Determining erbium distribution in optical fibers using phase-sensitive confocal microscopy

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Abstract. Confocal optical microscopy augmented by the phase-sensitive detection technique has been used to determine the erbium ion distribution in the core of single-mode optical fibers. The fluorescence at 565 nm generated by erbium ions under 488 nm excitation has been used to map the distribution of these ions in several doped fibers and the total ion concentration was estimated. The minimum concentration of erbium ions that can be measured using this technique is estimated to be of the order of a part per million.

Subject terms: *confocal* ***optical microscopy;*** *erbium ion distribution; single-mode* ***optical fibers;*** *fluorescence.*

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1 introduction

Erbium-doped fibers have revolutionized the field of long-haul telecommunications. Optical amplifiers made of erbium-doped fiber have alleviated the need for costly electro-optical repeaters and have become an integral part of modem long-haul telecommunication lines. In addition to fiber amplifiers,'*' the ability to dope rare-earth elements into the core of fibers has made possible fiber laser technology where the active lasing atoms are the doped ions in the fiber. Erbium-doped fiber lasers are now routinely used in applications where a broad tunable laser source is required around 1550 nm. In all these applications, the concentration and distribution of the erbium ions play a crucial role in the performance and characteristics of these devices.

Previous measurements of rare-earth ion distribution present in the fiber core have used techniques such as secondary ion mass spectroscopy combined with electron probe microanalysis and x-ray fluorescence on the fiber preform.[3] However, there is no guarantee that such a distribution will remain accurate when the fiber is drawn from the preform. It is expected that some redistribution in the concentration of the erbium will occur during the fiber-drawing process.

Recently we reported the determination of erbium distribution in the core of optical fiber using confocal optical microscopy.[4] In that paper, it was demonstrated that a confocal microscope could be used for determining the erbium distribution. A severe limitation of the technique was the low signal obtained from fibers with a low concentration of erbium ions. This paper reports on a sensitivity enhancement technique using phase-sensitive detection with a lock-in amplifier in conjunction with the confocal microscope.

2 Experimental Methods

The objective of the experiment was to detect and obtain the spatial profile of the fluorescence produced by the erbium ions in the core of a number of erbium-doped fibers with different ion concentration and to determine the detection limit of this technique. A schematic of the experimental setup is shown in Fig. 1. A confocal microscope operated in the fluorescence detection mode was utilized as the means of measuring the fluorescence from the end face of erbium-doped optical fibers.

In previous experimental work, 488-nm laser light was coupled into the core of a small section of erbium-doped fiber. The output from this fiber was then directed into a spectrometer and the fluorescence was measured using a photomultiplier. The fluorescence signal was then normalized against a signal obtained with normal telecommunication fiber where no erbium atoms were present. This experiment demonstrated that erbium ions in doped optical fiber excited with 488-nm laser light will result in fluorescence with peak wavelength centered at 565 nm. This fluorescence was used

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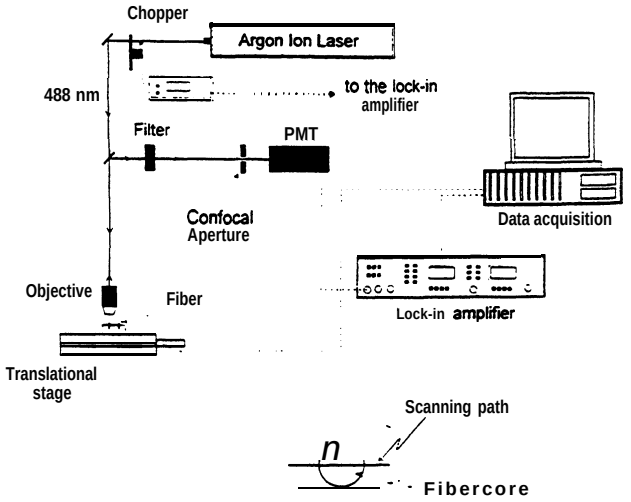

Fig. 1 Schematic of the experimental setup for determining the distribution of erbium ions in doped single-mode fiber. The insert corresponds to a close-up of the fiber surface near the core with the line representing a typical path for scanning the fiber.

as the means of identifying the concentration of erbium ions. The choice of a confocal microscope for the detection of the fluorescence was based on its high spatial resolution (determined experimentally to be ~0.25 μm for a 100 x objective lens) and planar discrimination (the depth sensitivity was estimated[5,6] to be less than 1 μm). The high spatial resolution along with the short depth of field for detection and the high sensitivity of a photomultiplier makes the confocal microscope an ideal system for studying the fluorescence from the erbium ions in doped fibers.

