Wide field-of-view optical broadcasting for bi-directional indoor optical wireless communications employing PAM-4 modulation

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Received 5 August 2019; revised 16 October 2019; accepted 28 October 2019; posted 29 October 2019 (Doc. ID 374598); published 9 December 2019

We present wide field-of-view (FOV) bi-directional point-to-multipoint indoor optical wireless communications operating over a range of 4 m. The system is designed to integrate with fiber-to-the-home/building networks realized by a passive optical network. A phase-only spatial light modulator (SLM)-based beam steering base station with a ±30° FOV broadcasts downstream transmissions to two nomadic user terminals that use mirror-based beam steering to provide a ±50° FOV. At the base station, a composite phase mask is constructed on the SLM not only to perform optical broadcasting, but also to steer upstream optical transmissions from user terminals at a different wavelength. Successful upstream and downstream data transmission of 25 Gbit/s PAM4 is achieved.

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https://doi.org/10.1364/OL.44.006009

The demand for high-capacity wireless communications is growing very rapidly, in particular in indoor environments. This is stimulated by exponentially increasing wireless traffic generated indoors by an increasing number of broadband mobile devices, as well as the devices for the Internet of Things and emerging bandwidth-hungry multimedia applications, such as virtual reality and augmented reality. Traffic growth is congesting current wireless networks and exhausting the available radio spectrum. As an attractive solution, optical wireless communications (OWC) can use a vast unlicensed optical domain of wireless communication resources [1,2]. Meanwhile, fiber-to-the-home/building (FTTH/B) networks enabled by passive optical network (PON) technologies can unlock terahertz scale bandwidths accessible to end users [3]. OWC using beam steered infrared narrow beams coupled directly from optical fiber networks can provide high-capacity wireless communications beyond 10 Gbit/s, and there is a wide range of choice of optical components available from the well-established fiber telecommunication industry. For OWC using infrared beams with wavelengths longer than 1400 nm, eye safety standards are less stringent than at visible wavelengths [4,5] making this wavelength region very attractive for communications. For λ > 1400 nm, transmitting power up to 10 mW is allowed within the eye safety limit [1], compared with the allowed blue light power of 1.01 μW in a white light communication system [5]. Nevertheless, there are substantial implementation challenges to be addressed. Owing to the very narrow field of view (FOV) of single-mode fiber-based components, optical beam steering is required at the fiber-based transmitter and receiver to provide a wide FOV, and it enables the implementation of tracking and localization functionalities. This has been demonstrated in a tracked point-to-point indoor OWC link [6]. To support a large number of user terminals in OWC systems effectively, wide FOV optical broadcasting (point-to-multipoint) is desired further from point-to-point links. We presented our initial results on wide FOV optical broadcasting in Ref. [7].

In this Letter, we describe many further details and demonstrate wide FOV optical broadcasting from a spatial light modulator (SLM)-based beam steering base station to two nomadic user terminals that use mirror-based beam steering in a bi-directional indoor OWC system over a range of 4 m. The OWC system is designed to integrate with local optical fiber networks connected to PON enabled FTTH/B networks. The SLM-based base station has a ±30° FOV, and it broadcasts infrared light at a designated wavelength from an optical fiber to nomadic user terminals. The user terminals use a mirror-based beam steering with a ±50° FOV. In the upstream direction (from the user terminal to the base station), transmitted light from an optical fiber at a different wavelength travels along the same free space optical path with the downstream transmission. A composite phase mask is constructed at the SLM-based base station not only to broadcast the downstream optical transmissions from an optical fiber, but also to steer the upstream optical transmissions back to the fiber. This significantly improves the optical coupling loss of the
upstream/downstream optical transmissions using a different wavelength, compared with a composite phase mask that only performs downstream/upstream optical broadcasting. This is because a liquid-crystal SLM gives different beam steering angles at different wavelengths. In the data transmission tests on the OWC system, we employ spectrum-efficient pulse amplitude modulation with four levels (PAM-4) for its low complexity and power consumption, and have experimentally demonstrated 25 Gbit/s data transmissions in both the downstream and upstream optical transmissions.

