Thulium-doped fibers promising for high-power laser amplifiers

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Thulium-doped fibers, pumped at 920nm and amplified at 2μm, can rival traditional ytterbium-doped fibers.

Achieving ever higher power is an eternal quest in laser science. Unfortunately, all high-power amplifiers are subject to thermal problems, i.e., heat is always generated because of the quantum defect (the difference in energy between the pump and signal photons). In recent years, however, remarkable progress has been made in scaling silica-based fiber amplifiers to kilowatt powers. The use of fibers in these amplifiers helps to alleviate the thermal problems. Such high-power fiber amplifiers are usually based on double-clad structures (see Figure 1). In these devices, the pump light—normally emitted from many diode lasers of modest beam quality—is confined in a transparent cladding that is a few hundred micrometers in diameter. In addition, the signal light is confined to a much smaller, doped inner core (usually 10–50μm in diameter). The pump light overlaps the inner core and pumps the rare-earth dopant ions to cause the population inversion necessary for amplification.

The quantum defect is unusually low in ytterbium-doped fibers (often only 10%). In most high-power amplifiers, therefore, ytterbium (i.e., Yb3+) ions are uniformly dispersed in a silica core. The signal wavelength in a Yb-doped fiber is generally about 1030–1060nm, and the pump light is usually close to 976nm. There are also other benefits to using fibers to achieve high-power amplifiers. For instance, the large surface area per pumped volume in a fiber helps to minimize the temperature rise in the core. Most importantly, the strong diffractive pressure of the light (i.e., which is confined to a small core by the guiding refractive index structure) overwhelms thermally induced signal distortion and lensing. The lowest-order transverse signal mode may be slightly smaller because of lensing, but the thermal lensing is not as overwhelming as in high-power amplifiers that are based on larger diameter beams in larger diameter gain media.

Scaling fiber amplifiers to even higher powers, i.e., for weapon applications (where megawatt powers are required) or for the acceleration of space vehicles (where gigawatt powers are needed), can be achieved by coherent combination of multiple kilowatt-class amplifiers. In this arrangement, the adaptive phase control of the individual amplifiers is easily incorporated so that atmospheric distortion can be corrected and the beam can be steered. For coherent combination, however, signal linewidths of a few GHz or less, as well as the highest beam quality, are required. For such narrow linewidths, the power is limited by the well-known nonlinear effects of stimulated Brillouin scattering (SBS), which back-reflects the beam and adds a frequency shift, and by stimulated Raman scattering (SRS), which frequency-shifts a portion of the forward propagating signal light toward the red by about 13THz. These two stimulated processes have sharp power thresholds that are proportional to the area of the mode (about the area of the core) divided by the length of the amplifier (usually a few meters). Increasing the core size helps to shorten the amplifier. The usual approach for minimizing the influence of the two nonlinearities is therefore to make the core as large as possible, but a balance needs to be struck. To keep the number of guided transverse modes low (to help maintain beam quality), the refractive index step must be reduced as the core size is increased. Practical limits to index control, however, mean that several modes are usually

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supported. In addition, larger cores experience higher light loss in bends and their weaker diffractive pressure leads to stronger thermal distortions.

In recent work, the unexpected sudden transfer of light into higher-order transverse modes above a sharp power threshold was discovered in large-mode-area, Yb-doped amplifiers. This modal instability has been explained as stimulated thermal Rayleigh scattering (STRS), and we have developed detailed numerical models that agree with the observations. As part of the modal instability, the pattern of quantum defect heating mimics the irradiance pattern of the signal. When a small amount of signal is in the higher-order mode, it produces a temperature profile that can couple—via the thermo-optic effect—light between the interfering modes and lead to strong exponential gain of the light in the higher-order mode. It has been shown that raising the STRS threshold requires strong depletion of the population inversion (or gain saturation), which can be achieved by using a longer fiber and smaller diameter core. This is exactly the opposite of the requirements for suppressing SBS and SRS. In the design of an amplifier, it is therefore necessary to find a balance between these processes. At present, however, maintaining this balance leads to power limits of 100–3000W for amplifiers with high beam quality and narrow linewidth.

