AXIAL VERSUS SIDE ILLUMINATION OF A FLUORESCENT CLADDING OPTICAL FIBER

Introduction

In this application we compare the signals between a side and axially illuminated fluorescent cladding optical fiber using Ocean Optics' USB-2000 mini-spectrometer. These types of measurements clearly indicate the superiority of the side illumination over axial illumination for fluorescence measurements.

Table 1. Comparison between side and axially illuminated fluorescent cladding optical fiber sensors.

Comparison Factor	Axial Illumination	Side Illumination
Maximum number of excitation light sources	Dependent on the fiber diameter: in general, only one due to the small fiber diameter.	Using 5 mm diameter LEDs and a 10 cm long fiber, it is possible to accomodate a total of 20 light sources increasing the amount of signal accordingly.
Amount of excitation light available	Available from the evanescent wave tail which is a very small portion of the total light.	All the light provenient from the source which is at least 1,000 times more than the light in the evanescent field:
Type of signal	Mostly from evanescent photons excited by the evanescent tail of the excitation light.	From both homogeneous and evanescent photons that couples into the fiber core as leaky and bound modes, respectively.
Estimate amount of signal (original excitation light intensity assumed to be one).	Because evanescent wave absorption and coupling are simultaneously required, amount of the fraction of light coupled light is between 10^{-4} and 10^{-10} depending on how fluorescent sources are distributed in the cladding.	Greater than 10^{-2}: signal mostly due to leaky modes that propagate inside the fiber. By tapering the fiber, these leaky modes can be coupled into bound modes further increasing signal sensitivity.
Signal to Noise ratio	Light from excitation source can be used to generate fluorescent signal but also acts as a source of noise. Original light that was not absorbed is at least four orders of magnitude more intense than fluorescence masking its intensity. Sorting between signal and noise requires high performance filters that are expensive and decrease signal even further.	Due to side illumination inherent "filtering" effect, most of the excitation light refracts away from the core. As a result excitation light serves mostly as a source of signal, rather than noise.
Multiple point sensing	Achieved by using a single expensive light source that generates ultrashort light pulses with a time of flight that must be measured. This is extremely expensive considering that the speed of the light is on the order of hundreds of thousands of km/s.	Achieved by deploying several small inexpensive light sources along the fiber length and using simple switching techniques: a far more cost effective proposition.
Spatial Resolution	Dependent on the pulse width of the light source and the time response of the detection system.	Dependent on the dimensions of the source. Most LEDs are 3 to 5 mm in diameter but 1 μm diameter LEDs are also available.
Maximum illuminated area	Area of the fiber end face, πr^2.*	Area of the cylindrical surface of the fiber is $2\pi rL$.* Notice that $2\pi rL >>> \pi r^2$ resulting in more signal.
System Cost	More than $20,000	Less than $1,000

(*) r and L are the radius and length of the fiber, respectively.

Background

The first side illuminated optical fiber sensor with a fluorescent cladding was a fiber sensitive to molecular oxygen reported by a group of AT&T Bell Lab researchers in 1989 [1]. Soon afterwards, in 1990, this author started working on this field: he confirmed Bell Lab researcher's discovery [2], [3], [4] and [5], reduced this technology to practice [6] and discovered several other configurations that use side illumination [7], [8]. However, only recently in 2008, [9] the advantages of side illumination are being "re-discovered" by the scientific community at large.

In axial illumination, the most commonly used technique, an excitation source is placed at the fiber end face. Its radiation propagates along the fiber core (blue light rays in Fig. 1a), some of its power penetrates the fluorescent region of the fiber, the evanescent tail, and excites the fluorescence which couples back into the fiber core (black light rays of Fig. 1a).

In side illumination however, Fig. 1b, the source directly illuminates the fluorescent cladding generating a much larger amount of fluorescence that couples into the fiber core. In addition to this advantage, side illumination offers several others over axial illumination (see Table 1).

Despite the fact that this phenomenon was first reported in 1989, it is not well-known by the scientific community which still prefers the axial illumination approach.

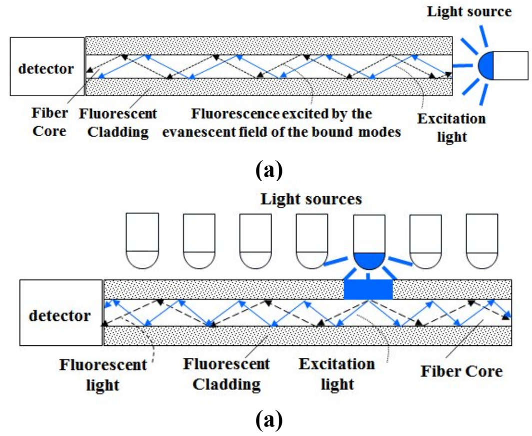

Figure 1. Optical fiber with a fluorescent cladding. Two different techniques to excite the fluorescence: axial (a) and side illumination (b).

In this application we used an Ocean Optics' USB-2000 mini spectrometer to show the signal difference between these two techniques.

