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Compound parabolic concentrator optical fiber tip for FRET based fluorescent sensors

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ABSTRACT

The Compound Parabolic Concentrator (CPC) optical fiber tip shape has been proposed for intensity based fluorescent sensors working on the principle of FRET (Förster Resonance Energy Transfer). A simple numerical Zemax model has been used to optimize the CPC tip geometry for a step-index multimode polymer optical fiber for an excitation and emission wavelength of 550 nm and 650nm, respectively. The model suggests an increase of a factor of 1.6 to 4 in the collected fluorescent power for an ideal CPC tip, as compared to the plane-cut fiber tip for fiber lengths between 5 and 45mm.

Keywords: CPC, FRET, Fluorescence, Equilibrium modal distribution.

1. INTRODUCTION

FRET based fluorescent sensors have been used widely to measure different biological quantities [1]. One limitation in such sensors is the lower intensity of the detected fluorescence signal, which could lead to higher noise and affect the readings [2].

To improve the signal to noise ratio, several approaches can be used, such as enhancing the quantum yield of flourophores using nanoparticle[3, 4] or using LUX-FRET ,which is an advanced spectral FRET analysis technique[2]. However, these techniques require changes in the sensor chemistry or increased computational needs [1].

For fiber-optical FRET based sensors, another technique that can be used is to taper the fiber tip to increase the collection efficiency of fluorescent light [5]. In case of multimode fibers, sharp linear tapering of the fiber can increase the numerical aperture but not all of the delivered light will be available for excitation of the flourophores as some of the light will leak out.

We propose a CPC fiber tip for such sensors. It concentrates the excitation light and enhances the fluorescence pickup efficiency from the isotropically emitting flourophores by increasing the numerical aperture. For biosensing applications, which are geometrically constrained, the CPC fiber tip can optimize the excitation of the sensor chemistry, as it concentrates the light to a smaller area around the fiber tip. For continuous measurement sensors, CPC fiber tip can reduce power consumption due to a more efficient light pickup over a period of time.

2. COMPOUND PARABOLIC CONCENTRATOR

A Compound parabolic concentrator (CPC) is a non-imaging optical component, which is widely used in solar energy systems and many other applications where concentration of light from a highly divergent source is required. CPC in a two dimensional geometry is essentially two identical but oppositely aligned parabolas truncated at their focal point, as illustrated in Figure 1. A more detailed geometrical description of the CPC in both 2 and 3 dimensions is given in Ref [6]. The shape of the CPC follows the edge ray principle, which requires that all the rays incident at the input aperture within a limited acceptance angle of the CPC will be reflected to finally reach the output aperture. This is shown in Figure 1, where the rays at edge points A and A” on the input aperture reaches the edge points B and B” at the output aperture, respectively. Any ray not in the acceptance angle will be rejected before reaching the output aperture. Derived from this principle, the geometrical parameters of the CPC can be given as:

$$\mathrm{a1} = \frac{\mathrm{a2}}{\sin \theta\mathrm{i}} \qquad (1)$$

$$\mathrm{L} = \frac{\mathrm{a1+a2}}{\tan \theta\mathrm{i}} \qquad (2)$$

where a1 and a2 are the radii of the input and output aperture, respectively, while θ_i and L are the acceptance angle and the length of the CPC, respectively.

The edge ray principle also holds true for a CPC in the reverse direction. In that case, all the rays incident upon the output aperture at the angles ≤ 180° will reach the input aperture at angles $\leq 2\,\theta_i$ [7].

The edge ray principle should also conserve the entendue [6], i.e.

$$\mathrm{a1} * \mathrm{NA1} = \mathrm{a2} * \mathrm{NA2} \qquad (3)$$

where NA1 and NA2 are the numerical apertures.

This equation shows that the numerical aperture at the output is increased for the CPC tip due to its reduced output aperture diameter. A detailed analysis of the CPC fiber tip is given in Ref [7].

