

# Smart Phones: an example application for fluorescent concentrators.

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**Abstract**— A key component of visible light communications systems are the receivers, which should be designed to maximize the signal to noise ratio (SNR) of the received signal. The most direct approach to increasing the SNR of a receiver is to increase the active area of its photodiode. However, larger photodiodes have a larger capacitance and this can restrict the bandwidth of the receiver. An alternative approach to increasing the SNR of a receiver is to use an optical concentrator. In this paper, the potential use of fluorescent concentrators in smart phones is discussed. In particular, limitations on the receiver design imposed by thin smart phones are considered. The results that are presented highlight the benefits of both the versatile shape of fluorescent concentrators and relatively modest optical gains.

**Keywords**—Visible light communications, fluorescent concentrators.

## I. INTRODUCTION

The aim when designing a VLC receiver is to achieve a particular data rate and bit error rate (BER) with the lowest possible transmitted optical signal power ( $\text{Wm}^{-2}$ ). However, when designing a receiver a designer must also consider constraints on the cost of the receiver, and sometimes its physical size, arising from the potential application and host system. In order to increase the amount of light that is detected designers prefer to use large photodiodes. However, larger photodiodes typically have a larger capacitance which can reduce the bandwidth of the receiver and increase the often dominant  $c_n$ -C noise. These problems could be avoided by using an optical concentrator.

Unfortunately, conventional optical concentrators, such as compound parabolic concentrators (CPCs), both restrict the field of view of the receiver and can be too large to be conveniently integrated into some host systems. In the past few years work has started on an alternative form of concentrator, fluorescent concentrators, that can have a wide field of view and be created in a wide range of forms [1-3]. The ability of thin fluorescent concentrators to surpass the limits imposed on other concentrators by etendue and to support MIMO have now been demonstrated [3,4]. However, these concentrators have not yet been incorporated into a VLC receiver integrated into a host system. One host system that creates particular challenges for a VLC receiver designer is a smart phone. In particular, the edge of smart phones that are exposed to light from a transmitter in the ceiling, which is less than 1 cm thick, will constrain the size of photodiode that can be used.

In this paper the benefits of using a fluorescent concentrator within receivers integrated into a typical and the thinnest existing smart phones are estimated. The results that are obtained emphasize the benefits arising from the versatile form of fluorescent concentrators and of relatively modest optical gains.

## II. FLUORESCENT CONCENTRATORS

The maximum capacity of a visible light communications (VLC) link depends upon two properties of the system: the receiver signal to noise ratio (SNR) and the receiver bandwidth. However, there is a tension between these two link properties. In particular, larger photodiodes will collect more light, and hence have a larger signal at a particular light intensity, however, they will also have a larger capacitance and therefore a smaller bandwidth. This means that typically the active area of the PD is only a small fraction of the area illuminated by the transmitter and an optical concentrator can therefore be used to increase the receiver SNR. Unfortunately, concentrators that are based upon reflection or refraction conserve etendue, which means that a high optical gain can only be achieved by reducing the receiver's field of view. In particular, for a concentrator that conserves etendue the maximum gain of the concentrator,  $G_{max}$ , is related to the field of view half angle  $\phi$  by

$$G_{max} = \frac{n^2}{\sin^2 \phi} \quad (1)$$

where  $n$  is the refractive index of the concentrator.

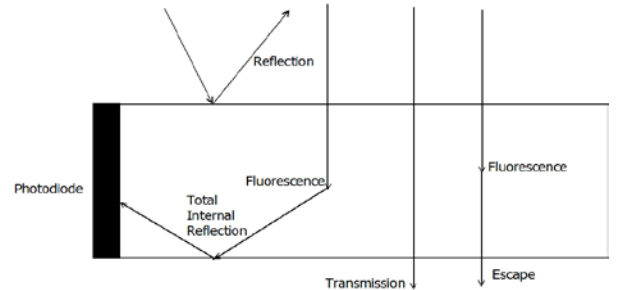


Fig. 1: A schematic diagram of the physical processes in a fluorescent optical concentrator

