Invited Paper

Thermally induced mode instability in high power fiber amplifiers

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ABSTRACT

We present a physical model that may describe the observed phenomenon of modal instability in high power fiber amplifiers. In the power range of several hundred watts, large-mode-area, cladding-pumped, Yb^{3+}-doped fiber amplifiers (both step-index and photonic crystal fibers), exhibit a sudden transition in the output beam profile from the fundamental mode to a higher order mode. We show how this behavior can be caused by a thermally induced mode coupling that leads to exponential gain of the higher order mode, and we implement a numerical model that quantitatively predicts the instability threshold for any large-mode-area step index fiber amplifier.

Keywords: Fiber amplifier, mode instabilities, Yb-doped fiber, large mode area

1. INTRODUCTION

As the power produced in narrow bandwidth fiber amplifier power has risen to the kW level a new performance limiting nonlinearity has been encountered which manifests itself as an instability in the transverse mode content at the amplifier output. The threshold for this effect varies from 100 W to 2 kW or more, depending on the fiber design. Several research groups have reported this effect, either anecdotally or in publications, and perhaps all researchers working on these devices have encountered the instability.[1,2] We present here a physical model for this process, along with a quantitative numerical model that can be applied to any large mode area (LMA) step index fiber amplifier and perhaps to photonic crystal fiber amplifiers as well. In our model a moving thermal grating couples the two lowest order modes, LP_{01} (mode 1) and LP_{11} (mode 2), to produce exponential growth of mode 2. The gain in a typical kW fiber amplifier is sufficient to amplify signals in mode 2 from the level of a single photon of quantum noise to the kW level, leading to complete power transfer from mode 1 to mode 2, mimicking the observed mode instability. This newly discovered effect presents a limit to amplifier performance that is just as fundamental as stimulated Brillouin or Raman scattering. Like them, it must be suppressed in order for a LMA amplifiers to reach the multi kW level while producing good beam quality.

2. PHYSICAL MODEL

Our physical model of mode coupling is based on a light-induced refractive index grating that couples light between modes 1 and 2. At each longitudinal location in the core, interference between modes 1 and 2 produces a transverse irradiance profile that is in general asymmetric. The light is more intense on one side than the other, depending on the relative phases of the two modes. Where the light is more intense the upper state is more depleted, leading to stronger pump light absorption there. Because the heat deposition rate is equal to the absorbed pump power multiplied by the quantum defect, the heat deposition is higher where signal irradiance is higher, and this causes a locally higher temperature which in turn raises the refractive index higher via the thermo-optic effect. If the light in the two modes has identical spectra, the thermal grating in the fiber core is stationary along the fiber and coincides with the irradiance grating. This is similar to a Kerr effect. It is well known that the Kerr effect does not lead to mode coupling but only to cross phase modulation because there is no phase shift between the index grating and the irradiance grating.

However, if the light in modes 1 and 2 has slightly offset frequencies, the irradiance grating moves along the fiber, either up stream or down stream, depending on the sign of the frequency offset. The thermal grating lags the irradiance grating due to thermal diffusion and this creates the phase offset between the irradiance grating

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and the index grating which is necessary for coupling light between the modes. We will show that if the frequency offset leads to a beat time approximately equal to the thermal diffusion time across the core the mode coupling is maximized. For typical fiber designs the optimum frequency offset is in the range 1-2 kHz. Further, the strength of the grating and thus the strength of the mode coupling is proportional to the strength of mode 2, assuming it is much weaker than mode 1, so the gain of mode 2 is exponential in z. Our numerical analysis will show that the gain is sufficient to amplify quantum noise in mode 2 to the kW level in typical high power fiber amplifiers.

We can estimate the gain necessary to amplify quantum noise to the kW level. If we assume one photon in mode 2, the starting level for mode 2 power is $h\nu/\tau$ where τ is a characteristic time which we can take to be the inverse of the gain bandwidth, or approximately 1 ms. The exact starting value matters little since the exponential gain is enormous. The starting power in mode 2 calculated this way is 2×10^{-16} W. Amplifying this to 1 W requires a gain of 157 dB. For comparison, this is more than twice the Raman gain of 70 dB required to reach the Raman threshold in fibers. The difference is due to the kHz linewidth for thermal mode coupling compared with the THz linewidth of Raman gain.

3. NUMERICAL MODEL

We have incorporated our physical model into a numerical model capable of quantitative predictions of mode coupling thresholds.[3] The model combines a beam propagation model that can propagate any time-dependent optical field stepwise along the fiber using FFT propagation methods. This is combined with a thermal model that computes the time dependent temperature and index profile at each z location using the local pump power and signal field in the rate equations describing the Yb^{3+} level populations. We solve the rate equations in the steady state limit, which is appropriate for the high powers in the amplifiers of interest. The oscillating irradiance profile at z causes an oscillating heat profile that acts as the source in the time-dependent heat equation which we integrate to find the oscillating temperature and index profiles. The time dependent optical phase $\phi(x, y, t)$ due to the oscillating index profile is used in the propagation step to account for the moving index grating. The time dependent population inversion is also used to compute the localized amplification of the signal field. In solving the population and temperature equations several cycles of the mode oscillation are integrated to allow temperature transients to decay. At regular z intervals the signal light is decomposed into transverse modes and into frequencies.

