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Communication characteristics of high-brightness light sources based on luminescence concentration

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Abstract—**Communication characteristics of high-brightness solid-state light sources based on luminescence concentration generated using blue emitting InGaN light emitting diode arrays are demonstrated here for the first time. The proposed device is used as a transmitter in visible light communications, and its performance is evaluated.**

Keywords—visible light communication, luminescent concentrator, phosphor, LED.

I. INTRODUCTION

Luminescent concentrators (LC) attained increased attention in recent years due to its wide range of applications in laser pumping, digital projection, medical therapy, etc. [1-4]. These ultra-bright light sources are low-cost, energy-efficient, compact, flexible and can deliver stable and uniform light output, which is scalable. However, the potential of LC as a light source by itself hasn't been explored in the realm of optical communications. In recent years, we have seen a growing interest in visible light communications (VLC) for a range of applications including Internet of Things (IOT), smart environment, high-speed internet, etc., which used the light emitting diode (LED)-based lights for illumination and data communications [5-7]. LEDs have become the most favourable light source for VLC, not only because of their lower cost, but also the high switching rate, higher lifetime and lower power consumption. The red-green-blue (RGB) white-light LEDs and more commonly, white-light phosphor LEDs are naturally used in VLC systems [6,7]. However, the modulation bandwidth of phosphor-based LEDs is limited (2-3 MHz) due to the slow relaxation time of the phosphor coating [8]. Recent research shows that this bandwidth can be increased substantially from 2 up to 20 MHz by employing a blue filter in front of the receiver (Rx) [9]. Subsequently, laser diode (LD) pumped crystalline phosphors have attracted much focus in VLC due to its high data transfer rate [10]. Alternatively, white-light lasers could also be adopted in VLC, which offer higher data rates and longer illumination and transmission range [11].

Despite the various advantages, the use of LDs in VLC is challenged due to high cost, safety issues, colour mixing complexity and nonuniform illumination due to high coherence. Contrarily, LEDs do come with drawbacks that deem them inadequate for certain applications. The maximum brightness of LEDs has been increasing, but their luminance is far from what is essential for multiple applications, which still require higher brightness. LCs are LED-based high brightness light sources that can find applications where; flash lamps are challenged due to their short lifetime, LEDs due to their lower luminance and laser diodes because of their high-cost and sensitivity to electrostatic discharge etc. [3]. LED pumped LC utilise the ruggedness, stability and ultra-long lifetime of LEDs. It takes the low brightness LED light and enhances the brightness by one or two orders–of–magnitude using luminescence–converted light concentrated in light waveguides while generating new wavelength components. This unique feature enables several application areas such as headlights for vehicles, motorbikes and bicycles, spotlight, lights for entertainment, architecture, digital displays and projection, as well as medical and scientists advancing basic research [1-3].

As a complementary and new application, we investigate the performance of this high-brightness LED-excited luminescence light technology in the emerging field of VLC for future high-speed wireless networks. It should be noted that, all the performance enhancement techniques that have been developed for white-LED-based VLC systems can be adopted into LC-based VLC. In this paper, we report on both optical and electrical characterisation of LCs and further explore its potential use as an optical transmitter (Tx) in a VLC link. We assess the proposed LC-VLC link performance by means of eye diagrams.

The paper is organised as follows. Firstly (Section II (A)), we present a simple schematic of the experimental setup and description of the design and build of the LED-pumped LC light source. We then present the communication characteristics of the LC light source (Section III (A)) and further presents a simple non-return to zero (NRZ) on-off keying (OOK) setup (Section III (B)) to demonstrate the VLC performance of the light source. The impact of the design on the achievable bandwidth, data rates and Q-factor is discussed in Section III, and the paper is concluded in Section IV.

II. EXPERIMENTAL SETUP

A. *High-brightness light source*

The schematic diagram of the LED-pumped LC is depicted in Fig. 1. The luminescence conversion technique proposed here overcomes the so-called brightness theorem (or the law of etendue), which states that it is impossible to increase the brightness (W/mm^2.sr) of light using passive optical devices. Here the absorption of emitted light from a spatially inhomogeneous array of LEDs was used for pumping a large area face (s) of a light-guide (length L × width a) results in longer wavelength (Stokes-shifted) luminescence light, which is trapped by the total internal reflection (TIR) and accumulated over a long waveguide length L. By emitting the luminescence, which is uniform and speckle-free, from a small (rectangular) area end face (with the dimensions of a×b, where a and b are the width and thickness, respectively), a "geometrical" increase in brightness can be achieved. Several light guides (Ce:LuAG (LC-1)/Ce:YAG (LC-2)/Ce:GdYAG (LC-3)) in the form of thin rectangular slabs pumped by arrays of blue (InGaN) LEDs at a peak wavelength of 460 nm have been developed and characterised in this work. The dimensions of the light guides used are 100 × 8 × 0.5 mm^3. These single crystal light guides can be effectively pumped by three single LED arrays (LED-1, LED-2 and LED-3) with a light-emitting surface area of ~18.5 × 8 mm^2 each, see Fig. 1.

