Optical Broadcasting and Steering by Demultiplexing Incoherent Spatial Modes

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Abstract: We realize optical broadcasting and reconfigurable beam steering by demultiplexing incoherent spatial modes. We demonstrate point-to-multipoint optical wireless communications using multimode VCSEL and multi-plane light conversion. © 2020 The Author(s)

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1. Introduction

Compared to the existing radio frequency wireless technologies, optical wireless communication (OWC) can provide higher data rate, reduce cost-per-bit and avoid the requirement of spectrum licensing [1]. OWC has potential in applications including wireless local, personal, and body area networks (WLAN, WPAN, and WBANs) [1], as well as board to board and intra-data center interconnect [2]. The disadvantage of the optical wireless is the typically narrow coverage of an optical beam, meaning that creating an optical wireless path to link two ends requires optical beam steering which can be realized, for example, by using passive diffraction gratings [3], micro-electromechanical system (MEMS) [4] or liquid crystal on silicon (LCoS) devices [5]. However, these solutions either operate in a narrow wavelength range or cannot achieve point-to-multi-point optical broadcasting. Moreover, the beam combining losses for the up-link usually scale unfavorably with the number of users.

In this paper, we propose and demonstrate the use of incoherent spatial modes to achieve broadband optical broadcasting and steering. A cost and energy efficient multimode vertical cavity surface emitting laser (MM-VCSEL) is used to produce incoherent modes, as different modes lase at different frequencies [6]. After transmitting the incoherent modes over multimode fiber (MMF), a multi-plane light conversion (MPLC)-based mode multiplexer (MMUX) [7, 8] is used to demultiplex and steer the mixed modes, see Fig. 1. At the receiver, incoherent modes are summed in power instead of amplitude as observed in the coherent counterpart, which helps to mitigate power fading and relaxes the dynamic range requirement. The MPLC-based MMUX also performs as a low-loss beam combiner for up-link traffic, as demonstrated in passive optical network [9]. We demonstrate reconfigurable optical beam steering using a programmable LCoS and a bi-directional fiber-wireless link (200-m MMF with 6 spatial modes and 1.5-m free space) with 1-to-6 optical broadcasting.

2. Reconfigurable optical beam steering

MPLC-based components can realize arbitrary and lossless conversions between sets of spatial modes through a series of phase planes separated by free space [7, 8]. The setup for reconfigurable optical beam steering comprises an MMF collimator with a 3.1 mm focal length lens, an LCoS (Holoeye Photonics) with a pixel pitch of 8 μm and resolution of 1920×1080, a dielectric mirror, a lens with 20 mm focal length, a polarization beam splitter and a camera, see Fig. 2(a). The LCoS has a dielectric mirror on top of the backplane to reduce the losses below 0.2 dB per bounce. We use 8 planes to demultiplex 6 Hermite-Gaussian (HG) modes supported by a graded-index multimode fiber (MMF) [10] and form 6 Gaussian spots in five different arrangements, see Fig. 2(b). A modified wavefront matching method is applied to calculate the phase planes [8]. A broadband amplified spontaneous emission (ASE) source is injected

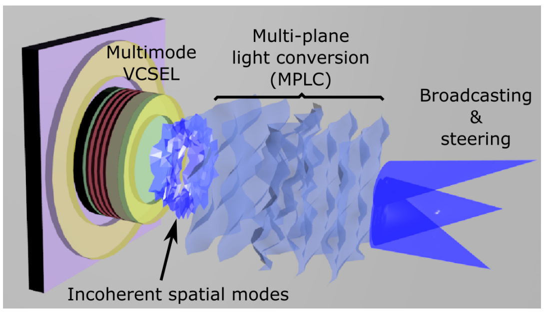

Fig. 1: Illustration of optical broadcasting and steering by demultiplexing the spatial modes of a MM-VCSEL.

