Free-Space Visible Light Communication with Downstream and Upstream Transmissions Supporting Multiple Moveable Receivers Using Light-Diffusing Fiber

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Abstract: We demonstrate a free-space bi-directional visible-light-communication (VLC) system using a light-diffusion-fiber (LDF) optical antenna. It allows 360° field-of-view (FOV) non-contact and moveable VLC detection, achieving 210-Mbit/s downlink and 850-Mbit/s uplink transmissions. © 2023 Author(s)
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1. Introduction

The demands for wireless communication services are increasing very rapidly in recent years, using optical communication spectrum to provide extra wireless communication capacity is a recent trend. Visible light communication (VLC) has been developing rapidly in the past decades [1]. VLC can provide both communication and lighting simultaneously. Besides, it can offer the advantages of license-free and electromagnetic interference (EMI)-free. As optical signal does not interference with radio-frequency (RF) signal, VLC can be used to augment RF wireless communication to provide extra communication capacity while without degrading the performance of both signals. In order to increase the receiver (Rx) signal-to-noise ratio (SNR), lenses or compound parabolic concentrators (CPCs) can be install in front of the Rx. However, these will limit the Rx field-of-view (FOV) and making the VLC transmission more subjected to misalignment issue. This is the étendue limit issue [2]. Many creative optical antennas have been demonstrated using special optical materials as well as special Rx structure to enhance the FOV of VLC systems. For example, Manousiadis *et al* fabricated a wide FOV and high gain fluorescent optical antenna, enabling wavelength division multiplexing (WDM) [2]. Peyronel *et al* reported a tight array of polystyrene fibers doped with an organic dye (Saint-Gobain BCF-92), forming a rectangular detector with increased detection area [3]. Kang *et al* demonstrated a large-area scintillating-fiber-based Rx using ultraviolet-to-blue color conversion for underwater wireless optical communication (UWOC) [4]. Riaz *et al* demonstrated a 240° wide FOV VLC Rx for smart phone using a fluorescent fiber [5]. Ishibashi *et al* demonstrated an industrial vehicle communication system via two types of optical fibers (i.e. light-diffusing fiber (LDF) and wavelength shifting fiber) providing both downlink (DL) and uplink (UL) transmissions [6]. Recently, Tsai *et al* demonstrated a 360° wide FOV optical camera communication (OCC) system using a phosphor-coated LDF [7]. Table 1 summaries several optical antennas to enhance the FOV of VLC systems.

Table 1. Optical antennas enhancing the FOV of VLC systems

Ref.	Optical Antenna Type	Data rate	Modulation	Antenna length	Feature
[2]	Fluorescent layer sandwiched by 2 glass layers	12-Mbit/s	OOK	-	WDM capability
[3]	Polystyrene fiber array (Saint-Gobain BCF-92)	2.1-Gbit/s	OFDM	3.6 x 35 cm	Omni-directional detection potential
[4]	Scintillating fiber array (Saint-Gobain BCF-10)	250-Mbit/s	OOK	1.2 x 30 cm	UWOC
[5]	Fluorescent fiber (Saint-Gobain BCF-20)	1.1-Gbit/s	OOK	7.57 cm	For smart-phone Rx
[6]	Light diffusion fiber + wavelength-shift fiber (BCF-92)	100-Mbit/s (DL) + 100-Mbit/s (UL)	OOK	50 m (DL), 25 m (UL)	For industrial vehicles
[7]	Phosphor-coated light diffusion fiber	3.3 kbit/s	OOK	100 cm	OCC
This work	Light diffusion fiber	210-Mbit/s (DL) + 850-Mbit/s (UL)	OOK	100 cm (DL and UL)	Bidirectional + FSO capability

From Table 1, we can observe that in order to provide hundreds Megabit/s, wide FOV and large VLC detection area, LDF without the phosphor-coating (i.e. no wavelength shift) could be a promising candidate. It allows 360^o wide FOV non-contact and moveable VLC detection around the fiber circumference. In this work, we demonstrate a free-space VLC system with bi-direction transmissions supporting multiple moveable Rxs using a LDF. The system concept is shown in Fig. 1, in which the LDF acts as an optical antenna supporting multiple moveable Rxs. To increase the system flexibility, the LDF could be installed at a remote location where the DL data is sent from the head-end office via free-space VLC. In this proof-of-concept demonstration, a 100-cm long LDF and 100-cm free space VLC transmission are used. 210-Mbit/s DL and 850-Mbit/s UL transmissions, fulfilling the pre-forward-error-correction bit error rate (pre-FEC BER = 3.8×10^{-3}) threshold are achieved.