4. TEST FIBER

We have applied our numerical model to the test fiber design specified in Table 1. The parameters of the test fiber do not represent any particular fiber but are representative of the LMA fiber amplifiers used in high power applications.

Table 1. Test step index fiber amplifier parameters used in demonstrating our numerical model.

d_{core}	30 μm	d_{dopant}	30 μm
d_{clad}	250 μm	N_{Yb}	3.25×10^{25} m^{-3}
λ_p	976 nm	λ_s	1064 nm
σ_p^a	2.47×10^{-24} m^2	σ_p^e	2.44×10^{-24} m^2
σ_s^a	5.80×10^{-27} m^2	σ_s^e	2.71×10^{-25} m^2
P_p	$0 - 1200$ W	P_s	30 W
dn/dT	1.2×10^{-5} K^{-1}	L	5 m
n_{core}	1.452	n_{clad}	1.45
τ	901 μs	R_{bend}	∞

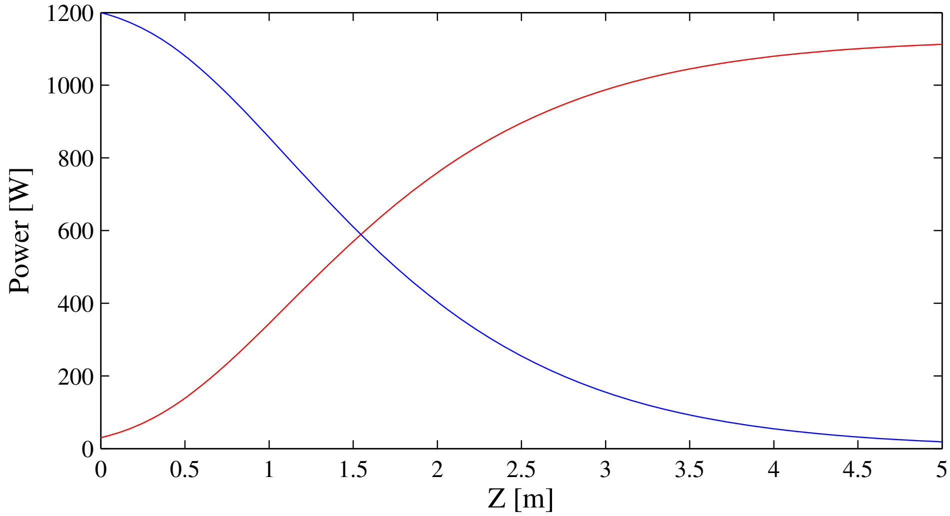

Figure 1. Signal (red curve) and pump (blue curve) powers for the co pumped test fiber. Mode coupling is not included in this model.

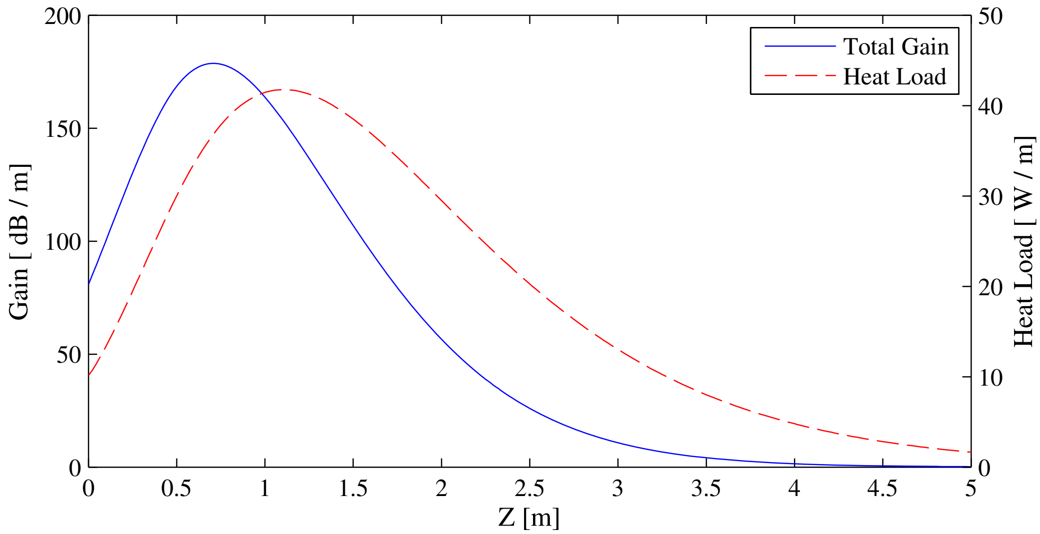

Figure 2. Small signal gain of mode 2 due to mode coupling due to quantum defect heating. The signal and pump powers shown in Fig. 1 are used to compute the gain at discrete points along the fiber. The mode coupling gain is much larger than the laser gain. The integrated gain in this example is 290 dB, which is well above the estimated threshold of 157 dB.