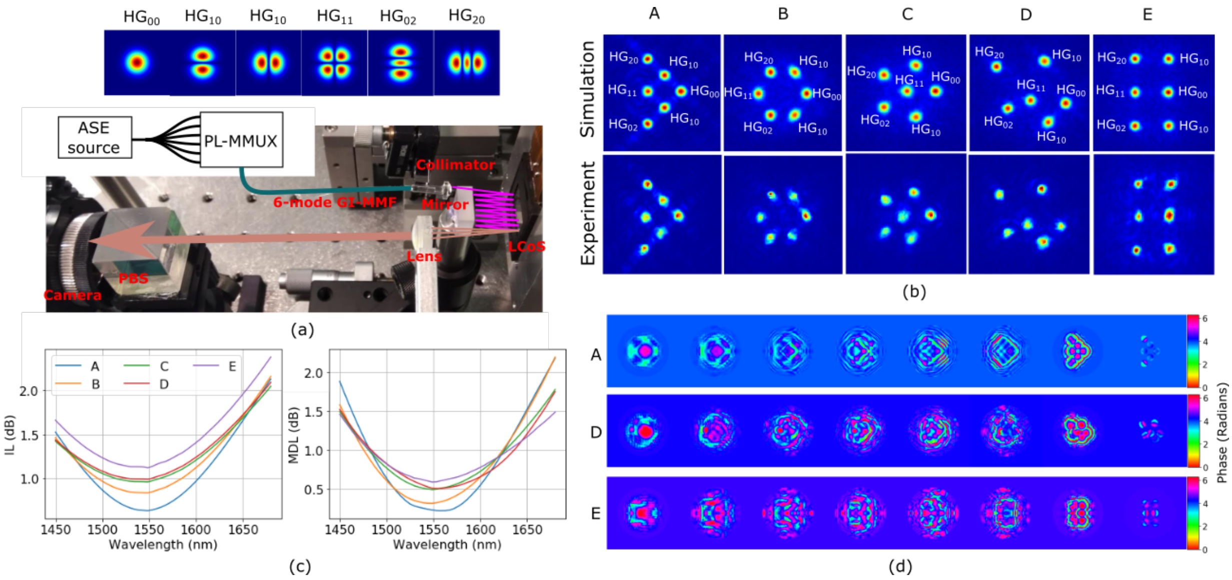

Fig. 2: (a) Experimental setup of dynamic beam steering using a programmable LCoS and MPLC, (b) simulated and experimental results of demultiplexing 6 HG modes into 6 Gaussian beams with five different arrangements, (c) simulated IL and MDL for five different spot arrangements and (d) examples of the calculated phase masks for configuration A, D and E.

into the 6 inputs of a photonic-lantern (PL) MMUX [11] with additional delays to add up all the modes incoherently. Figure 2(c) shows the simulated insertion loss (IL) and mode-dependent loss (MDL) for all the cases from 1450 to 1680 nm. MDL is calculated as the square of the ratio of maximum to minimum singular values of the transfer matrices at each wavelength and IL is the inverse of the mean of the squared singular values. It can be observed that the IL and MDL are mostly below 2 dB. The broadband operation is experimentally verified, see the lower images in Fig. 2, where 6 spots can be clearly observed. The quality of the spots can be further improved by compensating imperfections such as pixel-to-pixel crosstalk, which causes pixel blurring. The PBS is used to remove the polarization state which is unmodulated by the LCoS. Polarization diversity schemes could be used in a full system implementation.

3. Bi-directional optical wireless link

Figure 3(a) shows the schematic diagram of the bi-directional optical wireless communication over a 200-m MMF supporting 6 spatial modes and 1.5-m free-space link. Figure 3(b) provides the image of the free-space link and the MPLC-based MMUX, which converts the 6 HG modes to 6 spots arranged in a line with a 127-μm spacing and a 34-μm beam waist. The collimated multimode beam has a beam waist of around 130 μm. Fifteen smooth phase masks are designed for broadband operation and separated by 8-mm of free space propagation (4-mm mask-to-mirror distance). The phase masks were fabricated on a fused silica wafer using binary lithography with 64 phase levels between 0 and 2π and a 5 μm pixel pitch. The coupling matrix of the MMUX is characterized using digital holography [12] and presented in Fig. 3(c) with a measured MDL of around 3.1 dB and an IL of around 6 dB.

We runned Monte Carlo simulation with 10000 coupling matrix realizations to calculate the cumulative distribution function (CDF) of γ for different N as coupling to an MMF having 6 spatial modes where N is the number of launched modes, see Fig. 3(e). γ is defined as: $\gamma = P_j/P_i$, where P_j is the power of each output mode (j is from 1 to 6) and P_i is the power of the input mode (i is from 1 to N). The coupling matrix between the VCSEL modes and the fiber modes H is treated as a 6$\times$6 unitary matrix, which is randomly generated during the simulation. Polarization is neglected as the MMUX is polarization insensitive. For incoherent modes, output mode power can be summed up in power directly and expressed as: P_j=$|H|^2P_i$ with direct detection. Adding one incoherent mode (N=2), the possibility of P_j to be below 0.1P_i drops from 42% to 9%, which is beneficial to mitigate power fading. However, when modes are coherent, the equation becomes P_j=$|HP_i|^2$. The destructive and constructive interference between the launch modes will introduce a large output power variation, which requires a big receiver dynamic range.