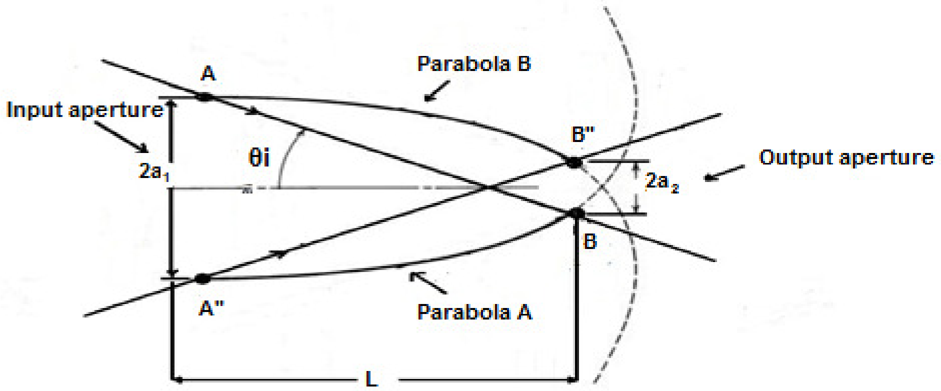

Figure 1: Geometry of a compound parabolic concentrator

3. ZEMAX MODEL

A simple Zemax model has been used to evaluate the CPC fiber tip as shown in Fig 2.

A 26 degree lambertian source (1 W) is collimated and coupled to a multimode step-index PMMA (polyvinyl methacrylate) fiber (core diameter: d_{core}= 240µm) with a 5µm thick PVDF (polyvinylidene difluoride) cladding and a CPC without cladding at the output end (see Table 1 for specifications) to excite the assay chemistry with known refractive index (n_{assay}=1.33), absorption, and emission coefficients. Thus the input aperture of the CPC is the fiber core diameter. The assay chemistry is enclosed in a membrane with refractive index; $n_{membrane}$=1.45 and a thickness of 40µm.

A bulk scattering model confined to one scatter event per ray is used to model the fluorescence event in the assay chemistry: Light at a first wavelength (550nm) propagate and bulk scatters isotropically in the assay and shifts to a second wavelength (650nm) with a chosen mean free path set by the chemistry properties. A detector is placed behind an optical filter that only transmits the light with emitted wavelength i.e. fluorescent light on the way back through the fiber. Further details on the modelling of fluorescent sources in Zemax are given in Ref [8].

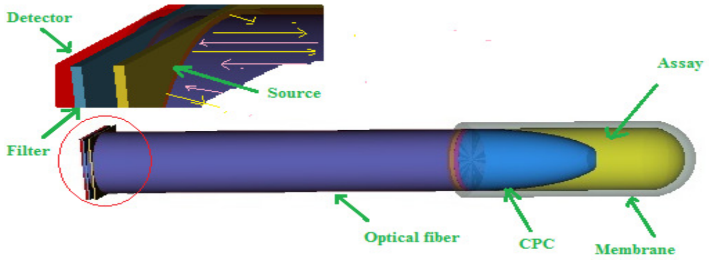

Figure 2: Zemax Model

Table 1: CPC parameters

Material	Input aperture	Output aperture	CPC Length
PMMA	240 µm	60-200 µm	According to Eq. (1)

4. RESULTS AND DISUCSSIONS

Using the Zemax program we calculated and compared the detected fluorescent power for 5 mm length optical fiber with the CPC and normal plane-cut fiber tip. CPC geometrical parameters were changed parameters were changed according to table 1.

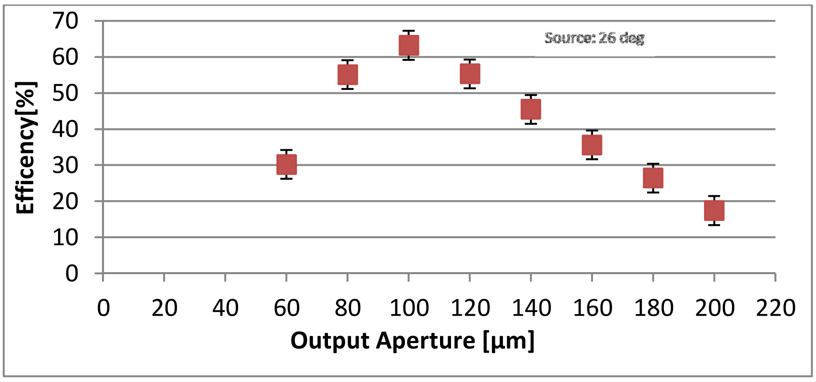

Figure 3: Increase in received fluorescence power for 5 mm fiber length and 240µm CPC input aperture diameter

A maximum increase of 63% can be achieved with a CPC of 100 µm output aperture for this fiber length, which we take as the geometrical parameters for an ideal CPC.