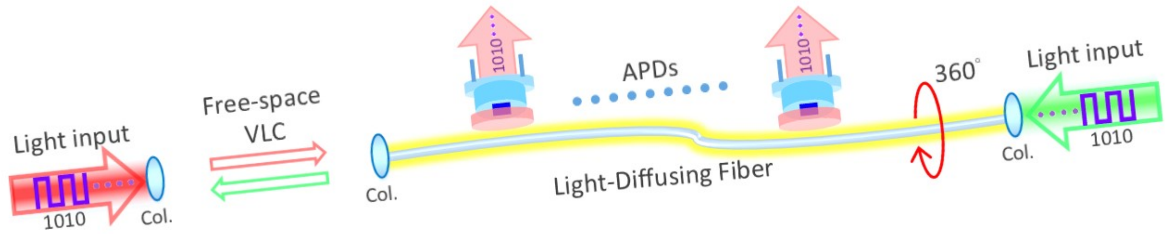

Fig. 1. Concept of using LDF as an optical antenna supporting multiple moveable Rxs.

2. Experimental Setup

Fig. 2(a) shows the experimental setup of the free-space VLC system with bi-direction transmissions supporting multiple moveable Rxs using a LDF. The LDF (Corning® Fibrance®) is primarily used for lighting decoration. Nanostructures are added to the inner core producing light diffusion out of the fiber circumference. A 633nm red laser diode (LD, Thorlabs®, HL63163DG) and a 520nm green LD (Thorlabs®, PL520) are used as the DL and UL transmitters (Txs) respectively. Two pulse-pattern generators (PPGs) are used to drive the DL and UP LDs to produce optical on-off-keying OOK signals respectively. Collimators (Col.) are used to couple lights into and out of the LDF as shown in Fig. 1. At the head-end side, dichroic Mirror (DM) is used to separate the red and green lights. The green UL signal is received by an avalanche photodetector (APD) (Thorlabs®, APD210) at the head-end. Another APD (Thorlabs®, APD110A) with red optical filter (OF) is used to receive the red DL signal via the LDF. The received OOK eye pattern is captured by a digital sampling oscilloscope (DSO) (Agilent®, 86100A); and the BER is measured by a BER tester (Anritsu®, MP1800A). Fig. 2(b) illustrates a photo when the LDF is launched by different color LDs, showing uniform light around the fiber circumference. The optical signal emitted via the LDF is safe for human eyes. Fig. 2(c) shows the optical powers measured by an optical power meter when sliding along the 100-cm LDF. We can observe that the light intensity is quite uniform in the 20 - 80 cm range with an average optical power of 25 µW. Figs. 3(a) and (b) show experimental photos of the head-end and the LDF optical antenna respectively when both the UL and DL LDs are ON. We purposely making turns in the LDF to illustrate the flexibility of the LDF optical antenna. Yellow color emitted via the LDF can be observed when both red and green lights are launched into the LDF. Fig. 3 (c) illustrates photos of the LDF without and with red and green light launchings respectively.

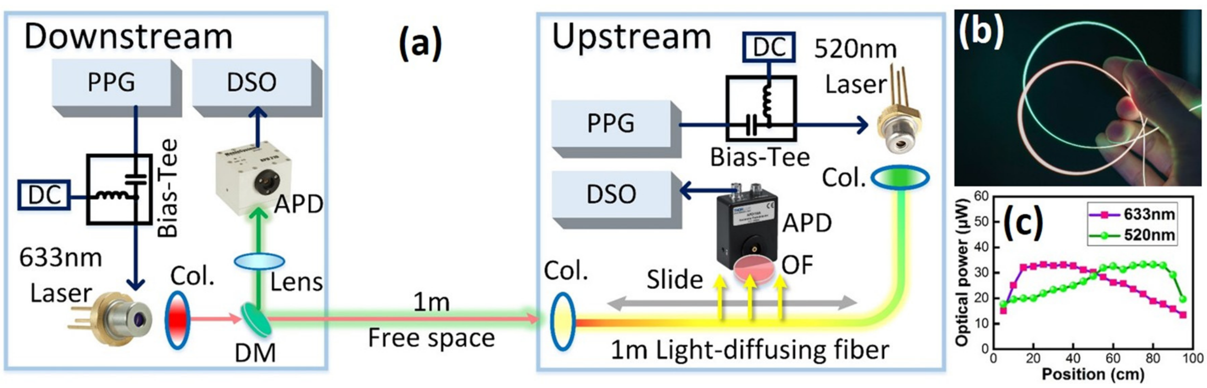

Fig. 2. (a) Experimental setup. (b) Photo of LDF and (c) measured power by a power meter at different fiber positions.

