Measuring the resonant absorption coefficient of rare-earth-doped optical fibers

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A method for measuring the resonant absorption coefficient of rare-earth-doped optical fibers is introduced. It can be applied to a broad range of fiber designs and host materials. The method compares the side-collected spontaneous emission at two arbitrary locations along the fiber as a function of the pump wavelength to extract the absorption coefficient. It provides an attractive and accurate alternative to other available techniques. In particular, the proposed method is superior to the cut-back method, which destroys the sample and is prone to inaccuracies due to the cladding mode contamination. Moreover, it does not involve any mechanical movement, so it can be used for fragile optical fibers.

I. INTRODUCTION

Fiber lasers and amplifiers are widely adopted in industry and scientific research because of their high power, good beam quality, and ease of operation [11,12]. In order to design and optimize fiber lasers and amplifiers, it is essential to know the geometrical and optical properties of the optical fiber gain medium to a high degree of accuracy [3-6]. Such characteristics may be considerably different from those anticipated from the fiber preform and can be altered during the fiber drawing process. Therefore, it is important to accurately measure these characteristics directly in the fiber. An important property of a rare-earth-doped optical fiber is the resonant absorption coefficient \( \alpha_r(\lambda) \), which can be determined from the dopant density \( N_0 \) and the absorption cross section \( \sigma_{\text{abs}}(\lambda) \). However, \( \sigma_{\text{abs}}(\lambda) \) is strongly dependent on the host glass, which can be affected during the preform fabrication and drawing. The dopant density profile can also be modified during the fiber drawing because of diffusion; therefore, it is imperative to determine \( \alpha_r(\lambda) \) directly using the optical fiber.

In this work, we present a novel method that can be used to accurately determine \( \alpha_r(\lambda) \) in the presence of rare-earth ions in an optical fiber at all relevant wavelengths. The method is based on analyzing the emitted side-light, which contains both fluorescence and pump scattering at different locations along the fiber. It is a universal technique that can be applied to single-mode, multi-mode, large-mode-area, photonic crystal, and double-clad rare-earth-doped optical fibers. It is also applicable to fibers made from different materials such as ZBLAN, silica, or chalcogenides. Because the method does not involve the movement of any mechanical or optical components in the measurement process, it can be readily applied to fragile fibers [7], including highly tapered fibers [8].

The presented method is an alternative to the cut-back method, which is widely used to measure the absorption coefficient of optical fibers [9]. In the cut-back method, the output power from the fiber is measured by gradually cutting back the fiber from the end and reducing its length [9]. The cut-back method is destructive; therefore, it cannot be employed in experiments that need to be performed on a single piece of optical fiber. In a sensitive experiment, e.g. for laser cooling, even a slight sample-to-sample variation can affect the outcome; therefore, two pieces of the same fiber may not perform the same way and must be characterized individually [10-12]. Another issue involves the excitation of the cladding modes that contaminate the cut-back measurements in short pieces of the fiber [13]. Moreover, in the cut-back measurements of highly absorbing rare-earth-doped optical fibers, because the core must be pumped well below the saturation intensity, the output signal can be quite weak and even comparable to the cladding power contamination. Finally, the cut-back method involves undesirable mechanical processing such as cleaving, polishing, and inspecting the fiber that at best can be quite elaborate, and in cases involving fragile fibers totally impractical.

We already mentioned that our proposed method is highly advantageous for characterizing fibers for laser cooling. In a similar context, accurate determination of \( \alpha_r(\lambda) \) is essential for designing radiation-balanced lasers (RBLs) [14-24]. RBLs have been proposed as a way to mitigate the thermal issues in high-power fiber lasers, which have hindered the progress in power-scaling because of the thermally induced transverse mode instability [25-29]. RBLs operate based on the radiative cooling principle, in which the rare-earth-doped optical fiber is pumped at a wavelength, which is higher than the mean fluorescence wavelength of the active ions; therefore, the anti-Stokes fluorescence removes some of the excess heat [14]. In RBLs, the heat generated due to the quantum defect, parasitic background absorption of the pump and laser, and the non-radiative relaxation of the excited rare-earth ions is balanced against radiative cooling. RBLs pose stringent requirements on the
type and level of dopants, as well as the host materials. In particular, the parasitic background absorption ($\alpha_b$) must be quite small for RBLs to work. Our proposed method, when combined with the laser-induced temperature modulation spectrum (LITMoS) test developed in Sheik-Bahae’s research group [12], allows us to also accurately determine $\alpha_b$ for the doped fiber and the cooling efficiency of rare-earth doped fibers [10] [11].

