Measuring the spatial distribution of rare-earth dopants in high-power optical fibers

A. D. Yablon*

Interfiber Analysis, 26 Ridgewood Drive, Livingston, NJ, USA 07039-3120

ABSTRACT

For the first time, a non-destructive technique for spatially resolving the location and relative concentration of rare-earth dopants in an optical fiber is demonstrated. This novel technique is based on computerized tomographic detection of spontaneous emission and achieves micron-scale spatial resolution with the aid of oil-immersion imaging. In addition to elucidating interactions between the signal, pump, and dopant distributions, the measurement described here can reveal shortcomings in fiber manufacturing. Since the technique is non-destructive and can be scanned along the fiber length, it can map the full 3-dimensional distribution of complex rare-earth-doped fiber structures including gratings, physical tapers, fusion splices, and even couplers. Experimental data obtained from commercially available Yb-doped silica optical fibers is presented, contrasted, and compared to refractive index profile data. In principle the technique can also be applied to Er-, Bi-, or Tm-doped silica or non-silica optical fibers.

Keywords: Rare-earth doped optical fibers, fiber lasers, fiber amplifiers, fiber measurements

1. INTRODUCTION

For the past 15 years, the maximum output power of rare-earth-doped optical fiber lasers and amplifiers has been growing at the remarkable rate of approximately 2 dB/year¹. This remarkable growth is partly due to novel fiber designs and innovative fiber manufacturing techniques that in turn, benefit from fiber measurement and characterization technologies. Here we describe the first-ever non-destructive approach for spatially resolving the location and relative concentration of rare-earth dopants in a high power optical fiber. This new measurement technique promises to permit the design and fabrication of new, more complex rare-earth-doped fiber designs.

Benefits to engineering the spatial distribution of rare-earth dopants independently of the fiber's refractive index profile were recognized early in the development of high-power fiber lasers and amplifiers²⁻⁶. For example, ASE was reduced by confining the rare-earth dopant to a ring surrounding the fiber's core^{2,3}. Rare-earth dopants have also been confined to regions of the fiber's core providing preferential gain to the desired fundamental mode⁴⁻¹¹. Higher-order-mode fiber technology can also benefit from inhomogeneous rare-earth dopant distributions¹².

Photodarkening is a poorly understood but serious impediment to the performance of many rare-earth doped fiber lasers and amplifiers¹. Recent investigations¹³ have provided evidence that photodarkening in Yb fibers is not spatially homogeneous but instead varies transversely depending on the fiber design and optical energy distribution. Near field intensity profiles were used¹³ to indirectly infer the spatial dependence of photodarkening. The technique described here may offer a more direct measurement of spatially-resolved photodarkening in Yb-doped fibers.

While spatially resolved spectroscopy can be performed in an optical fiber preform¹⁴, it is much harder in a drawn fiber due to the much smaller dimensions of the sample. Furthermore, spectroscopic changes are known to occur during the draw process, as is reorganization of the dopant concentration due to dopant diffusion, especially in co-doped glasses hosting rare-earths^{14,15}. Finally, some complex fiber designs can only be assembled on the draw tower and therefore there is no preform available for analysis prior to draw. While confocal microscopy has been used to map the erbium fluorescence in a fiber core¹⁶, the technique is necessarily destructive and requires a high quality cleave for accurate results.

Unlike wavelength dispersive X-ray analysis¹⁴⁻¹⁶, which provides a spatially resolved map of each constituent doping element, the present technique does not directly measure the local concentration of rare-earth but instead is based on the optical intensity of the spontaneous emission (SE) of the rare-earth doped glass. By directly measuring the SE, the technique described here reveals the relative gain (assuming uniform optical pumping). However, the gain available

from rare-earth dopants depends upon the host glass composition as well as upon the local rare-earth concentration and therefore the present technique cannot discriminate between low rare-earth concentration in a favorable host glass¹⁵ and high rare-earth concentration in an unfavorable host glass composition.

