Visible Light Communications Using Commercially Available Fluorescent Fibers as Optical Antennas

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***Abstract*—The use of fluorescent optical antennas in visible light communications (VLC) can enhance the transmission performance due to their multiple functions of optical filtering, light concentration and collecting light from a wide range of incident angles. One convenient way to create an optical antenna is by using commercially available fluorescent fibers. In this paper, we introduce a new antenna structure made of two bent fluorescent fibers and study its performance in a white light-emitting diode (LED)-based VLC system. We show that, since the fluorophore doped into the selected fiber only absorbs the blue light emitted from the gallium nitride (GaN) LED rather than the yellow light converted from the phosphor coating, it can result in a high modulation bandwidth. Also, by placing two bent fibers in an intersecting way, the receiver becomes omnidirectional. More importantly, our experimental results show that, when the illuminance at the receiver is a typical indoor lighting level, the receiver incorporated with this new fluorescent antenna can result in a much higher transmission data rate compared to the case when no antenna is used.**

***Index Terms*—Visible light communication, LED, fluorescent fiber antenna**

I. Introduction

Visible light communication (VLC) using white light-emitting diodes (LEDs) for both indoor illumination and wireless data transmission is a trending technique which is considered to be used in future wireless networks for supporting a wide range of applications, such as the connections of Internet of things (IoT) devices used in a smart home environment [1], [2]. The performance of a VLC transmission link depends on both the properties of the LED transmitter and the design of the optical receiver. In the transmitter, the commonly used white LED is made of a gallium nitride (GaN) blue LED coated with a phosphor layer. The phosphor layer converted part of the blue light into yellow so that the overall emitted light can be perceived as white. However, when this type of white LED is used for data transmission, the modulation bandwidth is usually very limited due to the long photoluminescence (PL) lifetime of the phosphor [3]. The conventional approach to increase the modulation bandwidth is to place a blue filter in front of the receiver so that only the light emitted from the GaN LED can be detected [3]. However, since the blue light is only a small portion of the overall emitted light, optical filtering can significantly reduce the signal-to-noise ratios (SNRs) at the receiver output. To enhance the SNR performance, an optical concentrator is usually also installed in the receiver so that the optical power of the detected light can be increased. However, the use of an optical filter together with a light concentrator leads to a bulky receiver structure which can hardly be incorporated into small devices. Moreover, typical optical concentrators (e.g. lenses, compound parabolic concentrators) have a trade-off between their field-of-views (FOVs) and the concentration gains known as the étendue limit [4]. A small FOV of the receiver can significantly limit the mobilities of the user devices. This means many of the high-speed experimental works conducted in lab-based environments can hardly be used in real-life applications.

To build compact VLC receivers with wide FOVs, a new approach of using optical antennas made of fluorescent materials has been recently studied and shows promising performance [5]. First, because the fluorescent materials only absorb light of certain wavelengths and the antennas have the functions of optical filtering. Second, the antennas are designed to have both the cladding layer and the core layer so that many emitted photons from the fluorophores can be trapped within the antenna and guided to the photodiodes. Therefore, they are capable of light concentration. Third, since its light concentration principle is based on fluorescence rather than reflection and refraction, it can exceed the étendue limit and simultaneously achieve a high light concentration gain and a wide FOV. Currently, several different antenna structures and various fluorescent materials have been explored and tested in different optical wireless communication (OWC) systems [6]–[14]. Among these designs, the most convenient way of creating an optical antenna is to use commercially available fluorescent fibers [11]–[14]. Other benefits of using fluorescent fibers as optical antennas include their flexible structure and the advanced fiber cladding technique which increases the photon trap efficiency.

In [14], the performance of fluorescent antennas made of different colors of commercially available fluorescent fibers is studied. The results show that one type of fluorescent fiber manufactured by Kuraray (model YS-2) not only has strong

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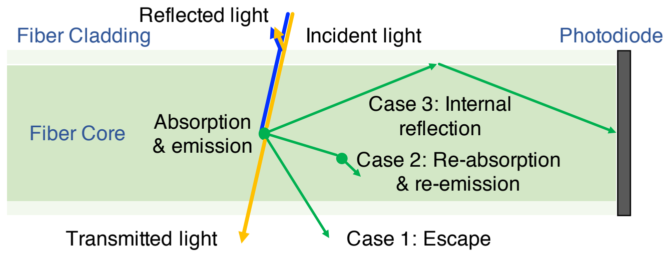

Fig. 1. The physical processes of the light within the fluorescent fiber.

