Broadband emission from a multicore fiber fabricated with granulated oxides

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We demonstrate a multicore multidopant fiber which, when pumped with a single pump source around ~800 nm, emits a more than one octave-spanning fluorescence spectrum ranging from 925 to 2300 nm. The fiber preform is manufactured from granulated oxides and the individual cores are doped with five different rare earths, i.e., Nd^{3+}, Yb^{3+}, Er^{3+}, Ho^{3+}, and Tm^{3+}. © 2008 Optical Society of America

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1. Introduction

Broadband light sources are a prerequisite for a large variety of applications, such as spectroscopy [1], microscopy [2], sensing [3], or medical diagnosis to name a few. One prominent example is optical coherence tomography [4]. Many of the applications rely on the extremely short coherence length, which is a consequence of the broad spectral distribution and which may be as short as a few micrometers. Commonly employed broadband light sources are thermal light sources, light emitting diodes, superluminescence diodes [5], amplified spontaneous emission and superfluorescence fiber sources [6], femtosecond oscillators, or white light sources based on a nonlinear continuum generation [7]. Other sources, such as very long Raman fiber lasers [8], have been investigated but are not as widespread. While most light sources have bandwidths of <100 nm, some are as broad as a couple of hundred nanometers. Because of their superior beam quality and high spatial coherence fiber based sources, most prominently superfluorescent rare earth-doped or highly nonlinear fibers, are often preferred to other sources. A further important characteristic is the output power of a light source. Generally, the broadest bandwidth but also the lowest output power is reached with spontaneous emission. Amplified spontaneous emission has a higher power but shows some narrowing of the spectra depending on the degree of amplification. Finally, the highest output power is reached with laser emission, but in continuous wave (cw) operation this comes at the cost of a bandwidth that is considerably reduced. Nevertheless, even in the case of cw laser activity, laser emission can cover a range of 50 nm in the case of an $Nd^{3+}:Al^{3+}:$ glass fiber [9,10] or 75 nm for a $Yb^{3+}:Al^{3+}:$ glass fiber [11]. The broadest bandwidths and the highest output powers, however, are undoubtedly reached with standalone mode-locked oscillators or with subsequent continuum generation at the expense of high costs. Here, we report on an alternative approach to realize an extremely broadband cw fluorescence light source, which is based on a fiber with multiple-doped cores pumped by a single pump source. Multicore fibers have been previously reported with an emphasis on enlarging the effective mode area for high power laser applications [12–14]; the cores were either doped with Nd^{3+} or Yb^{3+} and the fibers were not intended for broadband light generation. The reported approach has the advantage that the generated emission can be directly guided to the

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application. Further the small emitting area and the limited numerical aperture allow for reaching a high brilliance. For practical reasons the experiments were performed with a Ti:sapphire laser but the arrangement could also be operated with the use of a single-stripe diode laser [15]. Therefore it has the potential of a very compact tool for applications requiring a broadband light source.

2. Fabrication Procedure

The geometry of our design is shown in Fig. 1(a). Seven differently doped cores are arranged in a honeycomb geometry with six cores surrounding the central core. With the goal of covering an emission band ranging from ~900 nm to over 2 μm, five different trivalent rare earth ions have been chosen, i.e., Nd^{3+}, Ho^{3+}, Er^{3+}, Tm^{3+}, and Yb^{3+}. They are well suited because all can be excited with a single pump wavelength of ~800 nm [16]. Only Yb^{3+} has its maximum absorption at 977 nm but the transition is so broad that even at 800 nm the absorption is sufficiently high. The emission spectra cover the range from 925 nm ($Nd^{3+}{}^4F_{5/2} \rightarrow {}^4I_{11/2}$) to 2100 nm ($Ho^{3+}{}^5I_7 \rightarrow {}^5I_8$). The doping concentration is chosen to yield an absorption length of ~20 cm at the pump wavelength of 800 nm. With the Nd^{3+}, Er^{3+}, and Tm^{3+} absorption cross sections from [17,18] concentrations of 0.018, 0.342, and 0.235 at. % are used. For Ho^{3+} and Yb^{3+} a concentration of 1 at. % is chosen. To facilitate easy identification of the differently doped cores, two are doped with Nd^{3+}.

The fibers are drawn from preforms that are fabricated with granulated oxides [9,10,19]. In a first step the preform is assembled by closely stacking seven silica tubes of 3 mm × 5 mm diameter in the center of a bigger 17 mm × 21 mm silica tube and by filling the remaining space with undoped granulated silica of a typically 400 μm grain size as described in detail in [9,10]. Each inner tube is filled with a mixture of granulated silica, the appropriate concentration of rare earth oxide, and aluminum oxide. Aluminum prevents the rare earth ions from clustering and raises the index of refraction to facilitate the guiding of light. The aluminum oxide concentration corresponds to 7 at. % of Al^{3+} with respect to silicon. The preform is preheated at ~1400 °C, evacuated for 2 h, and then drawn at a temperature of ~1850 °C to a fiber with a diameter of 1.24 mm. In a second step, this fiber is then packed in the center of a larger silica tube (17 mm × 21 mm) and the remaining space is again filled with undoped granulated silica. After preheating and evacuation the final preform is drawn to a fiber with diameters ranging from 1.45 to 0.51 mm corresponding to core diameters of 16 to 5 μm, respectively. Thus, all cores are multimode, except for the smallest diameter of 5 μm, where the limit for a single-mode operation for all wavelengths of interest is reached.