One way to obtain optical gain whilst avoiding the constraints created by conservation of etendue is to use a fluorescent concentrator (FC) [1]. The various physical processes in an FC are shown in Fig. 1. In particular, this schematic diagram shows that an incident photon can be reflected from the front surface or transmitted through the concentrator. In contrast, other photons can be absorbed by the fluorophore and re-emitted as a second photon. Some of these escape from the FC, however, it is relatively easy to ensure that most are retained within the concentrator by total internal reflection. The critical difference between these concentrators and conventional concentrators is the absorption and emission of photons by the fluorophore, this is because it is this process that means that these concentrators do not conserve etendue. This process therefore means that with a FC it is possible to achieve a

wide FoV with an optical gain that exceeds the etendue limit [3].

The combination of gains and field-of-views that exceed the etendue limit have been demonstrated using a 200  $\mu\text{m}$  layer of Coumarin 6 encapsulated between two microscope slides [3]. In addition, a similar sample together with a Fresnel lens has been used to create a multiple-input multiple output (MIMO) receiver [4]. With these samples it has been possible to demonstrate that the limitations due to etendue can be overcome and that it is possible to support MIMO.

Unfortunately, the thin layer of Coumarin means that it is not possible to efficiently couple the bright light from the Coumarin layer to photodiodes that might be used within a commercial VLC receiver. In order to achieve efficient coupling to the photodiode the thickness of the Coumarin layer should match the smallest dimension of the photodiode. This means that the Coumarin layer needs to be thicker than it is in existing samples.

The need to couple efficiently to a photodiode determines the cross-sectional area of the end of the concentrator. However, there are several other parameters that need to be determined when a concentrator is designed, including the length of the concentrator and the concentration of Coumarin. Most importantly, this design process must lead to concentrators with high enough gains to improve the performance of a receiver.

### III. TRADE-OFFS IN STANDARD TIA DESIGNS

The possible benefits of employing a fluorescent concentrator can only be quantified if the performance limitations of receivers are considered. In most receivers a transimpedance amplifier (TIA) is used to convert the change in photocurrent in the photodiode to an output voltage.

With a resistance,  $R_f$ , and a capacitor in the feedback loop of an opamp with a gain-bandwidth product,  $GBP$ , the transimpedance amplifier and photodiode will act as a second order filter. Then if the filter has a second order Butterworth response its 3dB frequency will be

$$f_{3dB} = \sqrt{\frac{GBP}{2 \cdot \pi \cdot R_f C_s}} \quad (2)$$

where  $C_s$  is the total capacitance on the input of the amplifier, which is the sum of the photodiode capacitance and the capacitance of the op-amp in the TIA [5]

For a light intensity  $L$  ( $\text{Wm}^{-2}$ ) falling onto a photodiode with an active area  $A_{\text{active}}$  the output voltage will then be

$$V_{\text{out}} = \frac{A_{\text{active}} \cdot GBP \cdot \text{Resp}}{2 \cdot \pi \cdot C_s \cdot f_{3dB}^2} L \quad (3)$$

where,  $\text{Resp}$ , is the responsivity of the photodiode. The TIA should be designed to ensure that this output voltage is large enough to make noise in subsequent stages negligible. Since most of the other factors in (3) are determined by the op-amp or the receiver specification the photodiode capacitance per unit active area is an important parameter

when selecting a photodiode. Since the perimeter of a photodiode contributes to its capacitance larger photodiodes tend to have a smaller capacitance per unit area and are therefore often preferred.

### IV. FLUORESCENT CONCENTRATORS AND SMART PHONES

One application that places a significant constraint on the size of a photodiode in a receiver is integration of a VLC receiver into a smart phone. This constraint arises because a good location for a receiver in a smart phone is the edge at the top of the phone. Typically this is less than 1 cm wide and this will limit the dimensions of the package containing the photodiode and hence the active area of the photodiode in the receiver. A representative photodiode which would fit into this constraint is the Hamamatsu S1223-01, which has an active area of 3.6 mm by 3.6 mm and a capacitance of 20 pF.