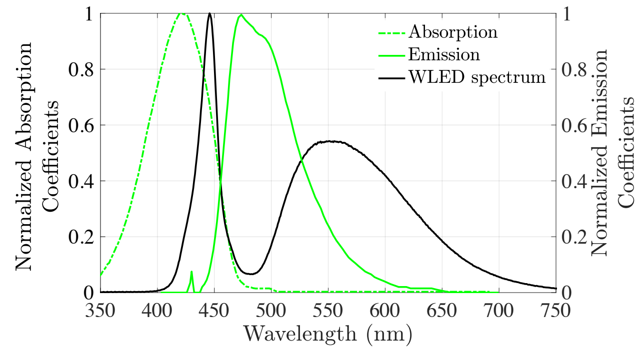

Fig. 2. The absorption and emission spectrum of the YS-2 fluorescent fiber and the spectrum of the white LED. The absorption and emission spectra of the YS-2 fiber were obtained from its datasheet and the spectrum of the LED was measured using a photonic multichannel spectral analyzer (Hamamatsu, PMA-11 model C7374-36).

absorptions of the blue light emitted from the GaN LED but also can avoid absorbing the yellow light converted from the phosphor coating. Consequently, when it is used in white LED-based VLC systems, a much higher modulation bandwidth can be obtained compared to other types of fluorescent fibers. However, the drawback of the YS-2 fiber is that the wavelengths of its emitted light are associated with low responsivity coefficients of the silicon photodetector. In [14], when only one fiber end is coupled with the photodetector, the received signal strength using the YS-2 fiber antenna is relatively low and this affects its performance when the transmission distance is long or the illumination level at the receiver is low. In this paper, a new fluorescent antenna structure made of the Kuraray YS-2 fibers is considered. This structure uses two bent fibers and both ends of the fiber are coupled with the photodiode. Using this way, the signal strength is significantly increased. Moreover, inspired by the ideas used in [11] and [12], the two fibers are placed in an intersecting way so that the receiver becomes omnidirectional. The measured results show that, when the illumination level at the receiver is 590 lux which is within the recommended lighting level range in indoor environments, this new receiver can support a transmission data rate of 39 Mbps which is much higher than the 21 Mbps achieved without using an antenna.

II. Fluorescent fiber antenna in VLC

Fig. 1 shows the main physical processes of the light within the fluorescent fiber. When the incident light arrives at the fiber surface, depending on the incident angle of the light, part of the light is reflected back into the air and the rest of the light transmits into the fiber. Within the fiber, the light can pass through the fiber if the wavelength of the light is not within the absorption range of the fluorophore. Alternatively, a photon can be absorbed by the fluorophore. This absorption can be relaxed non-radiatively or it can result in the emission of a photon with longer wavelengths. Since the emitted photons can go in any direction, as shown in Fig. 1, these photons can escape the fiber or be re-absorbed by the fluorophore. At the same time, many photons can be waveguided to the fiber end where a photodiode is placed. Overall, since the fluorescent fiber only absorbs light within a certain wavelength range, it can be used as an optical filter. Also, because many emitted photons can be waveguided to the photodiode, it can be used as a light concentrator. More importantly, its light concentration principle is based on fluorescence and therefore it can exceed the étendue limit and achieves both a high concentration gain and a wide FOV.

Fig. 2 shows the absorption and emission spectrum of the Kuraray YS-2 fiber and the spectrum of the considered white LED (LUXEON, LXML-PWC2). It can be seen that the spectrum plot of the white LED has two peaks. The first peak at 450 nm is associated with the light emitted from the GaN blue LED and the second peak at 550 nm is related to the light emitted from the yellow phosphor. Comparing the spectrum of the white LED with the absorption spectrum of the YS-2 fiber, it can be seen that the fiber almost only absorbs the blue light emitted from the LED. This information means that the use of the YS-2 fiber is a good choice for optical filtering in a white LED-based VLC system.

III. VLC experiment setup

A photo of our experiment setup is shown in Fig. 3. In the experiment, orthogonal frequency-division multiplexing (OFDM) was used as the modulation method. The transmitted OFDM signal was generated off-line using MATLAB and the main off-line signal processing steps are shown in Fig. 4. In the data transmission, as shown in Fig. 4, the generated OFDM signal was uploaded into an arbitrary waveform generator (AWG, Siglent SDG2082X). The signal output from the AWG was first amplified using an electrical amplifier (Mini-circuits, ZHL-32A-S) and then superimposed onto a DC current using a bias-T (Mini-circuits, ZFBT-4R2GW) to drive a white LED luminaire which contains seven individual LED chips (LUXEON, LXML-PWC2) connected in parallel. A photo of the LED array on an aluminium PCB board (SinkPAD-II 40mm round base) is shown in Fig. 3 (b).