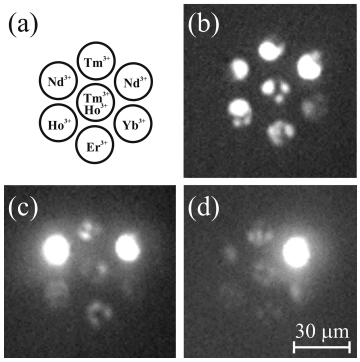

Fig. 1. (a) Arrangement of the seven differently doped cores. Images of the rear fiber end with (b) all cores pumped, (c) two Nd^{3+}-doped cores pumped, and (d) single Nd^{3+}-doped core pumped.

3. Experimental

In the first experiment a 21 cm long fiber with 16 μm large cores is selected and the seven cores are pumped either simultaneously or individually. The pump light of ~800 nm stems from an argon-ion laser pumped Ti:sapphire system (Spectra Physics, Model 3900) with a maximum pump power of 400 mW. The pump laser is focused with a lens (f = 14.5 mm) to a spot size of ~30 μm onto the front face of the fiber and the fluorescence is detected at the rear end. Prior to all the spectral measurements, the rear end of the fiber is imaged onto a CCD camera, and the pump light is aligned until either all or a selection of cores is pumped. Since the camera is equipped with a silicon-based CCD and protected with a 6 mm RG 1000 Schott filter its sensitivity is restricted to wavelengths between 900 and 1150 nm. Nevertheless, emission from all rare earth ions may be detected because they all have transitions within this range. Figure 1(b) shows the rear end of the fiber with all cores simultaneously excited. The emission from the different cores is assigned to $Yb^{3+}({}^2F_{5/2} \rightarrow {}^2F_{7/2})$, $Nd^{3+}({}^4F_{3/2} \rightarrow {}^4I_{11/2})$, $Er^{3+}({}^4I_{11/2} \rightarrow {}^4I_{15/2})$, $Ho^{3+}({}^5I_5 \rightarrow {}^5I_8$ or ${}^5I_6 \rightarrow {}^5I_8)$, and $Tm^{3+}({}^3H_5 \rightarrow {}^3H_6$ or ${}^3H_4 \rightarrow {}^3H_6)$, respectively. In Fig. 1(c) only the two Nd^{3+}-doped cores are pumped by aiming the pump light at the upper half of the core area. Finally, Fig. 1(d) demonstrates the controlled excitation of only a single core (Nd^{3+}) by focusing and aiming the pump light properly. To record the spectrum of a selectively pumped fiber core, its output is collimated with a 20× microscope objective and imaged with a second lens (f = 14.5 mm) onto the aperture of a fiber-coupled spectrometer. Depending on the wavelength range three different spectrometers (AVS-USB2000 for 650–1100 nm, AvaSpec-NIR256-1.7 for 900–1700 nm, and Ocean Optics NIR256-2.5 for 900–2500 nm) are used. The pump light is suppressed with a 4 mm RG 1000 Schott filter. The measured spectra of individually as well as simultaneously pumped cores are shown in Fig. 2. When only the Yb^{3+}-doped core is pumped [see Fig. 2(a)], the well-known fluorescence spectrum of Yb^{3+} is observed with the prominent sharp feature of the ${}^2F_{5/2} \rightarrow {}^2F_{7/2}$ transition at 977 nm. The spectrum

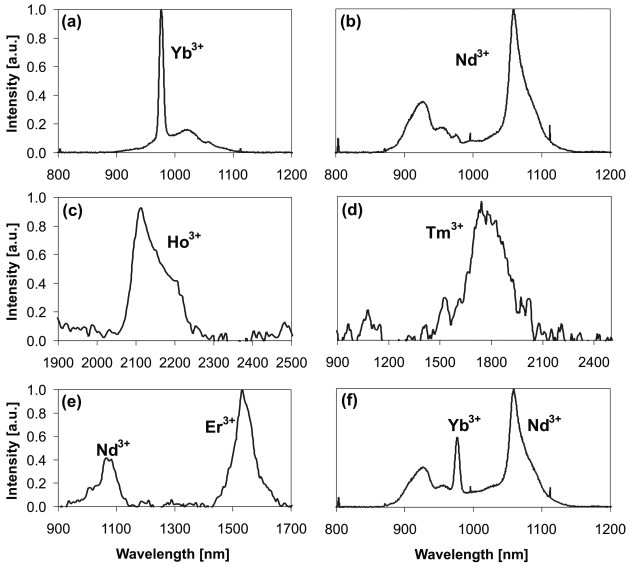

Fig. 2. Spectra of individually pumped 16 μm large cores: (a) Yb^{3+}, (b) Nd^{3+}, (c) Ho^{3+}, and (d) Tm^{3+}. When pairs of cores are simultaneously pumped mixed spectra are observed: (e) Nd^{3+} and Er^{3+} and (f) Nd^{3+} and Yb^{3+}.