In this experiment, an air-cooled argon ion laser was used as the excitation source for the confocal microscope. The argon ion laser was modulated with a chopper at a frequency of 1 kHz. The 488-nm laser beam from this source was focused onto the cleaved end face of an erbium-doped fiber with 100 x objective lens having a numerical aperture of 0.90 (Nikon, CF Plan Achromat). The power of the laser at the surface of the fiber was measured to be 10 μW. The fluorescence generated from the fiber was collected and separated from the laser light using a high-pass optical filter (Omega Optical. Inc.) whose low wavelength cutoff was at 5 15 nm. A photomultiplier (THORN EMI type 9828B) detected the. fluorescence at 565 nm. The combination of the high-pass filter and the spectral response of the photomultiplier provided a sensitivity window between 5 15 and 600 nm, enabling the detection of the erbium ion fluorescence.

In the normal mode of operation the confocal microscope would scan the argon laser beam across the fiber, resulting in an image of the fluorescence on a display monitor. To improve the sensitivity of the system the confocal microscope was used in a stationary mode ("park mode") where the scanning mirrors were set to one fixed point on the fiber. In this mode of operation, the excitation beam was fixed and the fiber was translated with a high-precision translational stage (0. 1-μm resolution). Translation of the fiber with the laser beam focused near the center of the optical fiber core results in detecting the Auorescence profile along the fiber (see the insert in Fig. 1). The signal from the photomultiplier was then fed into a lock-in amplifier set to detect a signal at the modulated frequency of the excitation (1 kHz) with integration time of 1 s.

The erbium-doped fibers were placed in a v-grove holder with the cleave end facing the microscope objective lens. Small (l-mm-long) sections of optical fiber were used to minimize possible effects resulting from guiding fluorescence from within the fiber. The holder was placed on the precision translational stage. The translation stage and the lock-in amplifier were computer controlled and data were taken using a Labview- (National Instruments) based data acquisition program.

A problem encountered in this work was the exact location of the core of the optical fiber, which is only a few micrometers in diameter. Using the confocal microscope in the normal mode of operation along with a broadband light source, which is coupled into the fiber core, this task becomes relatively simple and straightforward. Once the core was located, the confocal scanning mirrors were parked with the focus beam a few micrometers away from the center. The external light source was then turned off and the 488-nm laser light, modulated with an optical chopper, was directed on the surface of the fiber. At that point, the translational stage moved over the core of the fiber collecting data at 0. 1-μm step intervals.

3 Results and Discussion

The fluorescence distribution from an AT&T erbium-doped fiber (concentration of 450 ppm) using the enhanced technique with the lock-in amplifier is shown in Fig. 2. For comparison the inserted figure in the upper right comer shows the result of the same fiber under the same experimental conditions obtained with the normal confocal geometry. Clearly the signal is very weak and the confocal microscope is barely able to detect the changes in the distribution. On the other hand, the fluorescence signal obtained with the lock-in amplifier is very strong and has very little noise. The