At the receiver, a fluorescent antenna made of two bent fluorescent optical fibers placed in an intersecting way is used to collect the light and waveguide the light to a commercial APD (Thorlabs, APD130A). Two photos of the fluorescent fiber antenna under 400 nm blue light is shown in Fig. 3 (c). In this

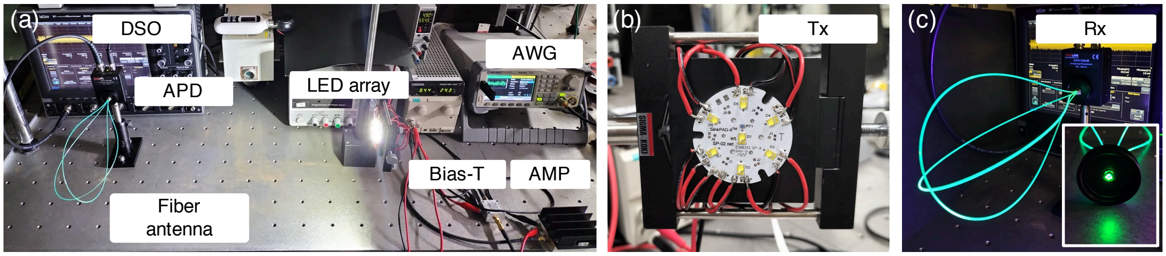

Fig. 3. (a) A photo of the VLC experiment setup, (b) a photo of the LED array on an aluminum PCB board, (c) a photo of the fluorescent fiber antenna under 400 nm blue light.

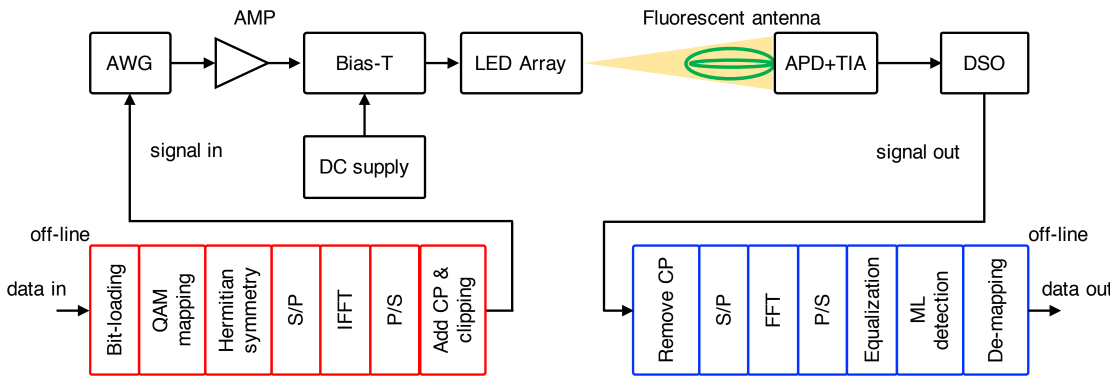

Fig. 4. The block diagram of the VLC experiment setup and the main off-line signal processing steps.

particular antenna design, each fiber has a length of 50 cm. The output signal from the photodetector was captured by a digital oscilloscope (LeCroy, 204Xi-A) and processed off-line using MATLAB to recover the transmitted data. In this setup, the considered illumination level at the receiver is 590 lux which is associated with a transmission distance of 0.4 m.

IV. Communication Performance

A. Bandwidth

The performance of a communication link highly depends on its modulation bandwidth. Although many factors can affect the modulation bandwidth in a white LED-based VLC system, it is usually dominated by either the PL lifetime of the phosphor without blue filtering or the carrier recombination lifetime of the LED with blue filtering. The 3 dB bandwidth, $f_{3\mathrm{dB}}$, is inversely proportional to the carrier recombination lifetime or the PL lifetime, τ, by [7]

$$f_{3\mathrm{dB}} = \frac{1}{2\pi\tau} \tag{1}$$

Fig. 5 shows the measured frequency response of the VLC transmission link with and without the fluorescent antenna. It can be seen that the 3 dB bandwidth is only 2.3 MHz when no antenna is used and the use of the YS-2 fiber antenna for blue filtering can increase the modulation bandwidth to 5 MHz.