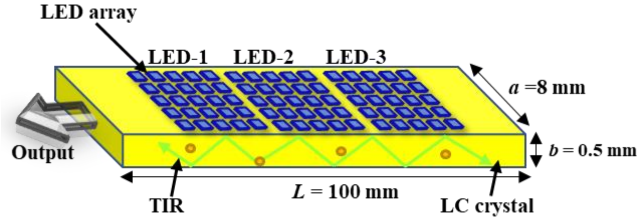


Fig. 1. LED-pumped luminescent concentrator (LC).

The output face of the LC light-guide cannot efficiently transmit due to TIR, therefore (*i*) one can further bond this face to a secondary coupling optic (e.g., glass tapers, compound parabolic concentrators, and optical fibre bundles) [12]; and (*ii*) transform the high aspect ratio rectangular output to other shapes and dimensions to interface with the intended applications. In this work, we have used LC with no coupling optics and the emitted output light (i.e., a power of 1.2 W at a maximum bias current of 3 A) at a small exit face was employed to realise VLC. The fraction of light, which is the light escape cone, launched into the free space channel from an isotropic medium with the refractive index n, is given by:

$$\eta_{escape} = \frac{1}{2}\left[1 - \sqrt{\left(1 - \frac{1}{n^2}\right)}\right] \tag{1}$$

Note, the predicted value of η_{escape} is only 8% for YAG (i.e., n = 1.83). Using appropriate coupling optics, we can harvest most of the light trapped inside the LC for transmission of data in a VLC system.

III. RESULT AND DISCUSSION

A. *Communication characteristics*

To characterise the LED (InGaN LED array)-pumped LC for communication applications, we have carried out a number of tests and measurements. (*i*) A measured voltage-current (*V-I*) plot, as presented in Fig. 2, shows a linear profile over a wide current range, i.e., 0.1 A < I < 3 A, which is highly desirable in multi-level and multi-carrier modulation schemes such as orthogonal frequency division multiple access (OFDM) and quadrature amplitude modulation (QAM) in VLC systems [13,14].

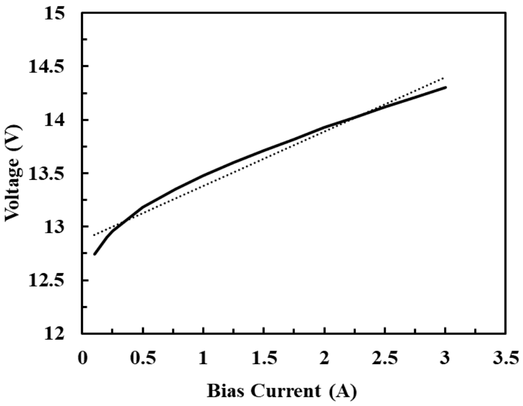


Fig. 2. *V-I* characteristics of the pump LED array under CW operation at 20°C.

Fig. 3 depicts light-current (*L-I*) characteristics of the LC and LED with respect to the bias current. The light source design provides a significantly large output if combined with coupling optics, and more pump LED arrays (i.e., using all 3 arrays (LED-1, LED-2 and LED-3) in Fig. 1 for a 100 mm LC light guide). The work here uses only LED-2 for excitation. Note, in theory, to produce more optical power there is no limit except the thermal consideration.

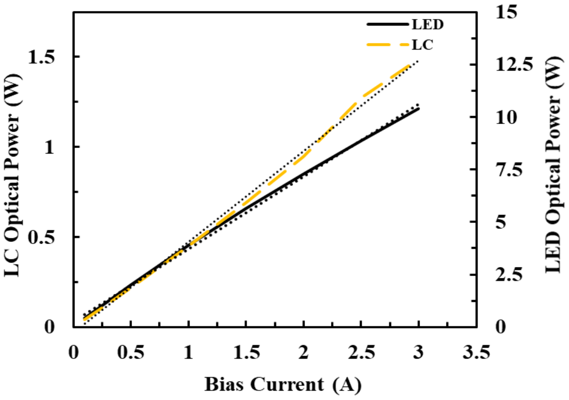


Fig. 3. *L-I* characteristics of the LC and LED array under CW operation.