Experimental Setup

The following setup was used (Figs. 2a and 2b):

1. A tapered bare core optical fiber coated with the fluorescent dye Rhodamine B.
2. Six UV LEDs, 370 nm peak wavelength, deployed along the fiber length.
3. A multichannel LED driver to power the LEDs and
4. An Ocean Optics USB-2000 mini spectrometer.

The UV LEDs were grouped into three different sets: the first set with three LEDs, the second with two and the third with one. The first group was positioned to illuminate the fluorescent cladding whereas the second and third groups were positioned to side illuminate the bare core fiber effectively *emulating* axial illumination.

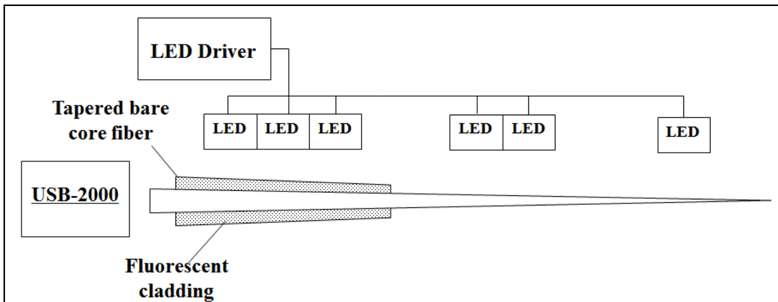

Fig. 2a. Illustration of the optical fiber setup.

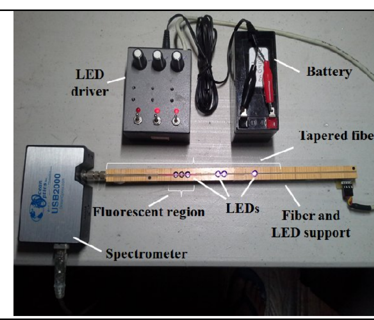

Fig. 2b. Actual picture of the setup.

Procedure and Results

First the bare core region of the optical fiber was side illuminated effectively emulating axial illumination: this involved turning on the second and third sets of LEDs. In this case, some of the excitation light is coupled into the fiber core and, after reaching the fluorescent cladding region, it excites fluorescence. The resulting spectrum is shown in Fig. 3a. Notice we have four different peaks: the first, from the left to the right, corresponds to the excitation light that survives propagation, the second is due to core fluorescence, the third due to cladding fluorescence and the fourth is the second harmonic of the excitation wavelength. It is clear that the amount of power in the excitation wavelength is far greater than the one in the cladding fluorescence.

In the second part of the experiment, we side illuminated the fiber and obtained the spectrum of Fig. 3b. As it can be seen, there are several crucial differences. We see that, for axial illumination:

1. The spectrum of the excitation light is far broader because more of its power reaches the detector and less of it is absorbed by the fluorescent cladding. This intensity, effectively acts as a source of noise to the system especially in cases where the fluorescence peak is closer to the excitation peak.
2. The amount of light in the second harmonic is also very high adding more noise.
3. The peak intensity of the cladding fluorescence is far lower compared to side illumination.
4. Whereas core fluorescence is observed in the first graph, no core fluorescence is seen in the second one. Consequently, side illumination eliminates another source of noise.

From these two experimental results it is obvious that side illumination excites far more fluorescence than axial illumination while, at the same time, decreasing the amount of noise in the system.

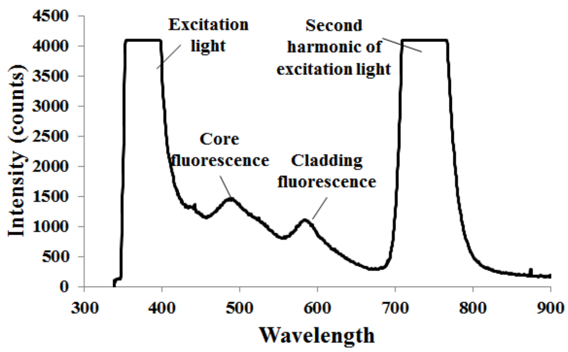

Fig. 3a. Spectral curves of the first, second and third sensing points of the fluorescent cladded optical fiber.

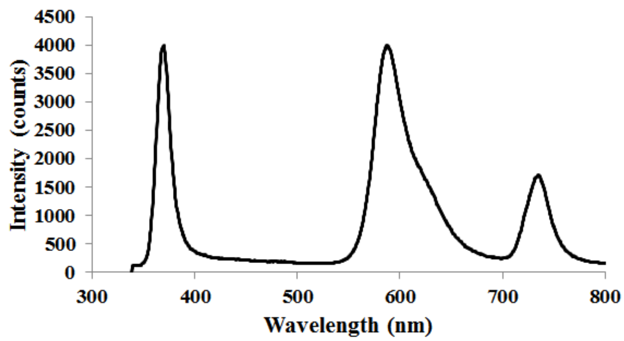

Fig. 3b. Spectral curves of the first, second and third sensing points of the fluorescent cladded optical fiber.

Conclusions

Experimental results using Ocean Optics' mini spectrometer USB-2000 clearly shows the superiority of side illumination over axial illumination in collecting cladding fluorescence.

References

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