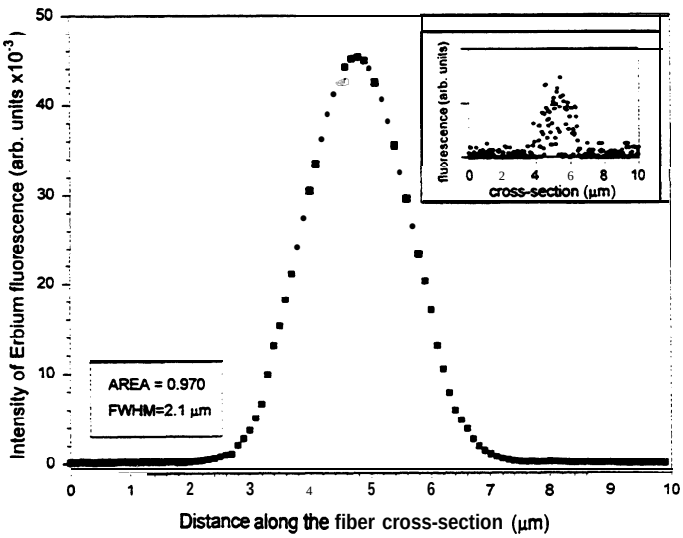

Fig. 2 Fluorescence distribution of the center near the core of the AT&T fiber. The Gaussian fluorescence curve maps the shape of the erbium ion distribution in this fiber. The area under this curve is estimated to be 0.970 arbitrary units (au) and the FWHM 2.1 μm.

distribution of the ions in this fiber appears to be Gaussian with an FWHM of approximately 2.1 μm. The total integrated intensity of this profile is estimated to be approximately 0.970 arbitrary units (au). Note that other pieces of the same fiber gave similar distribution with approximately the same integrated intensity value. Fluorescence measurements were also carried out as a function of incident pump power to ensure that saturation effects were not present in these experiments. Figure 3 shows the total integrated fluorescence intensity of the erbium-doped fiber for different incident powers. Clearly for incident powers lower than 40 μW the total integrated signal behaves linearly, however, for pump powers higher than 45 μW the signal starts saturating. As a result, all experiments were carried out with pump power of 10 μW (a value well below the saturation level).

In addition to the erbium-doped fibers used in these experiments, a normal telecommunications fiber with no erbium ions present was used under the same experimental conditions. There was no detectable fluorescence from such a fiber. This result enforced our conclusions that indeed the observed fluorescence must be generated from the erbium ions.

To further investigate this technique for determining the erbium concentration in doped single-mode fibers, we measured the fluorescence from several fibers with different erbium concentrations. The measurements were made under the same experimental conditions as those for the AT&T fiber. Figure 4 shows the distribution of a single-mode optical fiber A doped with erbium supplied by YORK (Er^{3+} concentration 200 to 240 ppm). It appears to have two peaks with a small dip in the middle of the core. Note that the relative value of the two side peaks varied somewhat, however, the general shape and total integrated intensity remained approximately the same. The FWHM of this particular profile was estimated to be approximately 2.6 μm and the total integrated intensity was measured to be 0.474 au.

Similarly, Fig. 5 shows the distribution of a single mode optical fiber B supplied by Brown University with Er^{3+} concentration between 70 and 80 ppm. It is interesting to note that the distribution profile was more like a top hat with an

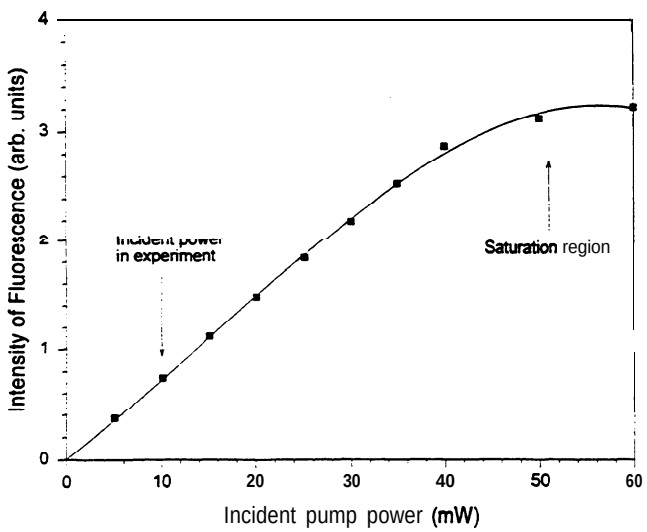

Fig. 3 Total integrated fluorescence intensity of the AT&T erbium-doped fiber as a function of incident power on the fiber. Note that the solid line is intended as a guide to the eye.