The top edge of a smart phone is typically several centimeters long and the area of this photodiode is therefore only a small fraction of the area of the top edge. This creates an opportunity to increase the amount of light reaching the photodiode by embedding a concentrator in this edge and coupling its output to a photodiode. Although a conventional optical concentrator could be used their shape makes them unsuitable. In contrast, fluorescent concentrators can be created using plastic optical fibres doped with a fluorophore that could easily be integrated into the edge of a smart phone [6].

The potential increase in the amount of light reaching a photodiode if a fluorescent fibre is used as a concentrator has been estimated numerically. These estimates are based upon the probability that an incident photon will be absorbed by a fluorophore and causes the emission of a second photon which is then retained inside the concentrator and reaches the end of the fibre that is coupled to the photodiode. The method also takes into account the probability that some of these emitted photons might themselves be absorbed by a fluorophore and cause the emission of another photon that might reach the photodiode [7].

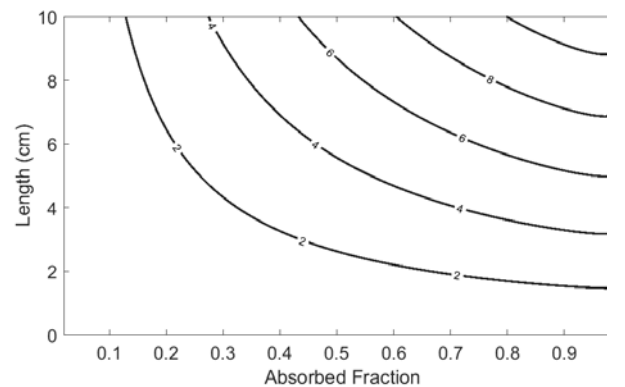


Fig 2: The estimated gain when blue light is used to transmit data if different concentrations of Coumarin 6 are used to absorb different fractions of incident light in different length concentrators that are all 3.6 mm thick.

The results obtained using the absorption and emission spectra of Coumarin 6, Fig. 2, show that if the edge of the smart phone is 7 cm long then the concentrator could increase the amount of light reaching the photodiode by a

factor of approximately 8. If the concentrator is as wide as the photodiode the ratio of the length of this concentrator to its width is 20. A gain of 8 therefore arises when 40% of the photons incident on the concentrator result in a photon reaching the photodiode.

Although 8 might seem to be a relatively modest optical gain it would mean that the effective area of the photodiode is  $1\text{cm}^2$ . This would significantly increase the range of the link or dramatically reduce the bit error rate that could be achieved. However, the most significant benefit will probably be an increase in data rate. This advantage arises because the BER for a link is determined by  $Q$  which is defined as

$$Q = \frac{\text{Worst Case Separation}}{\text{Sum of the rms noises for 0 and 1}} \quad (4)$$

where *Worst Case Separation* is the worst case separation between the receivers response to the two OOK logic levels [8]. Increasing the amount of light reaching a receiver by a factor  $G$  will increase the separation between the two logic levels by a factor of  $G$ . The impact of a gain of  $G$  upon the maximum data rate will then depend upon a range of different factors. However, our experience suggests that a gain of 8 would support a 50% increase in data rate [6].

#### V. FUTURE PROOFING THE RECEIVER

The trend is for smart phones to become even thinner and some phones are now so thin, 5 mm, that the S1223-01 is too large to fit into their edge. An example of a photodiode that could fit into these thinner smart phones is the Hamamatsu S10993-02CT which has a 3.1 mm by 1.8 mm package containing a photodiode with an active area of 1.06 mm by 1.06 mm and a capacitance of 6 pF.