The bi-directional point-to-multipoint indoor OWC system is designed to integrate with FTTH/B networks enabled by time-division multiplexed (TDM) PONs, which broadcasts all optically the data-carrying time frames to the desired user terminals. As summarized in Ref. [8], different PON systems are standardized to operate at their allocated wavelength bands. Here we target the OWC system to operate at the wavelength bands planned for the second next generation PON (NG-PON2). That is, the upstream and downstream wavelength bands, respectively, are located in the C-band (1524–1544 nm) and L-band (1596–1603 nm) [8]. Figure 1 shows the system design architecture. The SLM-based (15 μm pixel pitch, Meadowlark HSP512-1550) base station has a ±30° FOV at 1550 nm, which is gained by 10× angle magnification of the SLM steering range (±3°) using a telescope lens system. The steering range of an SLM increases with a smaller SLM pixel pitch and longer operating wavelength [9]. An increased FOV would be available with small pixel pitch SLM devices. Such multiple SLM-based base stations can be installed per room to provide the full coverage of a room, as well as backup links, while one beam from a base station is blocked. At user terminals, we use mirror-based beam steering. The dual axis steering mirrors (Optotune, MR-15-30-G) at user terminals are accurately controlled by electronics and have up to ±50° optical deflection from each axis and a steering resolution less than 5 μrad. Tracking and localization are important to make such OWC systems practical. We propose a tracking and localization scheme as illustrated in Fig. 1. A cost-effective near-infrared camera with a wide FOV at the base station tracks the locations of individually recognizable infrared "tags" placed on the user terminals simultaneously. At a user terminal, a position sensitive detector tracks the angle of arrival of the directed communication signal from the base station, using about a tenth of the receiver optical power. Circulators are employed at the base station and nomadic user terminals for supporting bi-directional operation. The polarizations of the downstream and upstream optical transmissions are aligned by polarization controllers at the SLM-based base station and mirror-based user terminals to the polarization required by the SLM.

A liquid-crystal SLM is dispersive and gives different steering angles at different operating wavelengths. Therefore, as illustrated in Figs. 2(a) and 2(b), a single downstream/upstream beam steering phase mask on the SLM would cause misalignment (additional optical coupling loss) to the upstream/downstream optical transmission, due to the different operating wavelengths of the downstream and upstream optical transmissions. In the rest of this Letter, we refer to this additional optical coupling loss as bi-directional operation coupling loss. We measured the bi-directional operation coupling loss to upstream/downstream transmission resulting from a single downstream/upstream phase mask on the SLM at different upstream and downstream operating wavelengths. The right parts of Figs. 2(a) and 2(b), respectively, show the measured bi-directional operation coupling loss to upstream and downstream transmissions versus different upstream and downstream wavelengths. We observe that for our optical system the bi-directional operation coupling loss resulting from a single upstream/downstream phase mask in the upstream and downstream operating wavelength bands is quite significant. As the separation of the downstream and upstream wavelength increases, the upstream/downstream steering angle deviation resulting from a single downstream/upstream phase mask becomes bigger, inducing more bi-directional operation coupling loss. As a result of a single downstream and upstream phase mask on the SLM, the bi-directional operation coupling loss to the upstream transmission ranges from 6.7 to 10.5 dB, and the bi-directional operation coupling loss to the downstream transmission ranges from 7.5 to 10.8 dB.

![Fig. 1. System design of the wide FOV point-to-multipoint indoor bi-directional OWC system to integrate with FTTH/B networks enabled by NG-PON2.](image1)