In any optical fiber, the equilibrium modal distribution will first be reached after a certain length, which will depend on the launch conditions [9]. If the modal distribution in the fiber has more power in the higher modes than the equilibrium condition, the fiber is said to be overfilled. If there is low power in higher modes, fiber is said to be underfilled. Attenuation rates for both conditions are different. Given these effects, we need to consider a range of fiber lengths in order to optimize the sensor.

Therefore, we fixed the CPC shape to be the ideal shape and changed the length of the fiber in the range of 5 to 45 mm. As one can see from Fig. 4a, the fluorescent power decreases with the increased fiber length for both the plane-cut and CPC tip fiber sensor but with different attenuation rates due to different launching conditions.

A plane-cut fiber tip overfills the fiber core. In other words, the angular distribution of the fluorescence from isotropically emitting flourophores injected into the fiber is larger than its numerical aperture. For such case, higher-order modes with high propagation losses may reach the detector for shorter fiber lengths, whereas they are lost for longer propagation lengths. This is why Fig. 4(a) shows a sharp drop at short fiber length for the plane-cut fiber tip.

A CPC tip underfills the optical fiber if its acceptance angle is smaller than that of an optical fiber.

CPC increases the numerical aperture and act as an angle transformer. Thus it accepts all the rays from isotropically emitting flourophores and bound them within its acceptance angle. In our case, the ideal CPC tip acceptance angle (derived from Equation 2) is 24° which is smaller than that of an optical fiber i.e. 30°. This way, a CPC tip couples less modes compared to the plane cut fiber tip, but with more fluorescent power in each mode and the power is concentrated towards the center of the fiber.

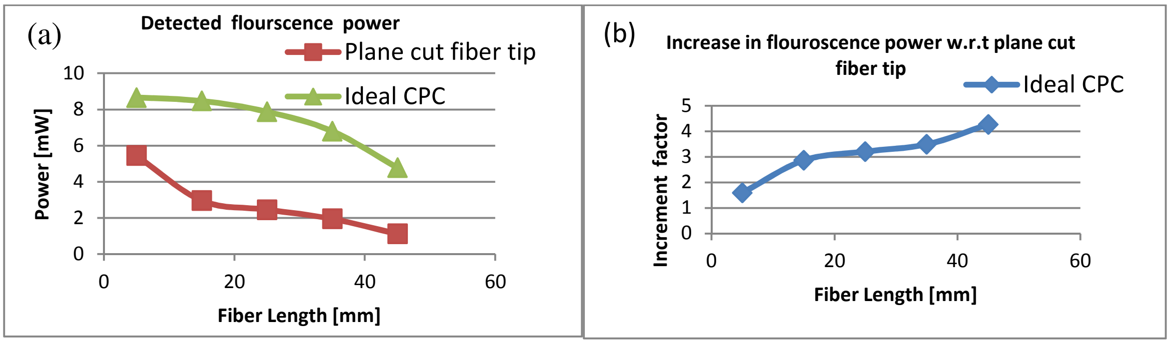

Figure 4: (a) Fluorescence power as a function of fiber length; (b) Increment factor of ideal CPC as function of fiber length

The propagation length where higher order modal losses rapidly reduce the detected fluorescence power will be different for the CPC and the plane cut fiber tip due to different modal distributions. Therefore the ratio of the detected fluorescence power between the two cases does not remain constant and changes with the fiber length, as shown in Fig. 4(b). The fluorescence power reaching the detector at relatively long fiber lengths when using the CPC tip is more than four times the power detected from the plane-cut fiber tip.

In conclusion we have shown that for fiber-optical biomedical sensors, the CPC tip is useful and can provide significant improvement in the detected fluorescence power.

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