dBm just before transmission to FS through a triplet lens collimator of 18.36 mm focal length. The launched beam then hits the 2D steering module constructed using two passive reflection gratings placed orthogonally to each other. The first is a 63° (31.6 grooves/mm) blazed grating and the second is a 75° (79 grooves/mm) blazed grating. The beam is captured by another triplet collimator and received with a 10 GHz photoreceiver. For the UL, the same laser source is modulated with an NRZ-OOK signal with PRBS $2^7 - 1$ bits using an MZM and the optical signal is amplified to 8.9 dBm by an EDFA for transmission. The beam then traverses the same path as the DL towards the diffractive modules, collected by the collimator and finally, is detected at the receiver. The UL measurement is repeated using PRBS $2^{31} - 1$ bits. The power loss in the FS path is measured to be as low as $-13.7$ dB at $\lambda = 1550$ nm.

B. 2D-steered Full-Duplex Transmission Experiment

Fig. 5 illustrates the testbed setup for symmetrical and asymmetrical full-duplex 2D-steered communication system with optical carrier recovery at the mobile device. As in the proposed architecture, the testbed consists of the CCC, the FS region and the mobile device. The CCC unit hosts a laser tuned to transmit at $\lambda = 1550$ nm. The transmitted beam acts as the carrier signal. Data signal of PRBS $2^7 - 1$ bits is modulated onto the carrier signal using an MZM at 10 Gbit/s. The ER of the signal is set by observing the signal on a sampling scope. An optical amplifier (OA) is used to amplify the optical signal to $\leq 9$ dBm. In this experiment, an EDFA is employed. Alternatively, an SOA is preferred as SOAs can be accommodated in photonic integrated circuits (PICs) and thus, enable miniaturization of the receiver units in the future using the PIC technology which is now capable of integrating various photonic components such as lasers,
Fig. 5. Testbed setup for full-duplex FS transmission with two-dimensional beam steering and wavelength re-use. Optical amplifier (OA), Mach-Zehnder modulator (MZM), Pseudorandom binary sequence (PRBS), Semiconductor optical amplifier (SOA).

Fig. 6. Eye-diagram for symmetrical 10 Gbit/s full-duplex with wavelength re-use system with a DL ER = 3.6 dB: (a) DL signal at BER $1 \times 10^{-9}$ and $1 \times 10^{-3}$. (b) Erased signal after SOA. (c) Re-modulated UL signal at BER $1 \times 10^{-9}$ and BER $1 \times 10^{-3}$.

Fig. 7. BER performances: (a) Asymmetric channels crosstalk PRBS $2^7 - 1$ DL and UL, (b) Asymmetric channels crosstalk PRBS $2^7 - 1$ DL and UL, (c) Symmetric channels crosstalk PRBS $2^7 - 1$ DL and UL, (d) Symmetric channels crosstalk PRBS $2^7 - 1$ DL PRBS $2^{31} - 1$ UL, (e) Asymmetric channels with wavelength re-use PRBS $2^7 - 1$ DL PRBS $2^{31} - 1$ UL with DL extinction ratio (ER) = 5.4 dB, and (f) Asymmetric channels with wavelength re-use PRBS $2^7 - 1$ DL PRBS $2^{31} - 1$ UL with DL ER = 10.5 dB. Both channels are transmitting (BO), free space (fs).

modulators, optical amplifiers, photodetectors, and waveguide gratings on a single substrate [5]. The signal is emitted into FS through the TRx collimator and travels towards the 2D beam-steering module. The transmission distance is extended to 3 m, by means of 2 silver-coated mirrors. On the receiving device, an identical Rx collimator is used to capture the signal. The received signal is carried toward the SOAs for data erasure. The re-modulated upstream data signal is set using PRBS $2^{31} - 1$ bits. An OA is placed to amplify the signal to ≤8 dBm. This UL signal then travels through the TRx collimator, and by the principle of reversibility, the signal travels through the same path as the DL signal in the optical system. The signal is then collimated by the TRx collimator and sent to the 10 GHz PIN photodetector, and thereafter, evaluated using the BERT and sampling scope for the eye diagram.
IV. RESULTS AND DISCUSSION

Fig. 6 shows the eye-diagrams for DL signal of ER = 3.6 dB for (a) DL signal (b) erased signal (c) re-modulated signal. We observe that data erasure and re-modulation is achieved with open eyes. With regards to the crosstalk evaluation [6], the bit error rate (BER) performance and eye diagrams are measured and observed. Measurements are carried out for (i) both the UL and DL when both links are operational, (ii) the DL when the UL is turned off, and (iii) the UL when the DL is turned off. The measurements are concluded for symmetric (10 Gbit/s) and asymmetric (2.5 Gbit/s UL and 10 Gbit/s DL) duplex transmissions. Single mode fiber (SMF), in place of FS for the same configurations is also performed as back-to-back (BtB) measurements. From the results in Fig. 7, we observe that the crosstalk performance of asymmetric full-duplex channels (Fig. 7a and Fig. 7b) stays consistent whether PRBS 2^7 − 1 bits or 2^{31} − 1 bits is set for the UL. However, the DL suffers from a 2 dB penalty (in comparison to their corresponding BtB measurements) when both UL and DL are transmitted. On the other hand, we observe that for symmetric full-duplex channels (Fig. 7c and Fig. 7d), the power penalty is less than 2 dB for PRBS 2^7 − 1 bits but when PRBS 2^{31} − 1 bits is used, the UL BER performance for symmetric full-duplex transmission tends towards the noise floor, giving a penalty of about 3 dB at BER of 1 × 10^{-9}. This trend could be due to high pass response (note that no low pass filter is used in the experiment) and bias drift. Additional investigation in a future work will be needed to determine the dominant cause(s). Fig. 7(e) and Fig. 7(f) show the transmission performance in the testbed of Fig. 5 for asymmetric channels with 10 Gbit/s DL and 2.5 Gbit/s UL. The performances are consistent in both trials using DL ER 5.4 dB and ER 10.5 dB. The DL has a negligible penalty of < 1 dB but both UL channels suffer from about 4 dB power penalty. This is due to the non-ideal erasure of the signal in addition to the amplified spontaneous emission (ASE) noise from the amplification. Fig. 8 illustrates the results for symmetric channels of 10 Gbit/s. As the DL channel has a smaller ER, the sensitivity of the DL is worse than the UL. However, it can be seen that the DL sensitivity improves from −9 dBm to −12 dBm and −14 dBm as its ER is increased from 2.0 to 3.6 and 4.3 dB, respectively. Conversely, the performance of the UL channel is compromised as expected due to less effective compression as the SOA is fed with a larger input signal. Moreover, a similar performance curve as the crosstalk performance in Fig. 7(d) is observed, nonetheless with additional effect contributed by the not-perfectly erased DL signal [2].

V. CONCLUSION

A novel full-duplex all-optical wireless system supporting symmetric 10 Gbit/s DL and UL channels with OOK signaling has been demonstrated. The experiment is conducted over a FS distance of 3 m deploying all-optical solution at λ = 1550 nm. The UL is implemented using the carrier re-modulation technique enabled by erasing the DL OOK signal by means of two cascaded SOAs operating in the saturation region. Error-free links with BER < 1 × 10^{-9} have been achieved for both DL and UL for a DL signal ER of up to 4.3 dB. The asymmetric full-duplex system has been demonstrated for 10 Gbit/s DL and 2.5 Gbit/s UL for a DL signal ER of up to 10.5 dB. The concept is scalable to higher data rates by designing proper SOAs for data erasure or by using phase/frequency modulation for DL and amplitude modulation for UL.

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