The technique described here relies upon computerized tomography (CT), a well-known approach for imaging inhomogeneous samples for purposes as diverse as medicine or non-destructive evaluation of engineering components¹⁷. During CT, the sample is typically rotated through a diversity of angles relative to a source and a detector and the resulting set of projections are combined into a spatially-resolved image of the sample. CT was first applied to the linear absorption of a collimated probe beam, for example a "CAT" scan of a medical patient using an X-ray beam (termed *absorption CT*). When imaging a phase object, such as an optical fiber, the phase delay accumulated through a sample, such as an optical fiber, is acquired from a diversity of projection angles to reconstruct the refractive index profile^{18,19} or the birefringence distribution²⁰ (termed *phase CT*). The fiber measurement technique described here involves a third type of CT, termed *emission* $CT^{17,21}$, in which a heterogeneous distribution of emission (rather than absorption or phase delay) is acquired at a multiplicity of angles and processed to reveal the spatial distribution of that emission. The emission exploited here is the SE from rare-earth dopants in an optical fiber that is pumped transversely.

2. EXPERIMENTAL METHOD

A schematic of the experimental apparatus is depicted in Figure 1. The fiber-under-test (FUT) is positioned in the focal plane of an infinity-corrected oil-immersion microscope objective and is pumped *transversely*, rather than axially. The cleaved end of a single-mode pump launch fiber is inserted into the meniscus of immersion oil and launches continuous wave pump laser light (about 130 mW at 976 nm from a *QPhotonics* fiber-coupled laser diode) from the side. Since the pump launch fiber is mounted on a 3-axis translation stage its position is optimized based on the intensity of the detected SE. The optimum distance between the pump launch fiber tip and the FUT was found to be about 1 mm and since the pump launch fiber's mode field diameter is about 7 microns, it casts an approximately 100 micron diameter Gaussian spot on the core of the fiber under test (see Figure 2). The single-mode fiber source emits a spatially coherent spherical wave in its far field that ensures the pumping is spatially homogeneous. In principle, graded-index fiber lens tipped fibers²² could be used to provide a larger, more planar pumping, although that was not implemented for the experiments described here. Typical rare-earth core diameters are between 5 and 50 microns in diameter and therefore the pump energy is negligibly depleted when traversing such microscopic distances, again ensuring spatial homogeneity of the pump source.



Figure 1. Schematic of experimental setup. Note that the lower oil-immersion objective lens serves as a mechanical substrate for the immersion oil and does not participate in the measurement.

The refractive index oil ensures that the reflectance experienced by the laser pump is negligible and that the cladding surface of the FUT does not refract either the pump or SE signals. Furthermore, the refractive index oil permits the objective lenses to achieve extremely high numerical aperture thereby achieving sub-micron spatial resolution.

The pump light excites any rare-earth dopants (i.e. Yb) present in the FUT thereby producing SE. The SE is captured by the high-NA infinity-corrected oil-immersion objective lens and imaged onto the active area of a conventional 16-bit-depth silicon CCD camera by a tube lens. While such silicon CCD cameras are only weakly sensitive in the near-infrared, they are adequate for this application. Since optical fiber coatings are typically turbid, they must be removed to provide micron-scale spatial resolution and therefore the cladding glass is in contact with the surrounding refractive index oil.



Figure 2. Sample SE intensity image showing the emission from the 25 micron diameter core of the FUT (*Thorlabs Yb1200-25/250DC*). The FUT is oriented vertically in this image and the field width (93 microns) is much less than the fiber diameter so that the fiber's cladding edges lie outside the field of view. The brightness gradient in the vertical direction is due to the finite spot size of the pump radiation.

Two aspects of the experimental setup preclude the possibility that the CCD measures spurious pump signal power: (1) a 90 degree angle between the pump signal axis and the CCD imaging axis; and (2) a pump-stopping filter placed between the objective and the tube lens. The pump-stopping filter was a long-pass optical interference filter (*Thorlabs FEL1000*) cutting on at 1000 nm. The efficacy of this filter was verified by comparing its optical density when pumping a Yb-doped FUT as shown in Figure 1 ($OD\approx0.92$ or 12% power transmission) to its optical density when it was shielding the CCD camera from direct illumination by the laser diode pump ($OD\approx3.3$ or 0.05% power transmission). The profound difference in filter attenuation shows that the signal emitted by the FUT does not have the same spectral content as the laser diode pump and therefore must not be elastically scattered by the FUT. While the pump was known to have a

wavelength of 976 nm, the SE is presumed to be distributed over the range of about 980 to about 1100 nm, as is typical for Yb-doped high-power optical fibers.