To determine the signal transmission feature of the proposed LED-pumped LC light source, we measured the 3-dB modulation bandwidth B_{mod} for three different types of crystallite of similar dimensions with results presented in

Fig. 4. As shown in Fig. 4, LC-1 has higher B_{mod} compared with the two others. This was expected, as LC-1 has a spectrum more towards the blue end of the visible band when compared with the other two phosphors, see Fig. 5.

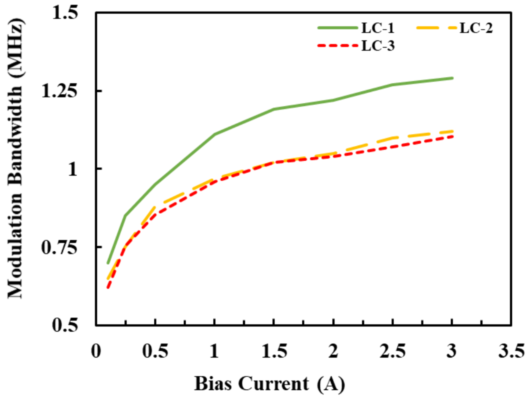


Fig. 4. The relationship between 3-dB bandwidth and LED bias current for three different light concentrators. LC1-Ce:LuAG, LC2- Ce:YAG and LC3-Ce:GdYAG, respectively.

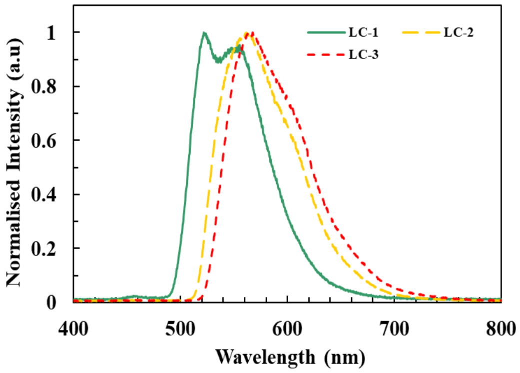
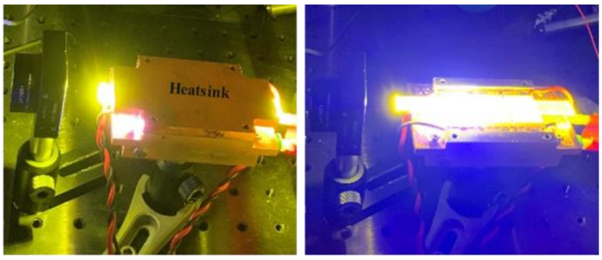


Fig. 5. The LC emission spectra.

The LC phosphors used here possess high quantum yield, high refractive index for efficient guiding, good thermal properties to withstand high heat load and good optical and mechanical properties owing to excellent polish quality. However, under higher LED bias current, heating of the light guide can be an issue [15,16]. Therefore, a conduction cooling heat sink was attached to the LC surface without affecting the light trapping, see Fig. 6(a). With the heatsink, both the LC light guide and the LED arrays were maintained at 20°C. It should be noted that the temperature of the light guide crystal without the heatsink, see Fig. 6(b), was ~120°C at the full power of the single LED array at 3 A. To investigate the effect of heatsink on communication performance of LC-based VLC, we measured B_{mod} of the light source with and without the heatsink with results depicted in Fig. 7. Note, the increase in B_{mod} when using a heatsink, which, in addition, protects the light source module from overheating.



(a) LC-light source with heatsink (b) LC-light source without heatsink

Fig. 6. The luminescent concentrator-LC-2; (a) with and (b) without a heatsink.

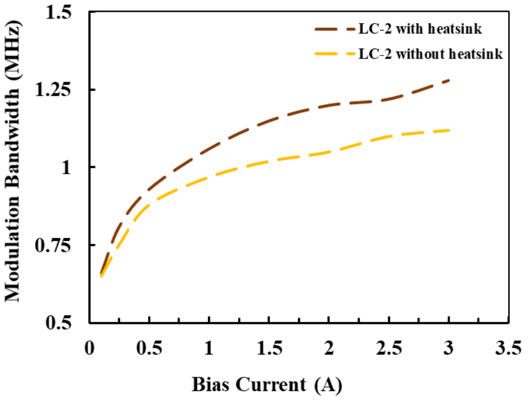


Fig. 7. The relationship between 3-dB bandwidth and LED bias current for a luminescent concentrator-LC-2; with and without a heatsink.

