SAND2007-7871C

Numerical Simulations of Yb^{3+}-Doped, Pulsed Fiber Amplifiers: Comparison with Experiment

R.L. Farrow, S.W. Moore, P.E. Schrader
Sandia National Laboratories, P.O. Box 969, Livermore, CA 94551
Email: farrow@sandia.gov, seamoor@sandia.gov, peschra@sandia.gov

A.V. Smith
Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185
Email: arlsmit@sandia.gov

Abstract: We have developed a numerical simulation of cw-pumped Yb^{3+}-doped fiber amplifiers seeded by pulses at 1064 nm. Results compare well to measurements of longitudinal upper-level ion populations and of output pulse energy versus pump power.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators, (140.3510) Lasers, fiber.

1. Introduction

Numerous applications calling for compact, high-brightness pulsed lasers have pushed the development of fiber lasers toward ever higher peak powers. To avoid nonlinear effects and maximize output power it is important to maximize doping density, pump power, and mode area. Accurate laser and amplifier simulations are thus required to consider strong population inversions with the possible presence of ASE and to quantitatively treat spatial hole burning of the gain. Moreover, fiber bending, when combined with large mode areas, results in large displacements and distortions of fiber mode fields [1], potentially affecting energy extraction efficiency. Thus, it is also necessary to include bend-sensitive, three-dimensional descriptions of mode fields and populations [2].

We have developed a quasi-3D model for an end-pumped, seeded fiber amplifier that describes the longitudinal variation of signal, ASE, and pump fields and two-level ion populations. In addition, a bent-waveguide modal analysis is used to describe the radial dependence of signal and ASE fields, and the radial population distribution includes the effects of spatial hole burning by the fields. To describe strongly saturated amplifiers at high seed-pulse repetition rates, the simulation solves time-dependent rate equations for the fields and populations. A more detailed description of the simulation will be presented elsewhere; here, we report comparisons with measurements of upper-level ion populations (i.e., inversion) along the fiber and of output pulse energy versus pump power.

2. Upper-level population and small-signal gain

Quantitative prediction of upper-level population distribution is central to the ability of the simulation to correctly predict amplifier gain and efficiency. We solve numerous coupled rate equations for the signal, pump, and ASE fields; the latter two used up to 200 wavelengths in the absorption/emission region of Yb^{3+} (900-1100 nm). To test the steady-state predictions of upper-level populations, we measured the Yb^{3+} fluorescence power emitted at right angles to the axis of a single-mode double-clad fiber at various positions along the fiber (10.9-µm diameter core, 125-µm diameter cladding, 6.4×10^{25} m^{-3} doping; Nufern). A long-pass filter was used in front of a Ge photodiode to reject pump contributions. The fiber was suspended in a straight line and cladding-pumped at one end by a ~976-nm diode pump laser. The pump spectrum was measured and used in the simulation for each pump power. Small-signal gain measurements at 1064 nm were used to put the fluorescence power measurements on an absolute basis in terms of upper-level population fraction (inversion) using a spectral model for the Yb^{3+} absorption and emission cross sections and adjusting a single normalization factor for all the measurements.

The results are indicated by symbols in Fig. 1; simulation results are shown as curves and used no adjustable parameters. At the lowest pump power (diamonds) corresponding to a small signal gain G_{ss} = 10.4 dB, the inversion decreases smoothly from ≈20% to ≈10% in the copropagating direction as a result of pump absorption. The simulation over predicts the inversion at this very low excitation, an effect we are investigating. At higher pump powers, the inversion profile is peaked slightly to the left of midpoint (toward the pumped end) as a result of depletion by ASE; the calculations reproduce this shape and are in closer agreement with the inversion magnitudes. At the highest pump power (most relevant for high-power operation), corresponding to G_{ss} = 27.8 dB, the measurements and simulation are in good agreement. Here, the simulation predicts G_{ss} = 25.7 dB; moreover, it agrees with the measurements to within ≈2 dB for all but the lowest pump power.

