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Infrared-to-visible upconversion: spontaneous emission and amplified spontaneous emission in a ZBLAN:Er^{3+} optical fiber

FRANCISZEK KACZMAREK[1*], JERZY KAROLCZAK[1, 2]

[1]Faculty of Physics, Adam Mickiewicz University, Umultowska 85, 61-614 Poznań, Poland

[2]Center for Ultrafast Laser Spectroscopy, Adam Mickiewicz University, Umultowska 85, 61-614 Poznań, Poland

[*]Corresponding author: F. Kaczmarek, efka@amu.edu.pl

Careful, intensity and spectral examinations of fluorescence in the process of infrared-to-visible upconversion, observed perpendicularly to the excited ZBLAN:Er^{3+} optical fiber (side fluorescence), and at the fiber end, point to the existence of amplified spontaneous emission (ASE), when the fiber is long enough. We have observed the narrowing of the fluorescence band centered at 544 nm ($^4S_{3/2} \to {}^4I_{15/2}$ transition) and an increase in the ASE intensity, when the fiber is pumped at 809 nm with a laser diode.

Keywords: infrared-to-visible upconversion, amplified spontaneous emission.

1. Introduction

Infrared-to-visible upconversion in ZBLAN:Er^{3+} optical fibers, leading to strong fluorescence and laser emission at 544 nm ($^4S_{3/2} \to {}^4I_{15/2}$ transition) is a well-known phenomenon described in detail in many papers, see, *e.g.*, [1–5].

Amplified spontaneous emission (ASE) has been extensively studied by PETERS and ALLEN [6, 7]. According to them, ASE is realized when a spontaneously emitted photon at one end of the active medium induces another one at the other end. ASE is likely to appear in a pencil-like excited medium which exhibits high optical gain. Such conditions are perfectly met in an optical fiber whose length could be of the order of meters. The threshold length L_c for ASE to appear is proportional to $1/\Delta N$, where $\Delta N = N_2 - N_1$ is the inversion of population between the appropriate energy levels. On the other hand, the amplification coefficient β is proportional to ΔN. In this way, we have: $L_c \sim 1/\Delta N \sim 1/\beta$. To calculate β we have used the well-known simplified laser threshold equation $I_o R_1 R_2 \exp(2\beta L) = I_o$, where R_1 and R_2 are the reflection coefficients of the resonator mirror, L is the distance between these mirrors. Furthermore, for the round-trip gain G we have: $G = \exp(2\beta L) = 1/R_1R_2$. Large inversion and high optical gain reduce the critical length L_c. In our case, we have calculated β observing the threshold for the laser action with $l = 400$ cm, $R_1 = 0.97$ and $R_2 = 0.04$, to be $\beta = 0.004$ cm^{-1}. We were unable to derive a strict relation between β and L_c, because ΔN and consequently β depend upon the excitation level which, in the fiber, is not constant and decreases exponentially along the fiber length [5]. However, the existence of ASE could be recognized by measuring the fluorescence intensity and the spectral characteristics of the pure spontaneous emission (side fluorescence) and the emission at the fiber end, as a function of the excitation power and the fiber length. Line narrowing and strong directional emission that appear in the process of ASE were observed in a long, pencil-like excited mixture of He-Ne [6, 7], and then in optical fibers by DIGONNET [8], LIU *et al.*[9], CARRUTHERS *et al.* [10], DESURVIRE and SIMPSON [11], GOMES *et al.* [12], NICÁCIO *et al.* [13], QIN *et al.* [14], and others. In general, ASE tends to limit the gain and contribute to the noise in lasers, and especially in optical fiber amplifiers. However, it might be a useful process when a low temporal coherence but good spatial coherence is required.