B. Data Communication scheme

A typical experimental setup, as depicted in Fig. 8, was used to assess the VLC link performance of the proposed light source operating over a transmission distance *d* of 1 m. We used the NRZ OOK signal format, which was generated using an arbitrary waveform generator (SG) for intensity modulation of the light source. The modulated light wave was launched into a free space channel and was captured using an optical Rx (Thorlabs PDA10A2), which is composed of a photodetector and a transimpedance amplifier with a bandwidth of 150 MHz and the noise equivalent power of 29.2 × 10^{-12} W/Hz at a gain of 10 kV/A. The regenerated electrical data signal was captured using a real-time digital scope for offline processing in MATLAB in order to extract the Q-factor, which is plotted in Fig. 9. Also shown in Fig. 9 is the data rate as a function of the bias current.

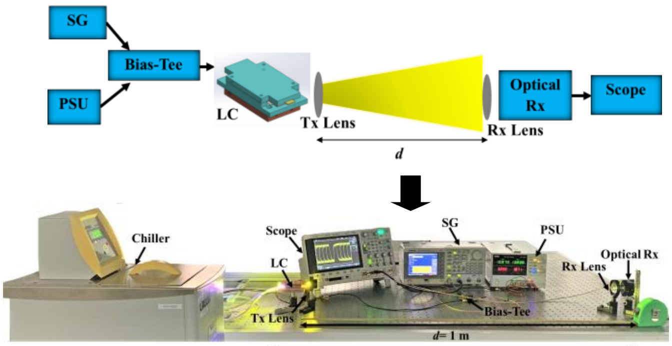


Fig. 8. Experimental setup for data communications. SG-signal generator and PSU-power supply.

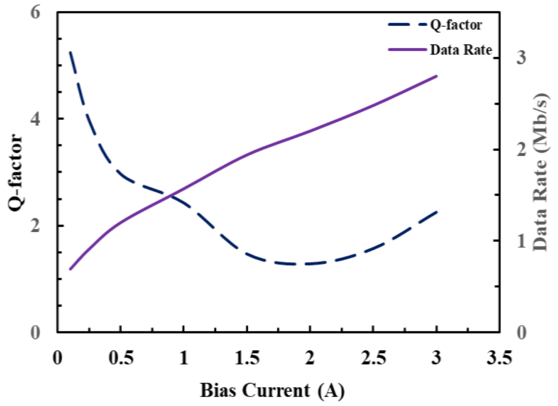
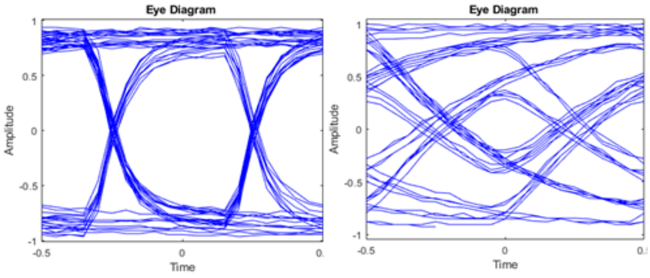


Fig. 9. The relationship between the Q-factor and the LED bias current for LC-2 with heatsink (the temperature of the module was maintained at 20°C).

Fig. 10 shows the measured eye diagrams for the two bias current values of 0.5 A and 3 A and data rates of 1.2 Mb/s and 8.4 Mb/s for the proposed link. As can be seen, for the bias current of 0.5 A, even with no extra circuitry in the Tx and Rx, the received signal has a wide-opening eye (i.e., high signal to noise ratio) hence lower bit error rate (BER), well below the forward error correction limit of 3.8 × 10^{-3}. Increasing the bias current to 3 A, which is very high compared with the most common white-LED VLC, the eye opening is reduced with a reduced Q-factor of 2.3, thus leading to increased BER.



(a) (b)

Fig. 10. Eye diagrams for the bias current and B_{mod} of: 0.5 A and of 1.2 Mb/s and (b) 3 A and 8.4 Mb/s, respectively.

IV. CONCLUSION

The LC light source is an attractive alternative in optical communication systems offering a high signal gain, combined with a large field of view. We have demonstrated the VLC performance of this light source using a simple NRZ OOK setup. We carried out full optical and electrical characterisation of the system in terms of the *V-L-I* characteristics and transmission bandwidth. We experimentally demonstrated the use of LC-based Tx in NRZ OOK VLC link and evaluated its performance in terms of Q-factor, data rates and the eye diagrams. The information gained from this work will be used further to improve the capabilities of the LC light source in the emerging area of VLC (or Li-Fi (Light-Fidelity)). The latter is a potential technology for smart environment within the fifth generation and beyond wireless networks. These ultra-bright light sources also enable a host of other applications like laser/maser pumping, optical metrology, street lighting, digital displays and projection etc. Future work involves a combination of an equaliser and multi-carrier modulation schemes such as optical OFDM to get the optimum data transmission rate. There is also a prospect for duality by using a luminescent concentrator instead for simultaneous data transmission and detection.

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