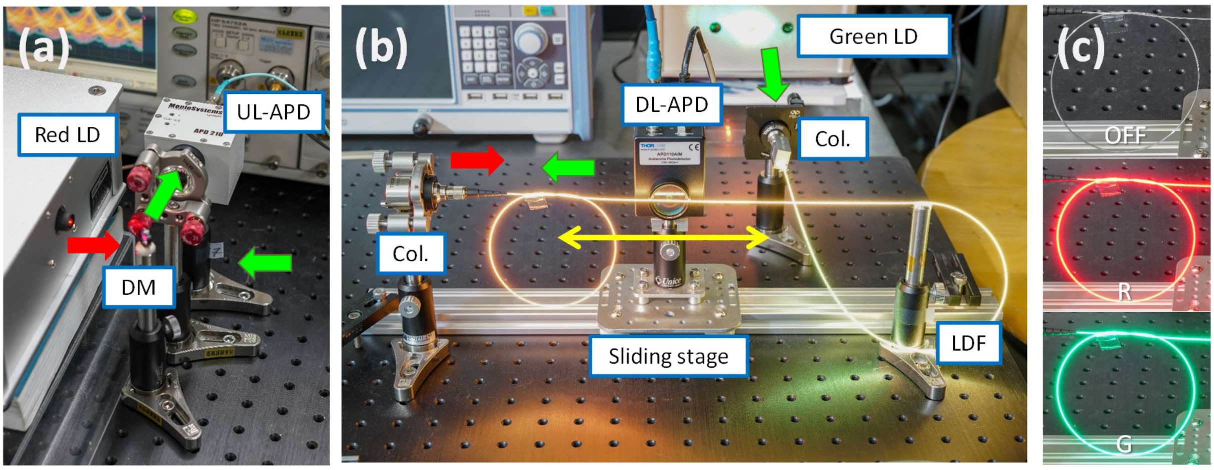

Fig. 3. Experimental photos of (a) head-end and (b) LDF optical antenna when both LDs are ON, and (c) LDF without and with red and green light launchings.

3. Results and Discussion

Fig. 4(a) shows the DL BER measurements via the LDF from data rates 100 Mbit/s to 220 Mbit/s, and the corresponding received OOK eye-diagrams. Clear eye-diagrams can be observed at data rate up to 180 Mbit/s. BER of 3.69×10^{-4} is measured when the DL data rate is 210 Mbit/s, satisfying the 7% pre-FEC threshold. Fig. 4(b) shows the UL BER measurement from data rates 100 Mbit/s to 1,000 Mbit/s, and the corresponding received OOK eye-diagrams at the head-end. Clear eye-diagrams can be observed at data rate up to 800 Mbit/s. BER of 2.15×10^{-3} is measured when the UL data rate is 850 Mbit/s, satisfying the 7% pre-FEC threshold. Fig. 4(c) show the DL BER curves at different data rates and at different position of the 100-cm LDF optical antenna. We can observe that at date rates of 100, 150 and 190 Mbit/s, error-free (BER < 10^{-9}) detection can be achieved at positions from 10 to 90 cm even the light is not quite uniform along the LDF as shown in Fig. 2(c). At data rates of 200 and 210 Mbit/s, pre-FEC BER (pre-FEC BER = 3.8×10^{-3}) detection can be achieved at the same range.

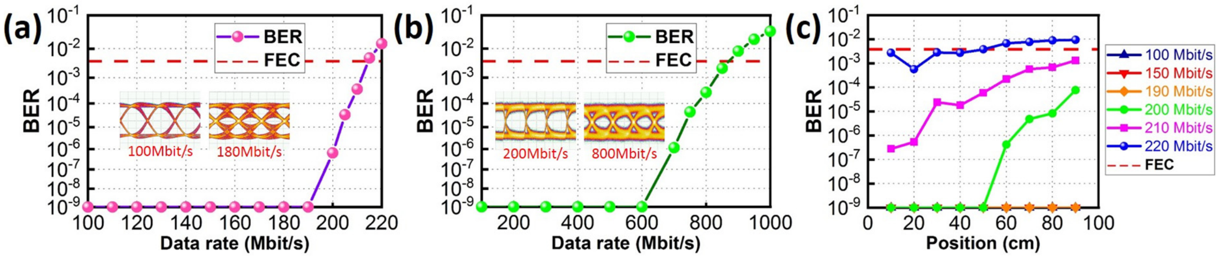

Fig. 4. Measured BER and eye diagrams in (a) the DL, (b) UL, and (c) DL at different data rates and at different position of the 100-cm LDF optical antenna.

4. Conclusion

We demonstrated a free-space VLC system with bi-direction transmissions supporting multiple moveable Rxs using a LDF optical antenna. The LDF could be installed at a remote location where the DL data is sent from the head-end office via free-space VLC. In the proof-of-concept demonstration, a 100-cm long LDF and 100-cm free space VLC transmission achieving 210-Mbit/s DL and 850-Mbit/s UL transmissions were achieved.

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5. References

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