The measured optical spectra of the off-the-shelf MM-VCSEL with and without 4-Git/s modulation are shown in Fig. 3(d). Two spectrum peaks indicate the MM-VCSEL has two spatial modes. In order to introduce sufficient mode coupling, the light from the VCSEL is launched into the MMF with a small offset for the downlink. The VCSEL is biased at 4 mA and directly driven by a pattern generator through a bias tee. Each output is first coupled into an MMF and detected a photo-diode (PD). Eye diagram is captured sequentially for each output using an

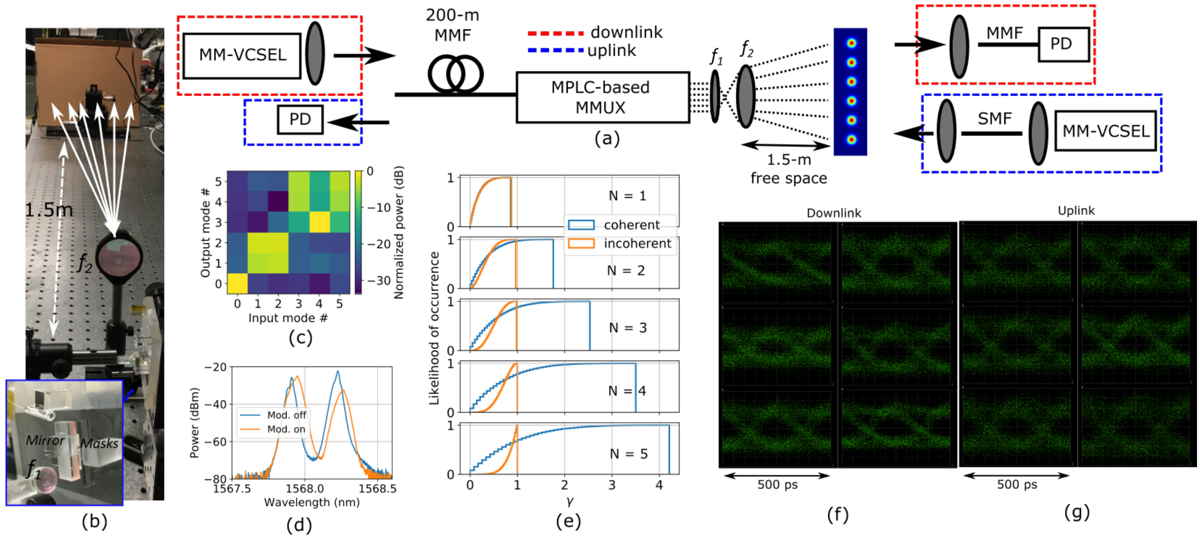

Fig. 3: (a) Schematic diagram of the bi-directional optical wireless link using a MM-VCSEL and an assembled MPLC-based MMUX with fabricated phase masks, (b) image of the MMUX and free-space link, (c) measured coupling matrix of the MMUX, (d) measured optical spectra of the MM-VCSEL w/ and w/o modulation, (e) simulated CDF of γ for different number of launch modes coupling to an MMF with 6 spatial modes, and measured 4-Gbit/s OOK eye diagrams of all the 6 modes for both (f) downlink and (g) uplink.

oscilloscope, see Fig. 3(f). Due to imbalanced mode coupling, some outputs have noisy eye diagrams, which can be further improved using a mode scrambler [13] or VCSEL supporting more spatial modes. For uplink, we used the same VCSEL and coupled into an single-mode fiber (SMF) before sending back to the MMUX, which performs as a low-loss beam combiner. Mode coupling has no impact for uplink performance which is consistent for all the 6 spatial channels, see Figure 3(g). The MMUX has a 6-dB measured combining loss (fabrication imperfections), which already outperforms a single-mode 1-to-6 splitter with an ideal IL of -7.78 dB. The simulated IL of the MMUX is below 1 dB.

4. Conclusion

We have realized optical broadcasting and dynamic beam steering by demultiplexing the spatial modes from a multimode fiber illuminated by a multimode VCSEL. We use this system to demonstrate point-to-multipoint optical wireless communication link using a multimode VCSEL and multi-plane light conversion.

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