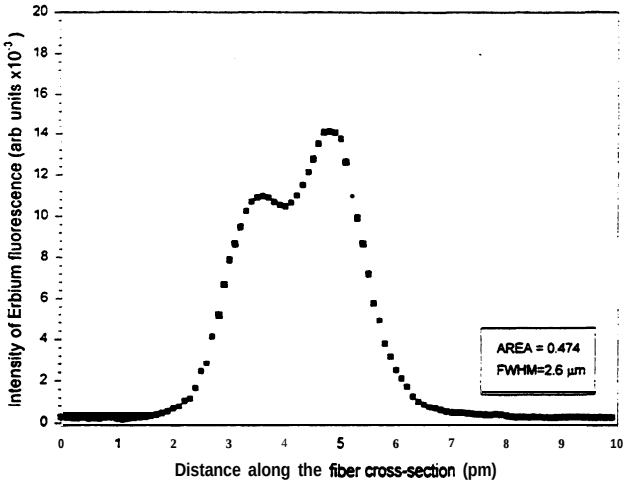

fig. 4 Fluorescence distribution of the erbium-doped fiber A. The area under this curve is estimated to be 0.474 (au) and the FWHM 2.6 μm.

FWHM of approximately 5.8 μm. The measured integrated intensity was estimated to be approximately0.169 au.

Figure 6 presents the distribution obtained from a YORK erbium-doped fiber C with concentration of 40 to 45 ppm. The profile of this fiber was approximately Gaussian with FWHM estimated to be 2.6 μm and the total integrated intensity 0.102 au. Finally, Fig. 7 shows the distribution of erbium in a very lightly doped optical fiber D (5 to 8 ppm). The profile of this fiber was also Gaussian with an FWHM estimated to be 2.4 μm with a total integrated intensity of 0.014 au.

To relate the total integrated signal for the different fibers to an equivalent erbium ion concentration, we have used the AT&T fiber concentration (450 ppm) as the reference. Using the same constant, the erbium concentration in the other fibers was calculated for comparison purposes and Table 1 shows these results. The AT&T fiber concentration was assumed as a reference because the manufacturer of this fiber was able to supply us with the exact erbium concentration. The esti-

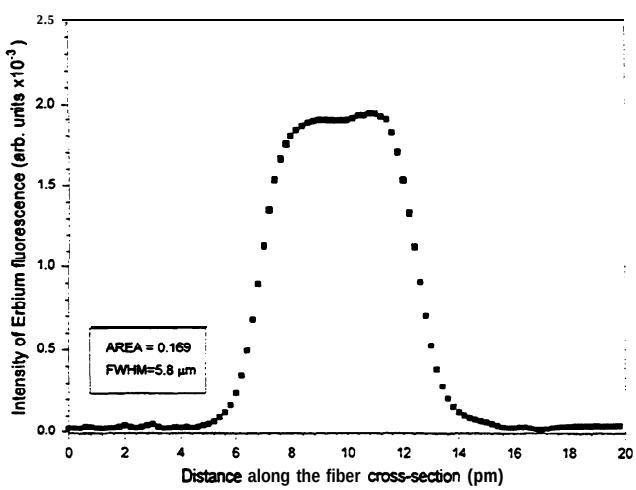

Fig. 5 Fluorescence distribution of the erbium-doped fiber B. The area under this curve is estimated to be 0.169 (au) and the FWHM 5.8 μm.

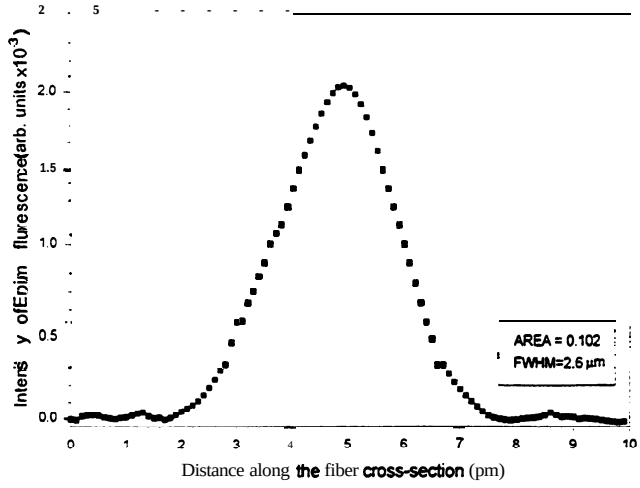

Fig. 6 Fluorescence distribution of the erbium-doped fiber C. The area under this curve is estimated to be 0.102 (au) and the FWHM 2.6 μm.

mated erbium ion concentrations obtained for the other fibers show very good agreement with the actual concentration given by their respective manufacturers.

