A wide field of view VLC receiver for smartphones

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Abstract— The directionality of visible light transceivers can be exploited to pack visible light communication links close together. However, this makes these links vulnerable to the random orientation of smartphones that occur when users are moving. Previously, it has been suggested that several transceivers can be used to increase the robustness of the link to a smartphone. However, this solution increases both costs and power consumption. In this paper, a receiver that incorporates a fluorescent fibre acting as an optical concentrator is described. Results from experiments with this receiver are presented which show that it is possible to transmit 1.1 Gbps with a BER of less than $3.8{\times}10^{-3}$ to the receiver. More importantly, it has a field of view (FoV) of 240º in one direction.

Index Terms— Visible light communications, smartphone, Optical Wireless, luminescent solar concentrators, Compound Parabolic Concentrators, fluorescent concentrators.

I. INTRODUCTION

User's demands for wireless communication services are increasing so rapidly that forecasts suggest that it will be increasingly challenging to meet the expectations of future mobile phone users [1,2]. In the past decade, the resulting demand for extra wireless communications capacity has stimulated interest in using visible light to support communications. Visible light has the advantage that it is license-free. Furthermore, visible light doesn't interfere with RF signal and so visible light communications (VLC) can be used to augment RF communications without risking degrading the performance of the existing RF system.

When designing a VLC receiver an important aim is to achieve a particular data rate and bit error rate (BER) with the lowest optical irradiance at the receiver [3]. However, field-of-view is also often important and in some applications, such as integration into a smartphone, cost and size will also be critically important.

Any receiver in a smartphone must be configured to support a robust link despite random orientation of the smartphone [4]. One solution to this particular challenge that has been suggested is to employ an omnidirectional receiver configuration [5]. Simulation results of four scenarios showed that for a single receiver at the top of the smartphone, the coverage probability varied between 40% and 70%. In contrast for the omnidirectional configuration coverage varied between 80% and 95%. Furthermore, using the omnidirectional configuration increased the maximum downlink data rate by 50% [6]. One drawback of the omnidirectional configuration is that the requirement for six transceivers increases both the cost of the system and the power that it consumes [6].

Recently, it has been suggested that an inexpensive fluorescent optical fibre could be used to create a receiver that is small enough in two dimensions to fit into the edge of thin smartphones [7]. The key component of this alternative receiver design is an optical fibre that contains a fluorophore. When this fluorophore absorbs light from a transmitter it emits light at a different wavelength that can be retained within the fibre by total internal reflection until it reaches a photodetector placed at one end of the fibre. Critically, unlike other forms of optical concentrators, such as compound parabolic concentrators or lenses, these fibres are not limited by etendue. This means that they can have both a wide field of view and a significant gain. In this paper results of experiments with this new type of receiver are presented for the first time. The most important result that is presented is that the receiver has a field of view of 240º in one direction.

The rest of the paper is organized as follows. A fluorescent fibre based receiver for a smartphone is described in section II. This section also contains a description of the experimental equipment used to characterize this receiver. The results of the initial characterization of the fluorescent fibres bandwidth and the receiver's field of view are included in section III. Section IV contains a description of the results of experiments to investigate the performance of the receiver. Finally, section V contains the conclusions of this work.

II. FLUORESCENT CONCENTRATORS IN A DUMMY SMARTPHONE

To investigate the field of view of a receiver containing a fluorescent fibre when it is integrated into a smart phone a 150 mm × 75.7 mm × 8.3 mm dummy smartphone, with the

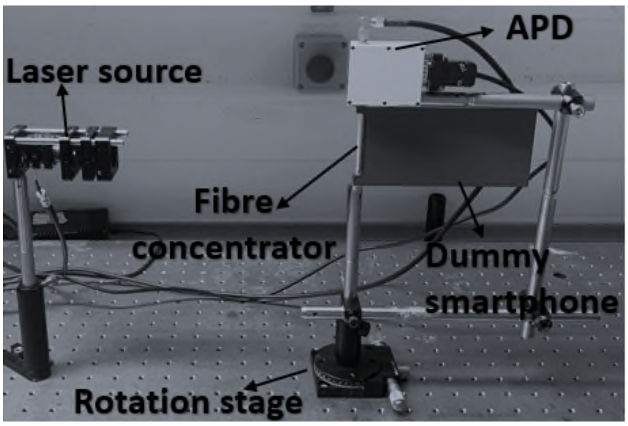

Fig.1. A photograph of the experimental set-up used to determine the performance of a fluorescent fibre with an APD coupled to the front end of a dummy smart phone to act as a receiver.

