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Characterizing Gain Properties of a Yb-doped Silica Transverse Anderson Localizing Fiber

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Abstract: A detailed analysis of a novel Yb-doped silica transverse Anderson localizing optical fiber is performed. Comparisons between measurements and theory determine the parasitic attenuation, gain, saturation power, and the number of modes.

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Anderson localization (AL) is defined as the absence of wave diffusion in random scattering media [1]. A two-dimensional manifestation of AL in transverse directions to light propagation can be realized in optical fibers as transverse Anderson localization (TAL) [2]. This is accomplished by having the entire fiber, or a large diameter core of the fiber, with a highly randomized transverse index profile, maintaining invariance along the length of the optical fiber [3,4]. TAL optical fibers (TALOFs) with embedded gain materials can have interesting (random) laser properties, including a relatively broad and stable spectrum and a directional beam. The first demonstration of a TALOF laser was carried out by Abaie et al. [5], where they filled the air-channels in an air-glass TALOF with a rhodamine-6G dye, pumped the active TALOF with a green laser, and observed lasing using the 4% reflections at the facets of the TALOF.

The natural next step is to explore active TALOFs using an all-solid-state gain material. We recently fabricated, at Clemson University, a new disordered optical fiber that features an all-solid-state core partially doped with ytterbium. Our goal is to make a TALOF-based random laser using this fiber; however, working with a random fiber has its unique challenges, and the cavity design must be customized to the quite non-trivial properties of the active TALOF. As such, it is essential to characterize the active TALOF in detail, especially its gain properties, to optimize the design of the cavity for reasonable performance. Here, we present comparisons between measurements and theory to determine the parasitic attenuation, gain coefficient, saturation power, and the number of modes supported in this active TALOF. These parameters are essential to understand the active behavior of the fiber, including the generation of amplified spontaneous emission (ASE), and eventually building a laser cavity.

Our general approach to analyzing the active TALOF consists of taking measurements of the input pump power (before free-space coupling into the TALOF) and the output power, either of the pump or the generated ASE. The output pump and ASE can be measured separately by using low-pass or high-pass optical filters.

Our first task is to determine the background loss coefficient. We perform this at a wavelength outside the absorption band of ytterbium. We used a He-Ne laser operating at 633nm wavelength and expect that the results provide a reasonable estimate of the background loss coefficient of TALOF, which is dominated by scattering, at around one-micron wavelength. We measure the output pump power versus the input pump power for several lengths of TALOF. The measurements fit very well to $P_{\text{out}} = \varepsilon_h P_{\text{in}} e^{-\alpha^b L}$, where L is the length of each TALOF, P_{in} is the input power, P_{out} is the measured output power, α^b is the attenuation coefficient, and ε_h is the coupling efficiency into the TALOF. We find that $\varepsilon_h = 85.8\%$ and $\alpha^b = 1.39\text{m}^{-1}$. The results match our expectation of a lower-than usual coupling efficiency and a relatively large attenuation due to scattering.

When pumping the TALOF at 975nm wavelength, in the range from 100mW to 9W of power, we expect a nearly quadratic relationship for the output pump power versus the input pump power. The quadratic behavior stems from a Taylor expansion in the ratio of the pump power to the saturation power of the fiber:

$$P_p = \varepsilon_p e^{-\alpha_p z} P_{p0} + \left(e^{-\alpha_p z} - e^{-2\alpha_p z}\right) \frac{\alpha_p^r}{\alpha_p} \frac{1}{P_p^{\text{sat}}} \varepsilon_p^2 P_{p0}^2, \qquad \alpha_p = \alpha^b + \alpha_p^r \tag{1}$$

The zeroth order term is the usual Beer-Lambert law, where α_p is the total pump attenuation coefficient and consists of both background attenuation represented by α^b and resonant absorption characterized by α_p^r. The next quadratic term