Another objective of this work was to determine the lowest concentration of erbium ions that can be detected with this technique. The lowest concentration doped fiber available in these experiments was approximately 6.5 ppm (see Fig. 7). To a first approximation, however, lower concentrations may be simulated by simply reducing the incident pump power. Following this approach and assuming linear behavior in the fluorescence (see Fig. 3) it was estimated that the lower limit of the erbium concentration that can be detected was ~ 1 ppm. Note that reducing the incident power also reduces the background noise. We therefore expect that the actual limit of the erbium concentration is larger than 1 ppm and it is more likely to be 2 to 3 ppm. This is in agreement with an estimated value obtained from the SNR from the fluorescence profile in Fig. 7. An attempt to improve this limit by increasing the incident pump power failed because of the increased scattering from the surrounding fiber. However, this sensitivity is more than adequate because most of the erbium-doped fibers manufactured have higher concentrations than a few parts per million.

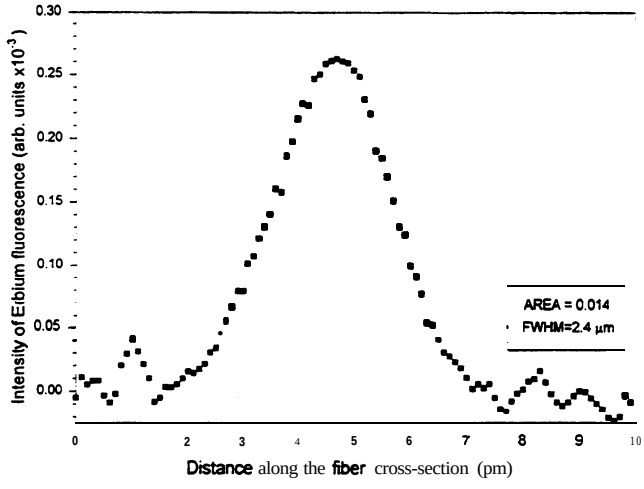

fig. 7 Fluorescence distribution of the erbium-doped fiber *D*. The area under this curve is estimated to be 0.014 (au) and the FWHM 2.4 μm.

Table 1 Estimate of erbium ion concentration in different types of doped fibers using the confocal lock-in amplifier technique.

Fiber	Er^{3+} concentration (ppm)	Total integrated fluorescence (a.u.)	Estimated Er^{3+} concentration (ppm)
AT&T	450	0.970±0.00 1	----
A	200-240	0.474±0.002	220±1
B	70-80	0.169±0.002	78±1
C	40-45	0.096±0.002	44.5±1
D	5-8	0.014±0.002	6.5±1

To further study the concentration and distribution of the erbium ion along the length of the doped fiber, different sections of the same fiber were examined using the phase-sensitive confocal microscopy technique. A set of 10 fiber samples were examined from both the AT&T and *B* fibers. The fluorescence from the AT&T fiber had very little variation in both the distribution and the integrated intensity. The range of the total integrated signal was between 0.969 and 0.971 (au). On the other hand, fiber *B* had values ranging from 0.157 to 0.170 (au), which correspond to a concentration of 73 to 79 ppm of erbium ions (similar variations in the erbium concentration along the length of the fiber were also noted in the other fibers used in this work). It appears that the AT&T fiber has a much better control of the ion distribution as well as concentration along its fiber length.

The combination of the confocal microscope with the lock-in amplifier appears to be an ideal system for determining the distribution and concentration of the erbium ions in small core optical fibers. Clearly this technique can be applied for any type of dopants as long as these dopants fluoresce under laser excitation.

4 Conclusions

A technique was presented to determine the erbium ion distribution in single-mode optical fibers. This technique, based on the detection of fluorescence with a confocal microscope in conjunction with a lock-in amplifier, was used to estimate the erbium ion distribution and concentration in five different types of erbium-doped fibers. The estimated concentrations are in a very good agreement with the data provided by the manufacturers. The minimum ion concentration that can be detected with this technique is estimated to be of the order of a part per million.

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Biographies and photographs of other authors not available.