Although Yb-doped fibers have been used in most kilowatt amplifiers to date, it has also been demonstrated that fibers doped with thulium (Tm$^{3+}$) ions in a similar geometry can be used to produce kilowatt power levels. In these Tm-doped cases, the pump wavelength was 920nm for signal wavelengths of about 2000nm (i.e., twice that of Yb-doped fibers). For an optimum doping concentration, the maximum optical efficiency of these devices was 60%, which is higher than that implied by the relative pump and signal photon energies. This is because the Tm-doped fibers benefit from an upconversion process in which one ion (created by a pump photon) creates two ions in the upper lasing level.

To investigate why modal instability has not been observed in Tm-doped fibers, we have recently adapted our STRS model to compare the effects of Yb and Tm doping. For this study, we used identical core diameters of 25μm, cladding diameters of 400μm, fiber lengths of 4m, and we kept the modal profiles identical (by adjusting the index step between the core and cladding). In our models, the amplifiers were bidirectionally pumped at 920nm (Tm) and 976nm (Yb), and we used signal wavelengths of 2040 and 1060nm (for Tm and Yb, respectively) to match the previous experiments. We found that the mode instability threshold of the Tm-doped fiber was 50% higher than the Yb-doped fiber, even though this corresponds to seven times more heating. If the heat distribution were the same in the two fibers, the doubled signal wavelength in the Tm fiber would halve the STRS gain relative to the Yb fiber and thus double the threshold power. A factor of two increase in heat could therefore be expected. We attribute the much larger heating factor (seven) that we predicted with our model to the greater saturation of the gain in the Tm fiber. The degree of saturation is dependent on the ratio of the pump absorption to the signal emission cross section. Therefore, operation at shorter signal wavelengths (where the emission cross section is larger) may give rise to even higher mode instability thresholds.

Tm-doped fibers also present other advantages over traditional Yb-doped fibers. For example, photodarkening (which causes the absorption of the signal after long exposure to pump light) has been found to be nearly absent in Tm-doped fibers. Even a small degree of photodarkening can lead to substantial reductions in the STRS threshold for Yb fibers. Another advantage is that SBS is easier to suppress in Tm-doped fibers because the SBS linewidth is half the size. Phase-modulation of the signal, or changing the SBS Stokes shift, by varying the temperature along the fiber is more effective at 2μm. It is also possible that the thermo-optic coefficient of the glass host for Tm is smaller than for Yb, which would also raise the STRS threshold of Tm-doped fibers. There are, however, also some drawbacks to the use of Tm-doped fibers. These include their efficiency (about half of Yb-doped fibers) and the doubling of the focal spot diameter that accompanies the doubled wavelength. In addition, atmospheric transmission is good at about 2μm, but less so than at 1μm.

In summary, Yb-doped fibers are attractive for use in high-power laser amplifiers because of their exceptional optical efficiency and their scalability (at least to the kilowatt power level). For higher power applications, however, Tm-doped fibers may be even more useful. Modal instability in such Tm-doped fibers has not previously been observed, and we therefore used a stimulated thermal Rayleigh scattering model to investigate why this is the case. Our results indicate that the mode instability for Tm-doped fibers is 50% higher than for traditional Yb-doped fibers. We also note that current power levels (about 1 kW) are far below the ultimate power limit that is set by intrinsic optical damage (which occurs at about 5 kW/μm²). This limit is proportional to the mode area. Therefore, overcoming the limit would allow the realization of powers of 1MW or more from an amplifier. Even for large modes, however, the critical power for self-focusing limits the power to 20MW at 2μm or to 5MW at 1μm. The next stage of our research is to apply our STRS model to study shorter signal wavelengths and smaller core diameters (these should both raise the gain saturation and
the STRS threshold). We will also look at pumping at longer wavelengths to reduce the quantum defect and possibly raise the STRS threshold.

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References