2. Experimental results

We have used three different arrangements and the S 2000 UV-VIS Ocean Optics fiber optics spectrometer with optical resolution of 2.5 nm measured at FWHM to observe the fluorescence in the green, Fig. 1. The ZBLAN:Er^{3+} (1000 ppm) optical fiber used had the following parameters: fiber core diameter of 1.8 μm, NA = 0.28, produced by KDD Fiber Labs. Inc. in Japan. Infrared-to-visible upconversion in the ZBLAN:Er^{3+} optical fiber was caused by launching a 809 nm beam into the fiber core. We used the SDL 5221-H1 laser diode with emitting area of 1 μm × 3 μm and maximum output power of 150 mW. The center wavelength emitted was 812 nm, which did not match the center of the absorption band of the fiber. Powerful enough, single mode laser diodes emitting at the most suitable wavelengths (800 nm, 970 nm) for pumping ZBLAN:Er^{3+} fibers are not commercially available. Thermoelectrically cooled, the diode wavelength decreases to 809 nm, at full driving current of 150 mA. Pumping at 809 nm requires higher launched power, however, as was observed earlier [15], it practically eliminates the undesired emission at 850 nm. Typically, the power density launched into the fiber core varied from zero to about 2 MW/cm^2. It is worthwhile to take into account also the waveguide characteristics of the fiber. It creates spatial confinement of the light beam generated in the fiber core. Pure spontaneous emission is completely isotropic, but, in the case of a fiber core, its fraction emitted within the numerical aperture of the fiber, cannot leave the fiber and propagates forward or backward along the fiber. This property may also enhance the process of ASE. In the arrangements of one or two mirrors in place, but with excitation below the laser threshold, bouncing of the light beam between the mirrors causes the length of the active medium to increase, even several times over the length of the fiber.

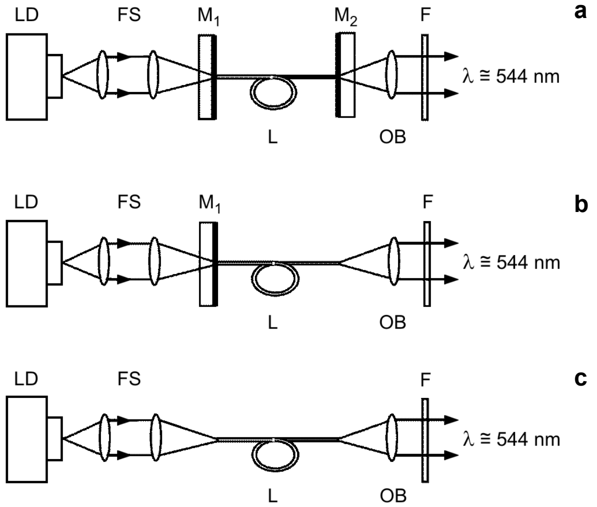

Fig. 1. Experimental arrangements for the study of fluorescence, ASE and laser action: laser action (**a**), spontaneous emission and ASE (**b**, **c**); LD – single mode laser diode ($\lambda = 809$ nm), FS – focusing system, M_1 – dichroic mirror, $T_1(\lambda = 809\text{ nm}) = 97\%$, $R_1(\lambda = 544\text{ nm}) \cong 100\%$, M_2 – dichroic mirror, $R_2(\lambda = 809\text{ nm}) \cong 100\%$, l – length of the ZBLAN:Er^{3+}, OB – microscopic objective ×10, F – filter and absorbing plate.

We have measured the side fluorescence and the fluorescence from ${}^4S_{3/2} \rightarrow {}^4I_{15/2}$ and ${}^2H_{11/2} \rightarrow {}^4I_{15/2}$ transitions at the fiber end (for a relatively long fiber of 400 cm), and also for a short one ($l = 35$ cm), as a function of the excitation power, Fig. 2. Fluorescence at the fiber end (for $l = 35$ cm) is relatively weak and exhibits a tendency towards saturation with higher pumping power. The character of the side fluorescence is similar but its intensity is much weaker. On the other hand, the end fluorescence

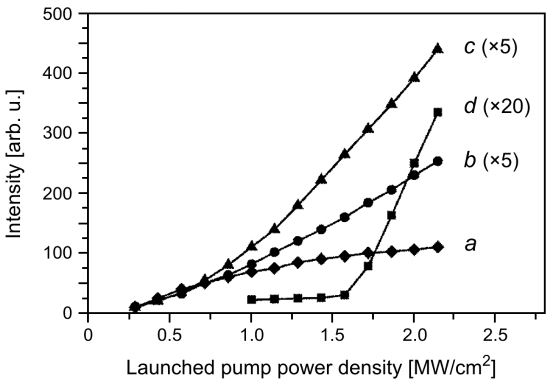

Fig. 2. Fluorescence intensity (544 nm) at the fiber end as a function of the launched power density and the fiber length: $l = 35$ cm (with no mirrors in place) – *a*, $l = 400$ cm (no mirrors) – *b*, $l = 400$ cm (no output mirror) – *c*, $l = 400$ cm (with both mirrors in place), $T_2 = 20\%$ (at 544 nm) – *d*. Laser threshold at 1.9 MW/cm^2.