same dimensions as the iPhone XR, was created. However, unlike a real smart phone this dummy has two small pillars at one end, each containing a 1.11 mm diameter hole to hold a fluorescent fibre. Since light is retained in the fibre by total internal reflection these holes held the fibre 5 mm from the body of the smartphone. In addition, the holes were positioned so that the centre of the fibre was located over the middle of the 6 mm dimension of the dummy. This fibre position was chosen so that the FoV of the fibre covered the fields of view of the two receiver configuration in a recent study [6].

An important factor when designing the experimental set-up to confirm the FoV of the fibre was to maintain the coupling between one end of the fibre and the APD photodetector in a wide range of orientations. To fulfil this requirement four Thorlabs TR4 posts were used to construct a structure, shown in Fig. 1, which holds the centres of both the fibre and the APD along the axis of rotation of a PR01 rotation stage. This rotation stage has a steel locking thumbscrew mechanism. When it is unlocked the stage can be rotated smoothly and continuously through 360°.

In the experiments reported in this paper a violet wavelength absorbing fluorescent fibre from St.Gobain (BCF-20 SC1.00) with a diameter of 1.1 mm was threaded through the two holes in 'smartphone'. For convenience a Tektronix AWG-700002A (10 GHz BW), was used to modulate the voltage applied to a PL405B 405 nm laser diode (LD). The maximum voltage that this AWG can generate, 500 mV_{pp}, was not large enough to drive this LD, therefore, a wideband high-power electrical Mini-Circuits ZFL-2500VH+ amplifier (2.5 GHz) was used to amplify the peak to peak voltage from the AWG. As shown in Fig. 2 finer control over the voltage used to modulate the LD was achieved using a BW-S6 2W263 6 dB attenuator. A Mini-Circuits ZFBT-6GW bias-T (6 GHz BW) was then used to add a d.c. bias of 4 V to the output from the AWG before it was applied to the LD. Experiments showed that with this d.c. bias voltage and an a.c. voltage of 1.5 V_{pp} the bandwidth of this LD was 850 MHz.

As shown in Fig. 1 an APD, a C5658 Hamamatsu APD, with a bandwidth of 1 GHz was coupled to one end of the fluorescent fibre. This 0.5 mm^2 APD was biased with a fixed 12 V power supply and its output was connected to an Agilent MSO9254A oscilloscope, which has a bandwidth of 2.5 GHz. This oscilloscope was used to capture the output from the APD so that it could be processed in MATLAB®.

A key requirement for the experiments was to ensure that light couldn't enter the APD directly. A cover which included a 1.1 mm diameter hole was therefore created. When the fibre was inserted into this hole the centre of the fibre was located over the centre of the APD and the only light detected by the APD was the light emitted from the end of the fibre.

III. INITIAL CHARACTERISATION.

The first experiment performed with this equipment was to determine the frequency response of the BCF-20 fibre. In these experiments, the AWG was used to modulate the LD with different sinusoidal frequencies. Then at each of these frequencies, the averaged peak to peak output voltage from the APD was measured. The results that were obtained showed that this fluorescent fibre has a single-pole response with a 3 dB bandwidth of 80 MHz, which is significantly higher than the BW of most commercial APDs with an active area of more than 1.5 mm^2 and a FOV of less than 20° [8].

