Increasing the power threshold in fiber amplifiers considering both the transverse mode and Brillouin instabilities

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Abstract: We study the Brillouin instability and the transverse mode instability in a combined computational model for fiber amplifiers. We find the optimal core diameter, which leads to the highest power threshold and output power. © 2022 The Authors

Fiber amplifiers for high-energy applications have seen an impressive increase in their output power in recent years [1], but this rapid growth has been limited by nonlinear effects that make it difficult to increase the power. The lowest-order nonlinear effects that have plagued fiber amplifiers include the Brillouin instability (BI) and the transverse mode instability (TMI). TMI is thermally seeded by quantum defect heating [2,3]. The constructive and destructive interference between the fundamental mode and higher-order modes (HOMs) leads to a temperature grating along the fiber due to the quantum defect. Since the refractive index of the fiber material depends on temperature, a refractive index grating is generated by the temperature grating. The refractive index grating induces coupling between the fundamental mode and HOMs, which leads to a time-dependent transverse mode output. BI arises from thermally-seeded acoustic waves and leads to a grating in the index of refraction due to electrostriction [4], which can couple the forward-propagating mode to a backward propagating Stokes mode [4]. The result can be a large drop in output power with much of the power going into reflected light that is directed toward the pump or laser source. In order to further increase the output power of fiber amplifiers, nonlinear effects like BI and TMI must be suppressed using optimized fiber design. This design requires computationally efficient modelling techniques that include BI and TMI in one simulation, which has yet to be done due to the wide disparity in the characteristic times for these two effects. In this paper, we use a multi-time-scale approach [5] to overcome this difficulty, and we study the pump power threshold predicted by a simulation that includes both BI and TMI. We also determine the optimal core diameter that leads to the largest output power considering both BI and TMI. Including both nonlinear effects in one simulation will lead to optimized fiber parameters and enhanced suppression techniques so that the output power may be increased.

Both instabilities impose limits on the output power of Yb-doped fiber amplifiers. These instabilities depend differently on the core size of the fiber. Increasing the diameter of the fiber core will increase the BI pump power threshold since the intensity is decreased if the total operating power stays the same. On the other hand, increasing the core diameter of the fiber leads to an increased interaction between the fundamental mode and the first higher-order mode, thereby decreasing the TMI pump power threshold. Hence, there is a tradeoff between the suppression of BI and TMI when changing the core diameter of the fiber.

There is also a large difference in time scale over which BI and TMI evolve. BI, which is generated due to the interaction between an optical mode and acoustic mode, has a response time on the scale of nanoseconds, whereas TMI, which is associated with thermal diffusion, has a response time on the scale of milliseconds. We used a multi-time-scale approach [5] that allows us to simultaneously model BI and TMI. We use the phase-matched model for TMI [6] so that we may reduce the number of required longitudinal points in simulation, which reduces the computational intensity, and allows us to practically model BI along with TMI in one simulation.

To quantify the impact of BI in our model, we define the reflectivity $\rho_S = P_S(0)/[P_S(0) + P_{\mathrm{out}}]$ where $P_S(0)$ is the optical power residing in the Stokes mode at the fiber input, and P_{out} is the averaged output power. The impact of TMI is quantified by the HOM content $\rho_H = P_{H,\mathrm{out}}/\, P_{\mathrm{out}}$ where $P_{H,\mathrm{out}}$ is the output power residing in the HOM. The pump power threshold is defined as when either $\rho_S = 1\%$ or $\rho_H = 1\%$. While TMI has often been studied well beyond this limit, operating over this threshold is of little interest since the output beam quality is unacceptably degraded once the HOM content reaches ~1%. We limited this study to a 1.6-m-long fiber [3] in order to compare our results to prior work.

