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Infrared-induced photodarkening in Tm-doped fluoride fibers

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We have observed a new type of infrared-induced photodarkening in high-numerical-aperture fluoride fibers doped with 3000 and 10,000 parts in 10^6 by weight of Tm. The loss induced in the visible region by 1140-nm radiation is very strong (as high as 25 dB in a 50-cm piece) and broadband; it can be removed by irradiation with the same pump wavelength at lower powers. © 1995 Optical Society of America

Upconversion lasing in fibers has proved to be a promising method of producing a compact blue laser source. There is now interest in identifying factors that may limit the performance of such a device. Following the first report of efficient 480-nm lasing on the ${}^1G_4-{}^3H_6$ transition in Tm^{3+}-doped ZBLAN fiber pumped at 1120 nm by a three-step sequential absorption process,[1] we have investigated the behavior of this system as a function of pump wavelength and fiber length, showing that thresholds as low as 11-mW absorbed power could be demonstrated in short lengths pumped at the preferred wavelength of 1140 nm.[2] The fiber used in both these previous studies had a Tm^{3+}-ion concentration of 1000 parts in 10^6 by weight (ppmwt) and a numerical aperture (NA) of 0.21. A more efficient laser could in principle be made with more highly doped fiber with a higher NA value. The lifetime of the ${}^1G_4$ upper laser level is not significantly shortened by concentration quenching up to doping levels of $\sim 10{,}000$ ppmwt,[3] suggesting the possibility of using shorter lengths of more highly doped fiber, with a corresponding reduction in the cavity loss at 480 nm owing to background absorption and scattering. Raising the NA value of the fiber permits the core diameter to be reduced, offering the possibility of lower lasing threshold and enhanced overall pump conversion efficiency.

In this Letter we report that in two Tm:fluoride fibers with NA values of 0.3 and Tm-ion concentrations of 3000 and 10,000 ppmwt a new effect is observed: a strong broadband loss at visible and near-infrared wavelengths is induced by the infrared pump light. This effect was found to be entirely absent in the original 1000-ppmwt, 0.21-NA fiber. All three fibers were supplied by Le Verre Fluoré, Verne-sur-Seiche, France. The 1000-, 3000-, and 10,000-ppmwt fibers were designed to have LP_{11}-mode cutoff wavelengths of 800 nm, 800 nm, and 1 μm, respectively. We have measured the spectrum, power dependence, and dynamics of this loss and found that it appears to be totally reversible by irradiation of the fiber with the same pump wavelength at lower powers.

Reversible photochromic effects induced by short-wavelength radiation in silicate fibers have been reported[4-6] and extensively studied in the context of Bragg fiber grating production.[7] Gratings have recently been written with 245-nm light in fluorozirconate fibers[8] that were doped with Ce to enhance their photosensitivity. Infrared-induced photodarkening has also been reported in Tm-doped aluminosilicate fiber, in which stepwise excitation of the rare-earth ion leads to photoionization.[9] This type of effect has to our knowledge not previously been described in a fluoride fiber, although photoinduced defect centers have been proposed, for example, to explain the unusual threshold behavior observed in Er^{3+}-doped fluoride when it is operated as an upconversion-pumped green laser.[10]

In a preliminary experiment a 0.5-m length of the 3000-ppmwt fiber was pumped at 1.14 μm, with a launched power as high as 77 mW, and two Si photodiodes were used to monitor blue fluorescence, one for guided fluorescence emerging from the fiber end and one for unguided fluorescence from the side of the fiber. Filters shielded the diodes from pump light. In the first few seconds after the 1.14-μm pumping was switched on, a decrease in the end light fluorescence signal was observed, whereas there was no change in the side light fluorescence. After a few tens of seconds the guided blue fluorescence signal approached an equilibrium value that could be as low as 20% of the initial value for a launched pump power of 77 mW. The experiment indicated that the reduction of end light fluorescence was due to an induced blue propagation loss rather than to an infrared loss or fluorescence quenching, because the side light fluorescence was not affected. The effect was further found to be reversible: when the launched pump power was reduced to a few milliwatts for a period of a few minutes the fiber apparently reverted to its original state, and it was possible to reproduce the experiment.

The magnitude of the induced absorption effects could be greatly reduced by heating the fiber. We repeated the preliminary experiment at temperatures as high as 49 °C by enclosing the whole fiber and launch optics in a box with a heater. The observed end light and side light fluorescence was significantly weaker than that for room temperature, and the reduction of end light fluorescence at launched pump powers as high as 100 mW was small (~7% in 100 s). The absorption was also removed faster in the heated fiber when it was pumped at a reduced power, recovering in one tenth the time of the fiber at room temperature.

The spectrum of the induced absorption was measured by counterpropagation of white light and the in-

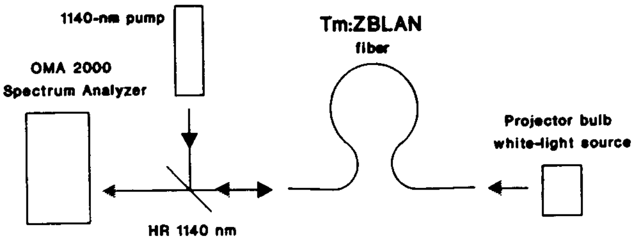

Fig. 1. Experimental configuration for induced loss measurements. HR, highly reflecting mirror.