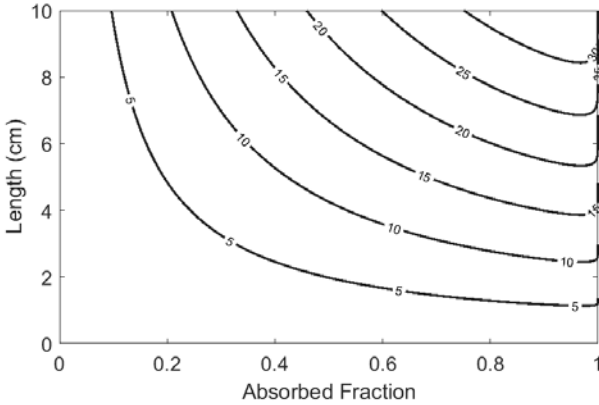


Fig. 3: The estimated gain when blue light is used to transmit data if different concentrations of Coumarin 6 are used to absorb different fractions of incident light in different length concentrators.

The estimated gains of concentrators with cross sections of 1 mm by 1 mm, Fig. 3, show that if the edge is 7 cm long the gain of the concentrator might be 25. In this case the ratio of length to thickness of the concentrator is 70 and so approximately 35% of the photons falling on the concentrator result in a photon that reaches the photodiode.

#### VI. PERFORMANCE COMPARISON

Efficient coupling means that the concentrator coupled to the S10993-02CT should be 1 mm wide whilst the one coupled to the S1223-01 should be 3.6 mm wide. Furthermore the wider concentrator collects 40% of the incident photons whilst the narrower concentrator collects 35% of the incident photons. When fluorescent concentrators are used and the illumination conditions are the same the S10993-02CT will receive 24% of the photons received by the S1223-01. This is a significant reduction in the received signal. However, it is significantly more than the 8% which would result from using a S10993-02CT rather than a S1223-01 without a concentrator.

The important parameter when comparing the two photodiodes in the receiver is the BER that can be achieved which also depends upon the noise in the receiver. The noise sources that need to be taken into account when a photodiode is integrated with a TIA circuit include input voltage and current noise from the op-amp, thermal noise in the feedback resistance and shot noise from the photocurrent itself. In addition, the op-amp input voltage noise creates a current noise flowing through the input capacitance. This noise is referred to as  $e_n$ -C noise [5] and the total power from this noise source increases as the cube of the bandwidth [8]. Particularly at high frequencies, and/or when the photodiode has a large capacitance, this is an important source of noise. In fact the frequencies of interest for visible light communications and the desire to use large photodiodes with large capacitances mean that  $e_n$ -C noise is often the dominant noise source.

Table 1: Key characteristics of two op-amps that could be used in trans-impedance amplifiers.

Part	GBP	$C_{in}$ (pF)	Input Current Noise (pA/rtHz)	Input Voltage Noise (nV/rtHz)
OPA859	900	0.8	0.0	3.3
OPA855	8000	0.8	2.5	0.98

The estimated noise current at various frequencies for the two photodiodes and two op-amps have been calculated. The important characteristics of the two op-amps are listed in Table 1. These two op-amps were chosen to represent the two board categories of op-amp. In particular the OPA859 has a CMOS input, which means that it has no input current and hence no input current noise. However, it has a

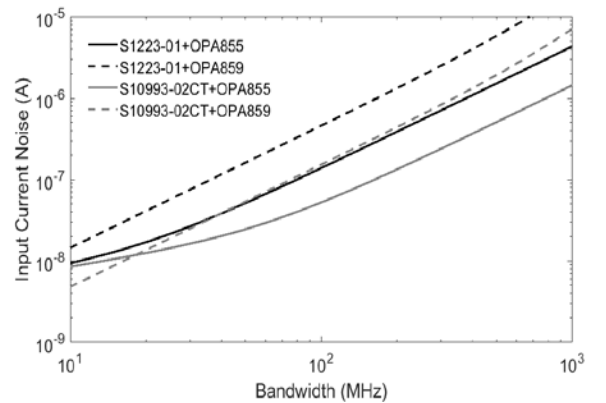


Fig. 4: The total current noise at various frequencies for the combinations of two photodiodes and two high frequency op-amps.

relatively small gain-bandwidth product (GBP) and large input voltage noise. In contrast, the OPA855 has a bipolar input which means that it has a larger input current noise but a lower input voltage noise. It also happens to have a larger GBP.