Previously, the FoV of a fluorescent fibre concentrator has been measured when it was enclosed and used in conjunction with a cylindrical Fresnel lens. The use of this cylindrical lens limited the FoV of the resulting concentrator in the direction perpendicular to the long axis of the lens to ±14°. In contrast in the direction parallel to the long axis of the cylindrical lens the FoV is more than ±40° [9]. In order to significantly increase the FoV of fibre concentrator the enclosure and the lens have not been used. Instead the concentrator that has been tested is formed from the fibre alone.

To determine the field of view (FoV) of the resulting fibre receiver (RX) the angular positions of the RX was changed by increments of 10° and the corresponding output peak to peak voltages were measured. To confirm the accuracy of results, the experiment was repeated twice for a full rotation of 360°. The results in Fig. 3 show that the fibre means that the FoV of the receiver is ±120°. For larger angles, the line of sight between the transmitter and the fibre is blocked by the thickness of the 'smartphone'.

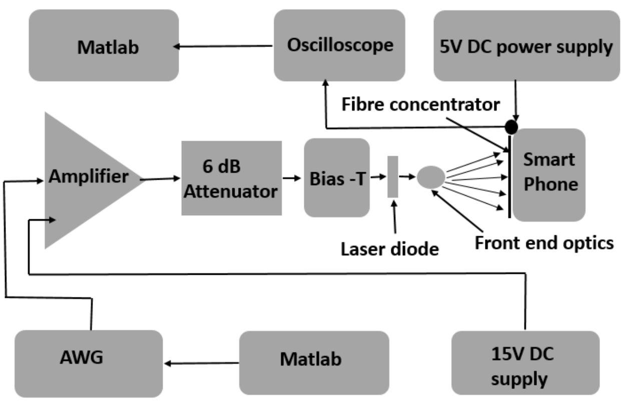

Fig.2. Block Diagram of experimental set-up used to determine the performance of the fluorescent fibre in a 'smartphone'.

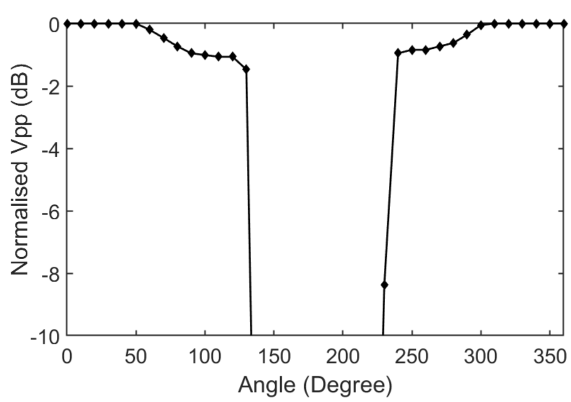

Fig.3. Measured field of view of the fibre concentrator coupled to the dummy smartphone.

IV. COMMUNICATION PERFORMANCE

The impact of the changes in peak to peak output voltage shown in Fig 3 has been investigated by determining the relationship between the peak-to-peak voltage at the output of the RX and the On-off keying (OOK) data rate. In the experiments whose results are described in this paper a randomly generated pseudorandom binary sequence (PRBS) of 2^{15}-1 bits was generated in MATLAB®. This sequence was then converted into an analogue signal by the AWG, which was used to drive the LD. The modulated light from the LD was then directed towards the receiver. For the communication experiments described in this paper, the output from the LD was diffused to create a uniform beam on the fibre, which has a maximum irradiance of 2.5 mWcm^{-2}. The output signal from the APD was collected from the oscilloscope for offline signal processing and synchronization in MATLAB®. To compensate for intersymbol interference (ISI) decision feedback equalization (DFE) was employed. Since DFE is a nonlinear process the number of taps required to compensate for ISI was determined experimentally. Based upon these experiments 40 feed-forward and 20 feed-backwards taps were subsequently used. After DFE the bit error rate (BER) was calculated.

To investigate the impact of the angle dependence of the output from the RX, Fig 3, on achievable data rate different length of the fibre were covered. The impact of covering different lengths of fibre was determined by measuring the peak-to-peak receiver output voltage when the LD bias voltage was modulated at 1 MHz. The data rate at which a BER of 10^{-3} could be achieved for the same length of fibre was also measured. As previously observed in this type of experiment the gradient of the line in Fig 4 is approximately 0.5 [9].