B. BER and data rate

Fig. 6 shows the results of a typical transmission measurement. Fig. 6 (a) shows the estimated SNR and the loaded

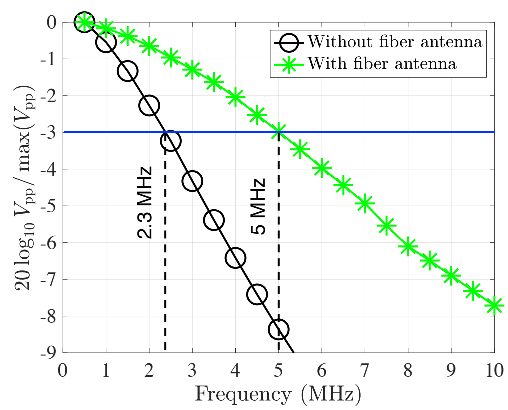

Fig. 5. The measured frequency response with and without the YS-2 fluorescent fiber antenna.

number of bits on different OFDM subcarriers when the transmission data rate is 25.6 Mbps using the YS-2 fiber antenna. Fig. 6 (b) shows the measured bit error rate (BER) of different OFDM subcarriers and the received signal constellation with different sizes after channel equalization. It can be seen that, although different subcarriers have different SNRs, the use of bit-loading can lead to similar BER performance on different subcarriers. This eventually results in a higher transmission data rate for a given acceptable BER level known as the forward error correction (FEC) limit [15].

Finally, the BERs were measured when the transmission data

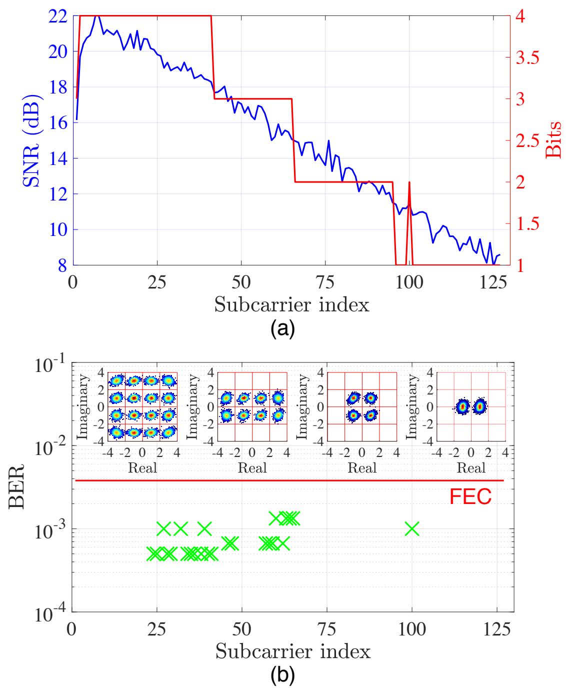

Fig. 6. (a) The estimated SNR and the loaded number of bits on different OFDM subcarriers when the transmission data rate is 25.6 Mbps using the YS-2 fiber antenna, (b) the BER of different OFDM subcarriers and the received signal constellations after channel equalization.

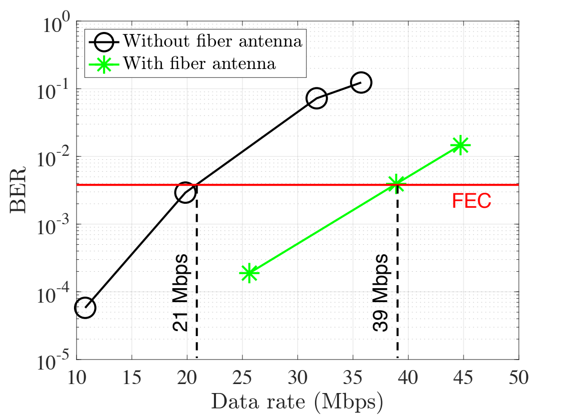

Fig. 7. The measured BERs at different transmission data rates with and without the fluorescent fiber antenna.

rate is changed from low to high and the obtained results are shown in Fig. 7. It can be seen that BER increases as the data rate increases. If the FEC limit is considered to be 3.8×10^{-3}, the use of APD alone achieved a transmission data rate of 21 Mbps. Also, it shows that the use of the new antenna made of YS-2 fiber can result in a much higher transmission data rate of 39 Mbps.

V. Conclusion

The use of commercially available fluorescent fibers as optical antennas in VLC is a promising approach for enhancing the transmission performance. In this paper, we show a new fluorescent fiber antenna which contains two bent fiber placed in an intersecting way and study its performance in a white LED-based VLC system. First, we show that, since the considered fluorescent fiber only absorbs the light directly emitted from the GaN LED, it can result in a much higher modulation bandwidth compared to the case when no antenna is used. Finally, by measuring the BER at different transmission data rates, we show that the use of the new antenna can lead to a transmission data rate of 39 Mbps when the illumination level at the receiver is within the recommended light level range for indoor environments.

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