The results in Fig. 4 show that the smaller capacitance of the S10993-02CT means that for the same op-amp the  $e_n$ -C noise for this photodiode is lower. In fact at low frequencies the noise when this photodiode is used is dominated by input noise from the op-amp in the TIA. This means that at frequencies below 20 MHz it is better to use the OPA859. In contrast, the larger capacitance of the S1223-01 means that, even when the op-amp with the lowest input voltage noise is used,  $e_n$ -C noise dominates at all frequencies.

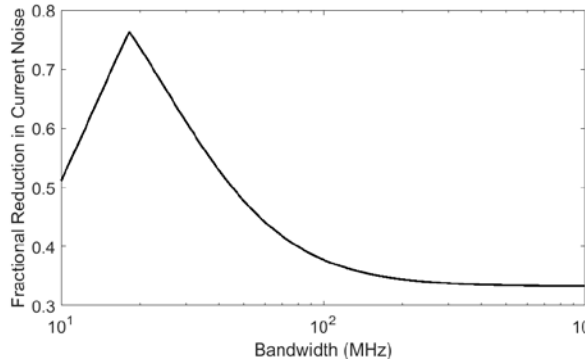


Fig. 5: The ratio between noise currents from the S10993-02CT and the S1223-01 when they are used with the most appropriate op-amp in a transimpedance amplifier.

When comparing these two photodiodes for use in a VLC system the important parameter is the ratio between the total noise currents at different frequencies. The ratio of the total current noise when the S10993-02CT is used to that when the S1223-01 is shown in Fig. 5. These results show that as expected the smaller capacitance of the S10993-02CT means that its noise is lower.

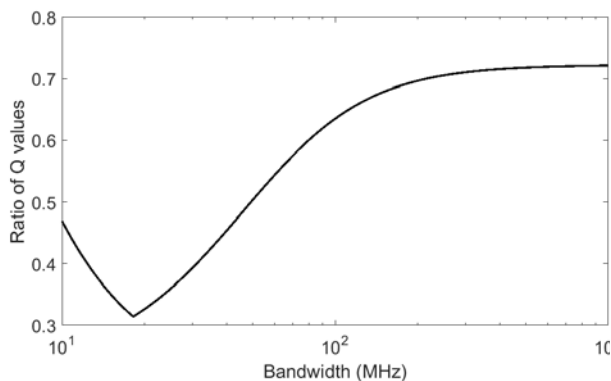


Fig. 6: The ratio of Q values for two photodiodes when they are both coupled to the appropriate concentrator containing Coumarin 6.

Although the S10993-02CT had a smaller input noise current it also has a lower photocurrent. When these two factors are combined the ratio of Q factors can be calculated. The results in Fig. 6 show that the Q factor when a S10993-02CT and concentrator are used is between 0.3 and 0.7 times the Q-factor when the S1223-01 and a fluorescent concentrator are used.

The comparison of Q values means that, if it fits within the size constraints of the host system, the larger S1223-01 should be used. However, when a change is necessary the

use of a fluorescent concentrator will mean that the reduction in performance will not be as large as expected from the ratio of active areas of the two photodiodes.

## VII. CONCLUSIONS

Despite the increase in the often dominant  $e_n$ -C noise in a receiver large photodiodes are preferred in receivers because they increase their signal to noise ratio. However, the form factor of smart phones, in particular the fact that they are only a few millimetres thick, imposes a significant constraint on the size of the photodiode that could be used in VLC receivers integrated into smart phones.

The area of the largest photodiodes that fit within the form factor of a smart phone is only a small fraction of the edge of a smart phone. There is therefore an opportunity to increase the Q value of the output of a receiver by incorporating a fluorescent concentrator along the edge of a smart phone. Results have been presented which suggest that using a fluorophore fibre as an optical concentrator for a VLC receiver in a smart-phone will increase the signal reaching the receiver by a factor of 8. In addition, it has been suggested that as smart phones become even thinner the fluorescent concentrators will become even more important. More generally this example application highlights the benefits of the versatility of the size of fluorescent concentrator and relatively modest optical gains.

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