The results in Figs 3 and 4 show that the lowest data rate will be possible at the highest angles between the line of sight and the normal to the top of the smartphone. This angle was therefore set at 120° and the BER was measured at different data rates. The results, Fig 5, show that in this worst case configuration a data rate of 1.1 Gbps was achieved at a BER of 3.7×10^{-3}.

To determine the impact of varying the relative orientation of the transmitter and the receiver the data rate was fixed at 1.1 Gbps. The angle between the transmitter and the dummy smartphone was then varied and the BER determined. The

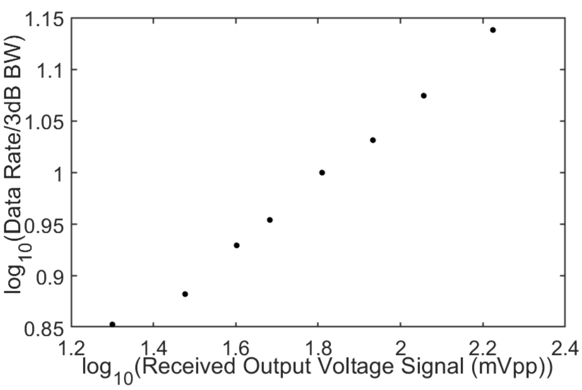

Fig.4. The voltage needed to support various data rates with a BER of 1×10^{-3} after DFE has been applied when a fibre coupled to an APD were used as a receiver for a 'smartphone'.

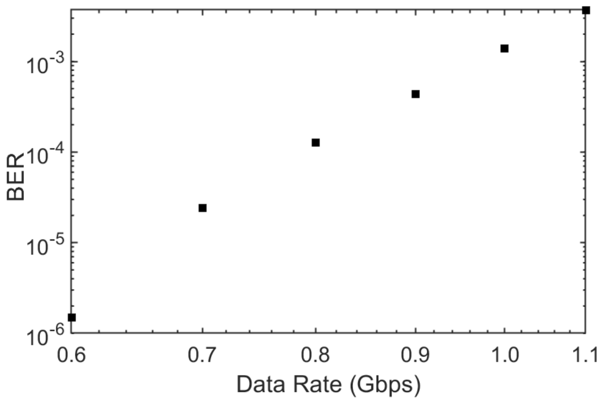

Fig.5. Bit error rate measured when different data rates were transmitted at a wide angle of 120°.

results of these experiments showed the expected symmetry with a lowest BER, 1.8×10^{-3}, when the transmitter is directly in front of the dummy smartphone. As expected from the reduction in receiver output in Fig. 3 the measured BER increases as the angle between the transmitter and the normal to the front of the dummy smart phone increases. However, as shown in Fig. 5, the BER remains less than the correctable limit of 3.8×10^{-3} at 120°. Using BER to define the field of view of the receiver leads to the conclusion this receivers field of view is ±120°. Previous results show that the field of view in the orthogonal direction is ±40°[9]. This means that this receiver has approximately the same FoV as the front, top and bottom receivers in the omnidirectional configuration in [6] combined.

V. CONCLUSION

Recently it has been pointed out that a major challenge that might prevent the deployment of VLC in smartphones is the unpredictable orientation of a smartphone. The solution to this problem that has been proposed is to incorporate several receivers into the smartphone [6]. Unfortunately, the best proposed configuration required six receivers which might cause unacceptable increases in costs and power consumption.

A VLC receiver that includes a fluorescent fibre concentrator has been described. In this paper, it has been demonstrated that with the inexpensive fibre and an irradiance of 2.5 mWcm^{-2} it was possible to transmit 1.1 Gbps with a BER that is better than the correctable limit. The achievable data rate depends upon a variety of factors. The most important result that has been presented is therefore that inexpensive fluorescent fibres can be used to create receivers with a FoV of ±120°. Further work is now required to exploit the various opportunities created by these thin receivers with extremely wide fields of view.

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