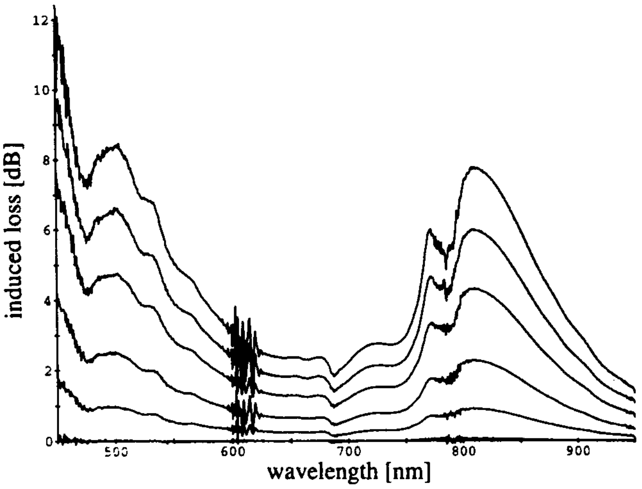

Fig. 2. Loss induced in 3000-ppmwt Tm-doped fluoride fiber by 22 mW (lowest curve) to 77 mW of launched 1.12-μm pump light versus the transmission after irradiation with 11 mW. The noise near 600 nm is an artifact, and the minimum near 800 nm is due to cladding modes that experience a lower loss in this region because of strong absorption of the Tm ions in the core.

frared pump laser in a 50-cm-long sample of the fiber, as shown in Fig. 1. The pump laser was a Nd:YLF-pumped Yb:silica fiber laser that can operate at wavelengths between 1.04 and 1.14 μm selected by a fiber Bragg grating.[11] The white-light transmission of the fiber was recorded with an optical spectrum analyzer (EG&G OMA2000). These measurements were taken with the pump off in order to eliminate the fluorescence signal.

The white light transmitted by the fiber was measured after irradiation of the fiber with various power levels at 1.1, 1.12, or 1.14 μm for typically 60 s. After some time at a particular power an equilibrium value of the transmission was reached; the required time varied between ~30 s for the highest powers and 10–20 min for a few milliwatts. The equilibrium appeared not to depend significantly on the previous treatment and also was stable for hours without further irradiation. By comparison of the spectra the increase in loss could be calculated. Figure 2 shows the induced loss spectra after irradiation of the 3000-ppmwt fiber with various powers as high as 77 mW launched at 1.12 μm for 60 s each; the transmission after irradiation with 11-mW launched power served as a reference state for all curves. Figure 2 shows that the induced loss is very broadband and strongest near 500 and 800 nm. We have carried out the same measurement in the range 1.25–1.6 μm but found no induced absorption there. Irradiation at 1.14 μm caused very similar loss spectra, while the effect was approximately three times weaker for 1.1 μm, which also leads to lower fluorescence levels. The bleaching of the absorption by application of low power was also slightly slower for 1.1 μm compared with that for 1.12 and 1.14 μm.

The same measurements have been carried out for the 10,000-ppmwt fiber. The induced loss spectra were very similar but ~2.5 times stronger than in the 3000-ppmwt fiber. In the 1000-ppmwt fiber, no effect at all was observed.

The absorption of the pump light by the Tm ions is very strong in highly doped fibers, resulting in great nonuniformity in the pump power distribution along the fiber. The induced loss must therefore be assumed to be nonuniform also, and only the total loss of a length of fiber is quoted here.

The reversibility of the effect seems to suggest that two different processes are induced by the infrared pump: the pump appears to create absorbing defect centers but also causes another process that decreases the absorption; after some time a dynamic equilibrium is reached at which the rates of both processes are equal. The loss-creating effect seems to grow faster with pump power so that the equilibrium loss value rises with power. The loss-creating effect is obviously related to the excitation of the Tm ions, as it is weaker for 1.1-μm pumping, where less excitation is observed. Indeed, we have observed 290-nm fluorescence from the high-lying ${}^3P_0$ level, which is populated by cross-relaxation processes; highly excited Tm ions may partly dissipate their energy in some loss-creating process. This would also explain why no effect was found in the lower-doped fiber (1000 ppmwt), in which cross-relaxation processes are much weaker. As a whole the situation seems to be similar to the one reported for germanosilicate fibers in Refs. 6 and 7. In principle, two types of defect could be involved: scattering centers, such as microcrystallites,[12] and point defects or color centers.[13] Discrete peaks in the spectrum of the induced absorption suggest that color centers make the dominant contribution to this loss.

Obviously the observed induced absorption is detrimental to the performance of a laser operating in the visible range such as the 480-nm laser reported in Refs. 1 and 2; the 3000- and 10,000-ppmwt fibers studied here are unsuitable for this application. They may, however, be useful for infrared lasers, as the effect seems not to appear at longer signal wavelengths. Further optimization of the infrared-pumped blue laser will call for a detailed study of the effect of fiber composition on infrared photosensitivity.

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