A desktop computer (PC) acquires and processes the intensity images detected by the CCD camera. Figure 2 shows a typical intensity image acquired on a commercially available double-clad large-mode-area high-power Yb-doped fiber (*Thorlabs Yb1200-25/250DC*) with a 25 micron diameter core and a 250 micron diameter octagonal cladding using the setup depicted in Figure 1. The FUT is oriented vertically, and the bright region in the center of the image is the core of the FUT. The variation in brightness in the vertical direction results from the finite spot size of the pump radiation. The variation of brightness with lateral position is quantified from the 16-bit-depth CCD image and weakly filtered to reduce noise. Several rows of pixels are extracted from the center of the image in Figure 2 (*green line*) where the pump illumination is strongest and these brightness values are depicted below the image (*red trace, arb. units*). The derivative (*blue trace*) of the brightness values highlights fine features that correspond to authentic fine structure in the fiber's core.

Standard CT algorithms are implemented by the $PC^{17,21}$. For example, when the FUT is strictly axisymmetric, only one single projection is necessary to quantify the spatial distribution via the inverse Abel transform²¹. When the FUT is not strictly axisymmetric, the PC rotates the fiber about its axis through a total range of 175 degrees using a fiber rotation chuck (not shown in Figure 1) acquiring data every 5 degrees. The inverse Radon transform²¹ is applied to the raw data to generate a 2-dimensional spatial image of the spontaneous emission. This approach permits the characterization of elliptical cores, or other non-axisymmetric SE distributions.

3. RESULTS

In Figure 3 the 2-dimensional distribution of SE from the 25 micron core fiber is compared to its 2-dimensional refractive index profile measured at 955 nm¹⁹. The rotational orientation of the fiber is identical in both measurements, although the fiber's core appears to be substantially axisymmetric. The octagonal cladding of the fiber is evident in the zoomed out fiber index profile. The region outside of the fiber is refractive index matching oil, nominally about 1.451 at 955 nm. It is worth noting that the refractive index contrast shown in Figure 3 is very small; the total range of the false color is about 0.0025 and the core-to-clad numerical aperture is only about 0.07. Weak fan-like artifacts are evident at large radius in the refractive index profile due to the finite number of tomographic projections and the octagonal cladding surface. The SE profile does not exhibit these artifacts because the cladding surface does not interact with the pump or SE signal. An approximately 3 micron diameter circular ridge (corresponding to the ripples in the blue trace of Figure 2) is evident in the center of the core in both the refractive index and SE measurements, which strongly suggests that it this is a real feature. Furthermore, this fine feature demonstrates the sub-micron resolution of both measurement techniques.



Figure 3. Measurement results. The refractive index profile (*zoomed out at left and zoomed it in middle plot*) was measured at 955 nm^{19} . The false color of the refractive index profile is indicted by the color legend below the index profile maps. The spontaneous emission profile (*right*) is also shown in false color, but with arbitrary units.

To further compare the fiber index profile with the SE, the data shown in Figure 3 was averaged over all azimuthal angles to produce the traces shown in Figure 4. This averaging eliminates the fan-like artifacts from the fiber index

profile and suppresses noise thereby permitting a high quality comparison between the two measurements. While both traces show a similar ripple near the center of the core and substantially agree concerning the fiber's core dimension, the index profile shows a trench at a radius of approximately 4 microns that is absent from the SE profile.



Figure 4. Azimuthally averaged comparison between fiber index profile (*red trace, normalized units*) and SE profile (*blue trace, normalized units*) obtained for 25 micron diameter core 250 micron diameter cladding fiber. While there is strong agreement concerning the core diameter and the ripple in the core's center, the index profile shows a trench with a radius of around 4 microns.

A comparison between data obtained from two different double-clad large-mode-area Yb-doped fibers (*Thorlabs Yb1200-25/250DC* and *Thorlabs Yb1200-20/400DC*) using the same setup is shown in Figure 5 and further demonstrates the possibilities of this new fiber measurement approach. Not surprisingly, the core diameter of the *Yb1200-20/400DC* evident from the SE intensity profile agrees with the expected 20 microns. Both the 2-dimensional SE profile and the azimuthally averaged data (Figure 5, right) show subtle differences in the core structure. More significantly, the SE intensity levels are slightly different, perhaps indicating a slight difference in Yb concentration, or perhaps differences in the host glass.