We show the performance of the test fiber in Fig. 1 in the absence of mode coupling. The fiber is co pumped by 1200 W, and the signal is seeded with 30 W in mode 1. No thermal effects are included in this run. In Fig. 2 we show the corresponding computed small-signal, thermally-induced gain of mode 2. The integrated gain is 290 dB, well above the 157 dB estimated threshold for mode instability. The gains are computed at 20 z locations evenly spaced along the fiber using propagation lengths of 3.6 mm which is one beat length for modes 1 and 2. This gain computation takes approximately an hour.

We verified the quick gain computation above by propagating continuously from the fiber input to its output. This run, which takes several days, is shown in Fig. 3. The initial power in mode 2 is 10^{-16} W, corresponding to the quantum noise level. After 1.2 m mode 2 reaches threshold and rapidly depletes mode 1. Thereafter the power remains in mode 2 in this example. The light in mode 2 is shifted 2 kHz to the red of mode 1. If the

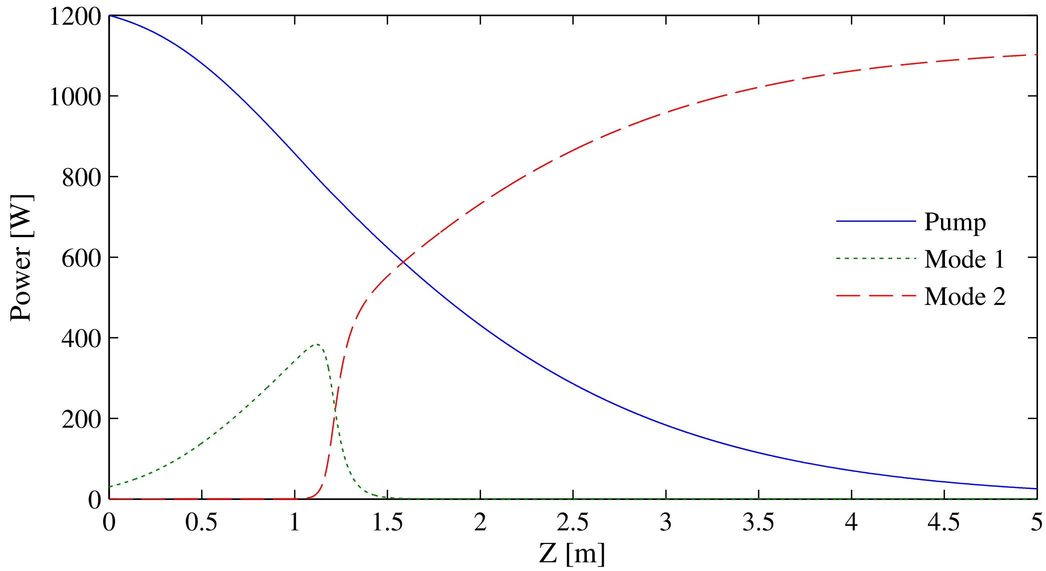

Figure 3. Evolution of powers in the pump, mode 1, and mode 2 for the test fiber amplifier.

pump power is increased, the light is transferred from mode 2 back into mode 1 but most of the mode 1 power is now shifted another 2 kHz to the red.

By reducing the input pump power we find the test fiber has an instability threshold of 800 W of pump light. This is close to the observed threshold powers in 25 μm diameter core step index fibers with 400 μm diameter pump cladding. This agreement is gratifying because we have no adjustable parameters in our model.

5. LINEAR ABSORPTION

Based on literature reports, the instability threshold is considerably lower for larger core photonic crystal fibers. In some cases the threshold is as low as 100 W. We have modeled these as well. We find the agreement with experiment is less satisfactory. The model thresholds are approximately twice the measured thresholds. Considering that the photonic crystal fibers may have substantial loss of mode 2 that we have not included, the agreement may be still worse. One possible explanation is additional heating due to dissipative absorption of the signal light. This heating can enhance the mode coupling gain. Considering that the quantum defect heating amounts to less than 10% of the absorbed pump power, an absorption of 10% of the signal power might reduce the mode instability threshold by perhaps a factor of two. This level of loss is seems well within the limit allowed by typical reported efficiencies for Yb-doped high power amplifiers. Typical slope efficiencies are 80% which leaves 10-15% of the absorbed pump power unaccounted for. We verified the threshold reduction by approximately a factor of two by adding a loss of 0.45 dB/m to the signal with all of the absorbed power converted to heat.

6. CONCLUSION

Our numerical model, with no adjustable parameters, appears to agree well with all documented features of mode instability. It predicts threshold powers close the observed values, it predicts complete power transfer from mode 1 to mode 2 within a narrow transition zone, it is immune to signal linewidth, at least for widths less than several cm^{-1}. Our next steps are to make further quantitative comparisons with experiment, and to perform parametric studies to learn how to maximize the instability threshold power. For narrow linewidth signals it will be necessary to accommodate SBS suppression as well as mode instability suppression. An SBS model will be used in conjunction with the mode coupling model to accomplish this.

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