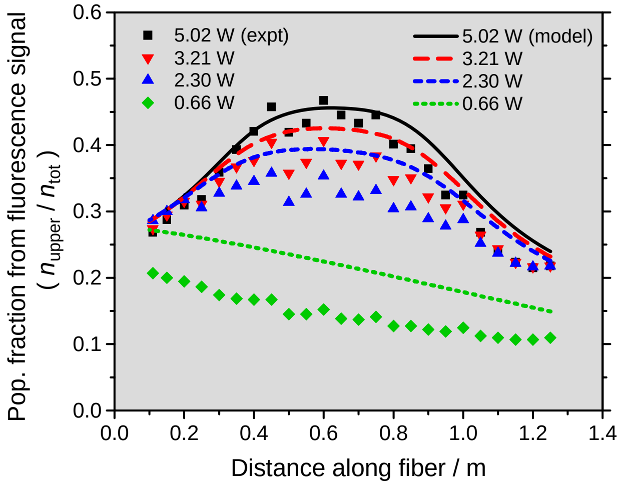

Fig. 1. Experimental upper-level Yb^{3+} population fraction (symbols) at various launched pump powers. Simulation results are given by the solid and dashed lines. Pumping was from left to right.

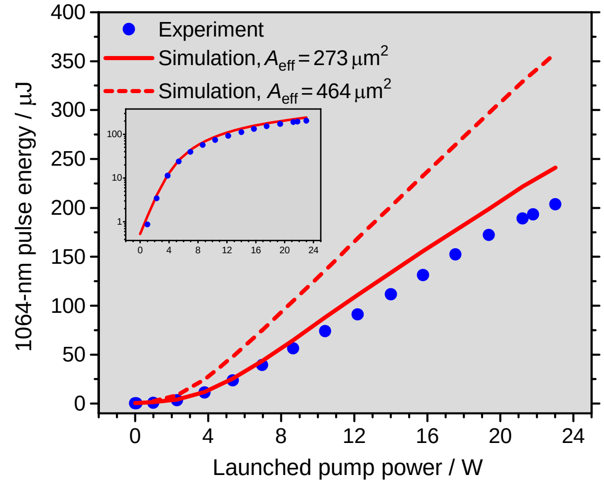

Fig. 2. Experimental pulse energy measurements (symbols) vs. pump power. Simulation results are given by the solid and dashed lines, with and without the effects of fiber coiling included, respectively. The fiber had a core/cladding diameter of 30/250 µm and was seeded with 1.2 µJ pulses at 36 kHz repetition rate and 1064 nm wavelength. Yb^{3+} doping concentration was 6.4×10^{25} m^{-3}.

3. Output pulse energy and effects of coiling

Prediction of absolute inversion profiles and G_{ss} is a stringent test for models of power amplifiers operating with strongly saturated gain. In this case, factors controlling energy extraction such as transverse mode-field overlap with the inversion profile are also important. Figure 2 shows output pulse energy measurements compared to simulation results for a 1064-nm seeded amplifier; the inset axes show the same results plotted with a logarithmic y axis. From the inset plot, it can be seen that the output energy departs from an exponential increase above ≈4 W of pump power; the gain is strongly saturated above ≈6 W. The calculations using the experimental fiber coiling radius of 27 mm (selected to provide high-order mode filtering) are in excellent agreement with the data. Only the fundamental LP_{01} mode was assumed to be present as indicated by external propagation measurements where an M^2 value of <1.2 was obtained. The LP_{01} effective area A_{eff} was calculated to be 270 μm^2 in the coiled fiber. However, the same calculations assuming a straight fiber gave a larger A_{eff} = 460 μm^2 and predicted ≈50% higher pulse energy at 23 W of pump power, significantly higher than observations. We found that the majority of the energy increase (70%) was due to improved energy extraction provided by the larger A_{eff}, with the rest due to lack of bend loss (1.5 dB).

In conclusion, we find that simulations must include three-dimensional profiles of fields and ion populations, along with bending effects, for accurate predictions of gain-saturated, large-mode-area fiber amplifiers. Although not discussed here, time-dependent solutions of all fields and populations were also found necessary to describe high-power amplifiers at repetition rates greater than 1 kHz.

Work supported by Laboratory Directed Research and Development, Sandia National Laboratories, U.S. Department of Energy, under contract DE-AC04-94AL85000. The authors wish to thank Dahv A.V. Kliner, Sandia National Laboratories, for many insightful discussions.

4. References

[1] R.L. Farrow, G.R. Hadley, D.A.V. Kliner, and J.P. Koplow, "Design of refractive-index and rare-earth-dopant distributions for large-mode-area fibers used in coiled high-power amplifiers," SPIE **6453,** 64531C-1-11 (2007) and references therein.

[2] G.R. Hadley, R.L. Farrow, and A.V. Smith, "Three-dimensional time-dependent modeling of high-power fiber amplifiers," SPIE **6453**, 64531B-1-10 (2007).