II. THEORY

We refer to this new technique as “measuring the absorption coefficient via side-light analysis” (MACSLA). This method is based on the fact that when a rare-earth doped optical fiber is pumped far below the saturation intensity, the spontaneous emission power emitted from the side of the fiber is directly proportional to the pump power. The method compares the side-collected spontaneous emission at two arbitrary locations along the fiber as a function of the pump wavelength and employs the McCumber theory [30] to extract the spectral form of the absorption coefficient.

![Figure 1](image_url)

**Figure 1.** Schematic of the propagation of the pump power in the optical fiber and the collection of the spontaneous emission from the side of the rare-earth-doped optical fiber.

Figure 1 shows a schematic of the proposed method. The pump propagates through the core of the optical fiber from left to right. The pump wavelength is assumed to be in the proximity of the peak absorption wavelength such that $\alpha_r(\lambda)$ is much larger than $\alpha_b$. The pump intensity in the fiber core is assumed to be far below the saturation intensity; therefore, the pump power propagating in the core, $P_{\text{core}}(z)$, attenuates exponentially due to the absorption by the rare-earth dopants:

$$P_{\text{core}}(z) = P_0 \exp (-\alpha_r(\lambda) z), \quad (1)$$

where $P_0$ is input pump power in the core at $z = 0$.

The side-emitted spontaneous emission power is collected by two large-core high-numerical-aperture multimode optical fibers at points A and B along the fiber, which are separated by a distance $\Delta z$. The collection efficiencies of the two multimode fibers may be slightly different due to inevitable misalignments. Therefore, we can write

$$P_{\text{coll}}(z_A) = \gamma_A P_{\text{core}}(z_A), \quad (2a)$$
$$P_{\text{coll}}(z_B) = \gamma_B P_{\text{core}}(z_B), \quad (2b)$$

where $P_{\text{coll}}(z_A)$ and $P_{\text{coll}}(z_B)$ are the collected powers at points A and B, respectively. $\gamma_A$ and $\gamma_B$ are coefficients that relate the propagating power in the core to the collected spontaneous emission power, which also incorporate the coupling efficiencies to the multimode fibers at points A and B, respectively. We now divide Eq. 2 by Eq. 2a take the natural logarithm of both sides, and obtain:

$$r(\lambda) = \ln \left( \frac{\gamma_B}{\gamma_A} - \alpha_r(\lambda) \Delta z, \quad (3)$$

where

$$r(\lambda) = \ln \left( \frac{P_{\text{coll}}(z_B)}{P_{\text{coll}}(z_A)} \right), \quad (4)$$

In Eq. 3, $\alpha_r(\lambda)$ follows a strict spectral function of the form [31]:

$$\alpha_r(\lambda) \propto \lambda^5 S(\lambda) \exp \left( \frac{hc}{\lambda k_B T} \right), \quad (5)$$

where $S(\lambda)$ is the emission power spectral density measured by the optical spectrum analyzer, $h$ is the Planck constant, $k_B$ is the Boltzmann constant, and $c$ is the speed of light in vacuum. We also assume that the ratio $\gamma_B/\gamma_A$ is wavelength independent over the narrow range of wavelengths used in this experiment. Therefore, the left-side in Eq. 3 ($r(\lambda)$) must also follow the spectral form in Eq. 5 when the pump wavelength is varied. Because the spectral shape of $\alpha_r(\lambda)$ is obtained from Eq. 3 all that is needed is to find its overall magnitude by balancing the left-side and right-side in Eq. 3 over the respective wavelengths. Therefore, we replace $\alpha_r(\lambda)$ in Eq. 3 with $\alpha_r^p \times \alpha_r^{\text{peak}}(\lambda)$, where $\alpha_r^{\text{peak}}(\lambda)$ is the absorption coefficient normalized to its peak value, $\alpha_r^p = \alpha_r(\lambda_{\text{peak}})$. This way, we can determine both $\gamma_B/\gamma_A$ and $\alpha_r^p$ through a fitting procedure that involves measurements of $r(\lambda)$ and $\alpha_r(\lambda)$ at multiple wavelengths near the peak absorption wavelength.