Figure 1(a) shows ρ_H as a function of pump power and time for a core diameter of 30 μm in which we only considered TMI in the model. The dashed-white line superimposed in Fig. 1(a) marks the TMI threshold when the maximum HOM content reaches 1%. For pump powers under 600 W, there is little growth in the HOM content. As the pump power increases to above 600 W, there is a rapid power transfer between the fundamental mode and HOM, which leads to a rapid increase in the HOM content. Figure 1(b) shows max[$\rho_H(t)$] as a function of pump power for a core diameter of 30 μm according to Fig. 1(a). The horizontal dotted black line in Fig. 1(b) marks the 1% power threshold criterion, and the vertical dotted black line marks the pump power threshold at 697 W. The threshold for BI is calculated in a similar fashion. Figure 1(c) shows the reflectivity ρ_S as a function of pump power and time for a core diameter of 30 μm, while we only consider BI in the model. The horizontal white line in Fig. 1(c) marks the pump power threshold for the BI simulation at 157 W, where further increase of the pump power leads to significant reflected power, which is characterized by the large ρ_S. Figure 1(d) shows the average of ρ_S over the last 50 ns in Fig. 1(c) as a function of pump power. The horizontal dotted black line marks the 1% threshold criterion, and the vertical dotted black line marks the BI pump power threshold at 157 W. Figure 1(e) shows the complete pump power threshold along with the output power as a function of core diameter when both BI and TMI are modeled simultaneously. The pump power threshold and output power are optimized when the core diameter is 40 μm, where BI and TMI make almost equal contributions. For core diameters less than 40 μm, BI dominates since the relatively small core increases the intensity. Increasing the core diameter lowers the intensity which suppresses BI but increasing the core diameter above 40 μm increases the interaction between the fundamental mode and HOM, which causes a drop in the pump power threshold.

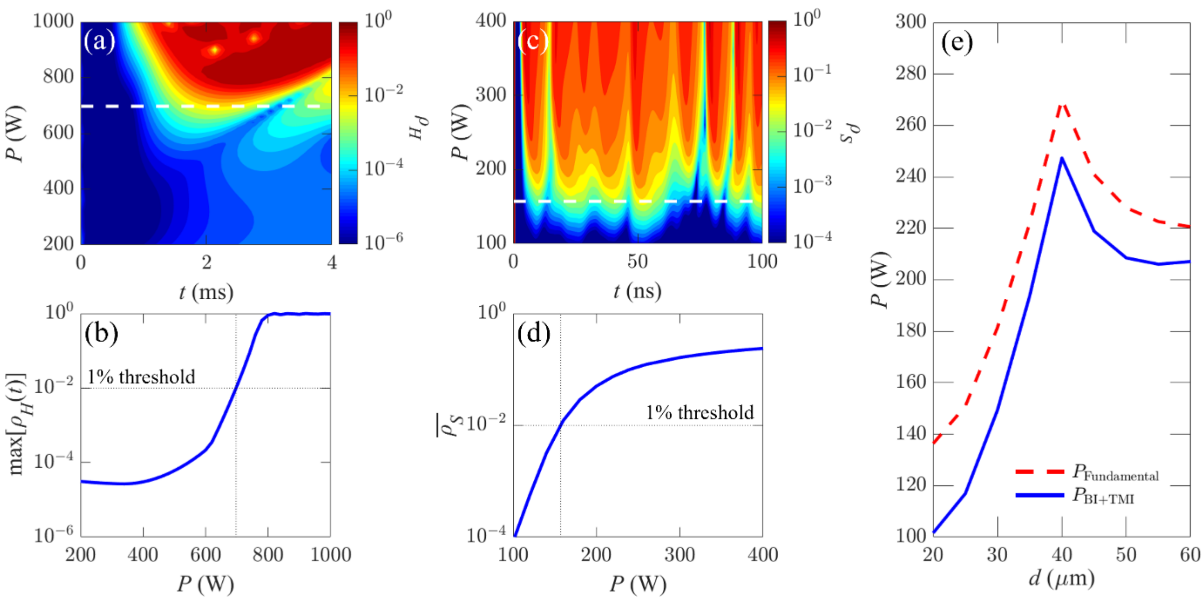

Fig. 1. (a) HOM content ρ_H as a function of pump power and time. (b) Maximum HOM content as a function of pump power. (c) Reflectivity ρ_S as a function of pump power and time. (d) Time average of the reflectivity $\overline{\rho_S}$ as a function of pump power. (e) Full BI+TMI pump power threshold, $P_{\rm BI+TMI}$ (blue), and the output power for the fundamental mode, $P_{\rm Fundamental}$ (red), as a function of core diameter.

In conclusion, we studied the pump power thresholds predicted by a combined BI and TMI model. At a core diameter of 40 μm where the threshold and output power are maximized, both instabilities contribute equally to the pump power threshold.

Previous modeling of BI and TMI has treated them separately. Including both nonlinear effects in one simulation is required to simultaneously suppress BI and TMI. We have used the phase-matched model, combined with a multi-time scale method to treat both simultaneously for the first time.

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