Figure 5. 2-dimensional spontaneous emission profile obtained from *Thorlabs Yb1200-20/400DC* fiber (*left*) and comparison between azimuthally averaged data obtained from *Thorlabs Yb1200-20/400DC* fiber and *Thorlabs Yb1200-25/250DC* fiber (*right*). The y-axis units on the right hand plot are arbitrary but the relative difference in SE intensity is real.

4. **DISCUSSION**

The measurement scheme described here can be used to map the location of Yb dopant, which is particularly useful when the Yb concentration is not identical to the core profile, but instead is confined to a particular region inside the

core⁷⁻¹¹ or to a ring outside the core^{2,3,12}. Although the fiber's measured here were substantially axisymmetric, the tomographic technique shown here is also valid for non-symmetric fibers, for example a fiber with an elliptically shaped Yb-doped region or a Yb doped region on only one side of the fiber's core.

It is important to note that the measurement technique described here does not require access to the end of the FUT and therefore could even be performed on a live fiber carrying an optical signal, although the removal of the coating and immersion in oil would pose difficulties for cladding pumped fibers. Transverse imaging¹⁹ offers the ability to make measurements along an axially inhomogeneous fiber, such as a fusion splice, taper, grating, or even a coupler, and measurement slices can be made at a multiplicity of axial positions by scanning the fiber along its length.

While we cannot independently verify the veracity of the discrepancy between the refractive index profile and the SE profile found inside the core of Yb1200-25/250DC in Figure 4, this discrepancy highlights the fact that the refractive index profile is not always a valid surrogate for the rare-earth dopant distribution. Discrepencies between the dopant concentration in the preform and the refractive index in the preform have been observed before¹⁵. Furthermore, the multiplicity of dopants comprising the fiber's core may not contribute to the refractive index in an additive manner, particularly when both aluminum and phosphorus are present¹⁵.

When the total cladding pump absorption is known, the spatially resolved pump absorption can be computed based on the measured spatial distribution of SE. For example, an estimate of the linear absorption coefficient of the pump inside the core can be made for the fibers plotted in Figure 5 based on their core/clad area ratios and the manufacturer specified total cladding pump absorptions. The total cladding pump absorptions²³ for *Yb1200-25/250DC* and *Yb1200-20/400DC* are specified as 2.5 dB/m and 0.7 dB/m, respectively. The core/clad area ratios for *Yb1200-25/250DC* and *Yb1200-25/250DC* and *Yb1200-25/250DC* and *Yb1200-25/250DC* and *Yb1200-25/250DC* and about 0.01 and 0.0025, respectively. Assuming that the cladding modes are uniformly populated by pump energy, the linear absorption coefficients of the pump in the core are predicted to be about 5.18/m (22.5 dB/m) and about 6.15/m (26.71 dB/m) for *Yb1200-25/250DC* and *Yb1200-20/400DC*, respectively. In other words, the predicted ratio in the linear absorption coefficients of the pump in the core is about 1.18, whereas the measured ratio between the SE intensity in Figure 5 is about 1.13, which is good agreement considering the assumptions required for the calculation. This type of analysis points the way towards determining a spatially resolved linear absorption coefficient. The spatially resolved pump absorption could conceivable by used to accurately predict the modal gain dynamics of a rare-earth fiber in a high-power laser or amplifier²⁴. Such modal gain dynamics are critical for achieving excellent beam quality in a multi-mode fiber design.

While these results were obtained for conventional Yb-doped silica fibers, this technique can also be applied to Er, Bi, Tm, or other dopants, and this technique can also be applied to non-silica optical fibers. Of course the detector and imaging optics must be effective in a spontaneous emission band.

5. CONCLUSIONS

We have described a new non-destructive computerized-tomography technique for spatially resolving the distribution of SE and therefore gain and rare-earth dopant distribution in an optical fiber. The technique was applied to commercially available double-clad rare-earth doped large-mode-area high-power optical fibers. A comparison between the SE profile and the same fiber's refractive index profile suggests small, but intriguing, differences. Knowledge of the cladding pump absorption coefficient permits computation of the spatially resolved pump absorption coefficient, which could be a powerful tool for predicting modal dynamics in high power fibers. The technique could conceivably be applied to axially inhomogeneous fiber sample, such as a fusion splice, taper, grating, or even a coupler. This technique could also be applied to a variety of rare-earth dopants and also to non-silica optical fibers.

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