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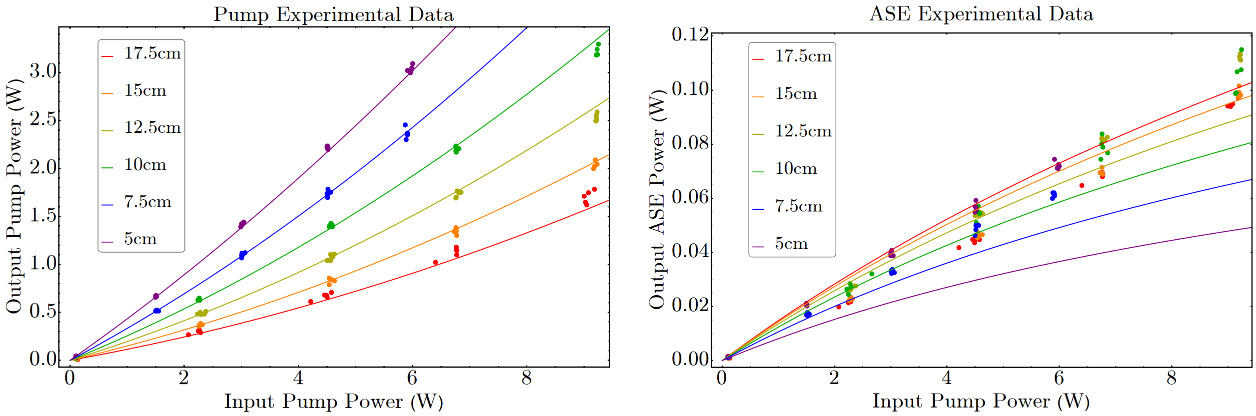

Fig. 1. Plotting of the experimental data when measuring the output pump and ASE versus the input power when pumping the TALOF with 975nm light. Each color represents a different length of fiber

(first order Taylor expansion) is inversely proportional to the saturation power. By measuring the output pump power versus the input pump power for a variety of TALOF lengths, we can use this equation to determine α_p^r, as well as the saturation power $P_p^{\rm sat}$. Note that we use the value α^b as determined by the previous experiment using the He-Ne laser as a reasonable estimate for this part.

In Fig. 1, left panel, we show the measurements of the output pump power versus the input pump power for six different lengths of the TALOF. The quadratic behavior mentioned above is quite clear. We use a nonlinear fit algorithm to determine the optimal values of ε_p, α_p^r, and $P_p^{\rm sat}$. The coupling efficiency of the fiber at 975nm was determined to be $\varepsilon_p = 72.1\%$, the resonant absorption $\alpha_p^r = 9.4\mathrm{m}^{-1}$, and the pump saturation $P_p^{\rm sat} = 7.7$W. The coupling coefficient of the pump power at 975nm is somewhat lower than that of the He-Ne laser, which is expected because the 975nm pump has a higher mode profile than the He-Ne laser.

Another critical parameter for this fiber is the number of modes that can participate in the lasing process. This parameter is especially important because it can determine the amount of ASE power generated from the TALOF. To determine the number of modes supported by the fiber, we pump various lengths of the TALOF and measure the output ASE versus the input pump power for each length. As mentioned earlier, the residual pump power at the output is eliminated by using a long-pass filter with a cutoff wavelength of one micrometer. The relevant equation for the generation of ASE can be written approximately as

$$\frac{dP_s}{dz} = \alpha_s^r \left[\frac{(P_p/P_p^{\rm sat})(\beta_p/\beta_{ps}) - 1}{1 + P_p/P_p^{\rm sat}} \right] P_s - \alpha^b P_s + g_s \frac{(P_p/P_p^{\rm sat})\beta_p}{1 + P_p/P_p^{\rm sat}} \Pi_s \tag{2}$$

where the goal is to find the unknown parameter Π_s, given that the other constants in the equation are known parameters. We have $\Pi_s = (\mathbb{V}_s^2/2)hc^2\delta\lambda/\lambda_s^3$, where λ_s is the representative wavelength of ASE and $\delta\lambda$ is its bandwidth, and $\mathbb{V}_s$ is the effective V-number of the core of the TALOF. The ASE total absorption coefficient α_s^r and gain coefficient g_s can be estimated using the value of α_p^r. β_p and β_{ps} are defined as $\beta_p = \sigma^a(\lambda_p)/(\sigma^a(\lambda_p) + \sigma^e(\lambda_p))$, $\beta_s = \sigma^a(\lambda_s)/(\sigma^a(\lambda_s) + \sigma^e(\lambda_s))$, and $\beta_{ps} = \beta_p\beta_s/(\beta_p - \beta_s)$. Here, σ^a/σ^e are the absorption/emission cross-sections. The best fit of ASE output measurements for the experiments shown in the right panel of Fig. 1 result in $\mathbb{V}_s \approx 1206$, which is in the expected range of the V-number of the TALOF.

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