![Fig. 2. Left, illustrations of bi-directional operations with different phase masks on the SLM. Right, the induced bi-directional operation coupling loss to corresponding upstream and/or downstream transmission(s) versus the upstream and downstream operating wavelengths. (a) With a single downstream phase mask, the upstream transmission experiences the additional loss. (b) With a single upstream phase mask, the downstream transmission experiences the additional loss. (c) With a composite phase mask for both upstream and downstream transmissions, both the upstream and downstream transmissions experience a relatively low additional coupling loss.](image2)
downstream transmission ranges from 9.5 to 17.2 dB. Our solution to this is to construct a composite phase mask for bi-directional operation between the base station and one user terminal by superposition of different downstream and upstream phase masks. As illustrated in Fig. 2(c), a composite phase mask for the bi-directional operation between the base station and a user terminal will split both of the downstream and upstream optical transmissions in two, one that is well aligned and the other that experiences a bi-directional operation coupling loss. This approach introduces up to 3 dB additional coupling loss to both the downstream and upstream transmissions of a bi-directional link between the base station and a user terminal, compared with a single upstream or downstream phase mask that causes a significant additional coupling loss to either the downstream or the upstream transmission. The right part of Fig. 2(c) shows the measured bi-directional operation coupling loss shown in Fig. 2(c). Figure 3(c) shows the replay field for a downstream wavelength of 1577 nm and an upstream wavelength of 1270 nm, with wavelengths specified in the XG-PON standard [8]. For this case, the two overlapped spots have been completely separated. This would induce a 3 dB additional coupling loss resulting from the bi-directional operation. In this Letter, we only demonstrate optical broadcasting to two user terminals. More user terminals can be supported by superposing more beam steering phase masks at the cost of extra splitting loss. The maximum number of user terminals that can be supported is mainly determined by the total loss of a link and power budget of transceiver systems used. We generalize the bi-directional optical link loss between the base station and one user terminal for the case of broadcasting to N user terminals in Eq. (2):

$$L_{\text{loss}} = L_{\text{loss,avg}} - 10 \log_{10} \left( \frac{1}{N} \right) + L_{\text{loss,bi-directional}}.$$  

The N broadcast bi-directional links have almost the same geometric loss as they use the same optical system, but experience varied diffraction efficiencies across the replay field [9] and different optical aberrations from the angle magnification lens system due to varying offsets from the optical axis of the lens system. The weighting factors of all the bi-directional transmissions in Eq. (1) can be adjusted through an iterative feedback loop to equalize the losses, resulting in $L_{\text{loss,avg}}$. Additionally, the optical broadcasting introduces splitting loss, which is reflected in the term $10 \log_{10}(1/N)$ in Eq. (2). The total optical loss of a bi-directional link between the base station and one of the N user terminals also needs to take account of the bi-directional operation coupling loss, $L_{\text{loss,bi-directional}}$.

An experimental demonstration of data transmission for a two user terminal-based system was undertaken, as shown in Fig. 4(a). The two mirror-based user terminals are angularly

![Image](https://via.placeholder.com/150)

**Fig. 3.** (a) Illustrative example of the bi-directional optical broadcasting to two user terminals with a 1599 nm downstream wavelength and 1536 nm upstream wavelength. (b) Downstream replay field with 1603 nm downstream wavelength and 1524 nm upstream wavelength. (c) Downstream replay field with 1577 nm downstream wavelength and 1270 nm upstream wavelength.
PAM-4 signals with an arbitrary waveform generator generating 12.5 Gbaud transmissions to emulate the highest bi-directional operation about a 1 dB bi-directional operation coupling loss. We added stream wavelengths, respectively. The selected wavelengths give to the selection of 1560 and 1530 nm as downstream and up-

downstream transmissions are almost identical, and each has a 1.9 dB power penalty compared with the back-to-back at a BER of $1 \times 10^{-4}$. The BER performance of the downstream transmission is also almost equivalent to the performance of its upstream transmission. Optical broadcasting to two user terminals has a 1.1 dB power penalty over the point-to-point operation (without the splitting loss) at a BER of $1 \times 10^{-4}$.

In summary, we have studied and successfully demonstrated wide FOV optical broadcasting for bi-directional indoor OWC at 25 Gbit/s using PAM-4 over a range of 4 m using an SLM-based base station and nomadic user terminals using mirror-based steering. Composite phase masks are constructed in a very simple way to perform optical broadcasting, as well as to support bi-directional transmissions at different designated wavelengths with a low additional coupling loss. The proposed system is designed to integrate with NG-PON2 fiber networks and broadcast TDM data to nomadic user terminals. With transceiver systems that have more power budget and optical loss improvement by optical aberration correction, we expect to achieve optical wireless broadcasting to a much larger number of nomadic user terminals.

**Funding.** Engineering and Physical Sciences Research Council (EP/P003990/1).

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