increases substantially (with no signs of saturation) in all three arrangements (for $l = 400$ cm), and is especially characteristic in the arrangement with both mirrors in place ($T_2 = 20\%$ at 544 nm), but below the laser threshold. The nonlinear increase of the fluorescence intensity clearly indicates the existence of ASE at high pumping power, in accordance with the earlier results [6–9]. We have observed vanishing of the spectral band centered at 522 nm ($^2H_{11/2} \rightarrow {}^4I_{15/2}$ transition). Spectral characteristics of the fluorescence are shown in Figs. 3 and 4. The narrowing of the line width in the case of a long fiber clearly indicates the appearance of ASE, contrary to the line width for a short one. We have also measured the spectrum of the fluorescence (at the fiber end) for an intermediate length of the fiber ($l = 140$ cm). The results, as compared to that for $l = 35$ cm, are shown in Fig. 4. A tendency towards narrowing of the line for a longer fiber is clearly visible. There is almost no difference in the line shape for pure spontaneous emission (side emission) and the end one, if

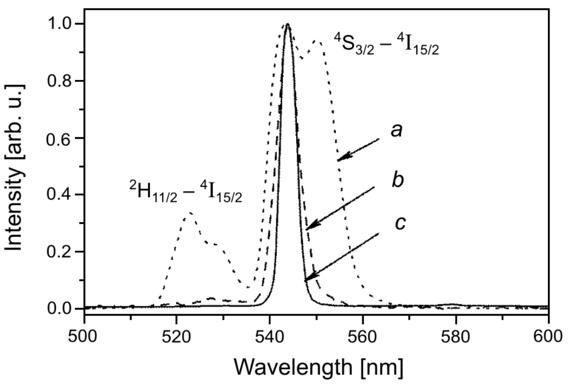

Fig. 3. Spectral characteristics of the fluorescence at 544 nm: *a* – pure spontaneous emission (side fluorescence), *b* – fluorescence at the fiber end (below the laser threshold), *c* – laser emission, $l = 400$ cm.

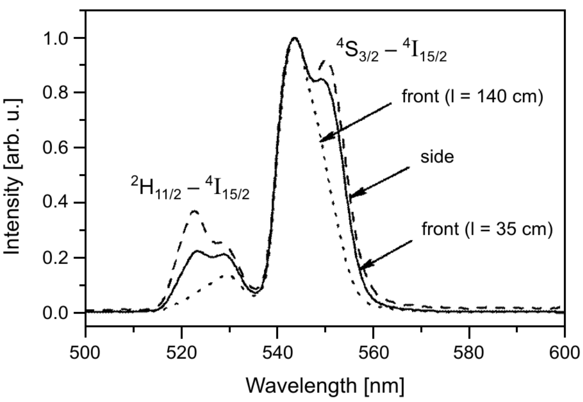

Fig. 4. Spectral characteristics of the fluorescence at the fiber end for shorter fibers as compared to pure spontaneous emission (side emission).

the fiber is only several tens of cm in length. With no mirrors in place (to avoid any laser action) the fluorescence intensity in the green measured at the fiber end increases with its length [6–8]. For $l_1 = 400$ cm, and $l_2 = 35$ cm we measured I_1 and I_2 and obtained: $l_1 : l_2 \approx I_1 : I_2 \approx 12$. Typically, the laser threshold corresponds to a sharp increase in the emission with a characteristic line narrowing. In the case of a long optical fiber, we have observed the following sequences of the emission. ASE is likely to appear first and gradually increases, changing into laser emission, with no characteristic jump of the intensity. If the optical fiber was relatively short (*e.g.*, several tens of cm), neither ASE nor laser action existed.

3. Conclusions

We have observed a smooth transition from ASE to laser emission (at 544 nm) for a long pencil-like active medium (*i.e.*, in an optical fiber), pumped with an infrared laser diode. The very broad emission profile in the case of pure spontaneous process, exhibits narrowing at ASE, and especially, above the laser threshold. When pumping at 809 nm with power density launched into the fiber core of 1 MW/cm^2, a full manifestation of ASE appeared for the fiber length of 400 cm. We have observed almost a four-fold decrease of the linewidth at 544 nm in this case, as compared to the spontaneous emission linewidth. To find the difference between ASE and laser action one has to check the state of coherence. Visually, for the green output beam, the difference is easy to determine.

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