III. EXPERIMENT

In our experiment, we used a commercial Yb-doped optical fiber (SM-YSF-LO-HP, Nufern, Inc.) to demonstrate the utility of the MACSLA method. SM-YSF-LO-HP is a low-doped Yb-silica single-mode and single-clad optical fiber. As we mentioned in the previous section, in order to use the Beer-Lambert exponential decay form in Eq. 1, the pump intensity must be kept considerably below the saturation intensity. As such, we first measured...
the pump saturation power \( (P_{\text{sat}}) \) by pumping the core of the doped fiber \( (P_{\text{core}}) \) and measuring the side spontaneous emission power \( (P_{\text{spont}}) \) for different values of the pump power at 976 nm wavelength. The measurements were fitted to the functional form of the saturated power in a doped fiber \[32\]

\[
P_{\text{spont}}(P_{\text{core}}) \propto \frac{P_{\text{core}}}{1 + P_{\text{core}}/P_{\text{sat}}}
\]  

For our fiber, the saturation power was determined to be 966 µW. In our later experiments, \( P_{\text{core}} \) was kept below 5% of the saturation power to make sure that Eq. 1 could be reasonably applied.

For the fitting procedure, we chose seven different pump wavelengths near the absorption peak wavelength for the Yb-silica fiber (\( \lambda_{\text{peak}} = 977 \) nm) by tuning the operating wavelength of the CW Ti:Sapphire laser. For each wavelength, the emission signal power was measured at positions A and B over sufficient time windows until the desired signal-to-noise-ratio was achieved. Seven independent measurements were also performed at each wavelength to obtain the proper statistics and error-bars. The distance between points A and B was also measured by a digital caliper. The power spectral density \( S(\lambda) \) of the Yb-silica fiber is shown in Fig. 3. The inset shows the resonant absorption coefficient, which is normalized to its peak value, and is calculated by using the McCumber theory \[30\].

**IV. RESULTS AND DISCUSSION**

The fitted line over the experimental measurements related to Eq. 3 are shown in Fig. 4. The points (with error-bars) indicate the values of \( r(\lambda) \) measured at seven different wavelengths, and the fitting curve comes directly from the resonant absorption spectrum shown as the inset in Fig. 3. The outcome of the fitting procedure was the peak value of the absorption coefficient \( \alpha_p = 0.198 \pm 0.008 \) cm\(^{-1}\). While unimportant to the procedure, the fitting also resulted in \( \gamma_B/\gamma_A = 0.69 \). Our result for \( \alpha_p \) should be compared with the value reported by the vendor, which is \( 0.220 \pm 0.033 \) cm\(^{-1}\). We also performed cut-back measurements, which resulted in \( 0.203 \) cm\(^{-1}\).

We would like to comment on a recent pioneering method proposed by Min Oh, et al. \[33\], where they also
FIG. 4. The points with error-bars indicate the values of $r(\lambda)$ from Eq. 4 measured at seven different wavelengths near the peak of the resonant absorption coefficient. The fitting curve comes directly from the resonant absorption spectrum shown as the inset in Fig. 3. The fitting parameters are $\alpha_p$ and $\gamma_B/\gamma_A$.

employ the side-light analysis to measure $\alpha_r(\lambda)$. In their procedure, the doped fiber is pumped at a fixed wavelength and the spontaneous emission is measured at different positions along the fiber by using an optical spectrometer. They measure $\alpha_r$ at the respective wavelength by fitting the side-collected power to the Beer-Lambert exponential decay form in Eq. 1. In their method, the coupling efficiency to the side-collecting fiber is assumed to remain unchanged at different locations along the doped fiber. This assumption is applicable when the measured fiber is multimode with a large core; however, it may result in inaccuracies if the fiber is single-mode with a small core. Moreover, the requirement to keep the pump power far below the saturation power, which is on the order of 1 mW in single-mode fibers, necessitates high-sensitivity spectrometers for adequate signal-to-noise-ratio.

In summary, the MACSLA method provides an attractive and accurate alternative to other techniques for measuring the resonant absorption coefficient in rare-earth-doped optical fibers. In particular, it is superior to the cut-back method, which destroys the sample and is prone to inaccuracies due to the cladding mode contamination. When combined with the LITMoS test [12, 34], the MACSLA method allows one to also determine the parasitic background absorption coefficient ($\alpha_b$). In laser cooling experiments and RBLs, the cooling efficiency is improved by reducing the ratio of background absorption coefficient to the resonant absorption coefficient ($\alpha_b/\alpha_r$) [10–12, 33–37]. Our techniques enables an accurate determination of $\alpha_b$ that is essential to design and interpret such radiative cooling experiments.

The methods presented here can potentially be modified and adopted for measuring $\alpha_r$ in bulk materials; e.g. in rare-earth doped crystals. One of the main advantages of the MACSLA method is the fact that it does not require precise alignments, which makes it suitable for commercial applications. Moreover, the technique does not require an accurate knowledge of the actual coupled power into the medium, hence one is not worried about surface reflections and scatterings. In practice, the lock-in amplifier may not be required if one uses a high-sensitivity detector such as a low threshold avalanche photodiode.

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