of the Nd^{3+}-doped core [see Fig. 2(b)] shows the ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition at 1060 nm, and the fluorescence of ~930 nm stems from the ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition. The emission spectra of the Ho^{3+}-doped core with the ${}^5I_7 \rightarrow {}^5I_8$ transition centered at 2113 nm and of the Tm^{3+}-doped core with the ${}^3F_4 \rightarrow {}^3H_6$ transition at ~1.8 μm are shown in Figs. 2(c) and 2(d). The spectra depicted in Figs. 2(e) and 2(f) are measured with two cores being simultaneously excited. Figure 2(e) shows the Er^{3+} ${}^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition centered at 1532 nm and the Nd^{3+} ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition. The combined excitation of the Nd^{3+}- and the Yb^{3+}-doped core yields the spectrum in Fig. 2(f). Thus, each excited core separately shows

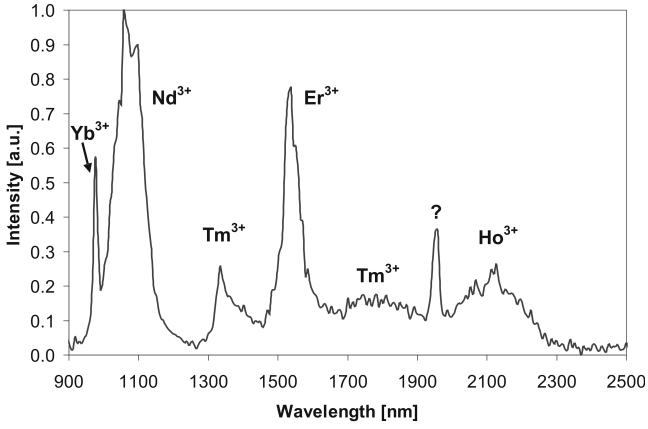

Fig. 3. Fluorescence spectrum emitted from a fiber with 5 μm large cores. The spectral intensities are as measured, that is, without correcting for efficiencies. The curve at 1954 nm labeled with a ? is assigned to a second order peak of the 977 nm Yb^{3+} emission.

the expected fluorescence proving that the ions are properly ionized and well embedded in the glass matrix. In other words, fabricating cores from granulated oxides seems feasible at least for all the rare earth ions used in this experiment.

In the second experiment a fiber with 5 μm large cores is used. The smaller core size allows for homogeneous pumping of all cores without changing the optical setup. Figure 3 shows the spectrum for a pump wavelength of 804 nm. The grating of the spectrometer (Ocean Optics NIR256-2.5) has only 150 lines/mm leading to feeble diffraction at the apertures of the grating and consequently to extremely weak and throughout negligible second order contributions. The spectrum indicates contributions from all five rare earths. Note, each core independently emits its spectrum and is largely undisturbed from the others. The width of the resulting spectrum corresponds to one octave plus a major third and nearly completely covers the wavelength range from 925 to ~2300 nm. Only below 1300 nm there is a gap between the emission of Nd^{3+} and Tm^{3+}. The spectral gap may be filled with, e.g., Bi^{3+}, which shows fluorescence at 1250 nm when pumped at 800 nm [20]. The relative spectral distribution can be considerably modified if the pump wavelength is changed. While a longer wavelength, e.g., ~820 nm, favors the Yb^{3+} fluorescence and reduces the Nd^{3+} fluorescence, a shorter wavelength, e.g., 786 nm, strongly favors Tm^{3+} and restrains the fluorescence from the other ions. That is, the overall spectral distribution can be manipulated within certain limits by a judicious choice of the relative rare earth ion concentrations and the pump wavelength. The efficiency of the broadband light source is mostly limited by the small solid angle that overlaps with the numerical aperture of the fiber, which is roughly between 0.1% and 1%.

4. Conclusion

To conclude, we have demonstrated a seven-core fiber where each core is fabricated from granulated silica mixed with the corresponding rare earth oxide and aluminum oxide. The dopants were selected so that all can be pumped with a single pump laser and simultaneously cover the widest possible fluorescence spectrum. Each core showed the expected fluorescence proving that the ions are properly ionized and embedded in the glass matrix. When all cores are simultaneously excited, the emitted spectrum ranges from 925 to 2300 nm. We would like to emphasize that in the current design different parts of the spectrum originate from different although well-defined spatial areas in the fiber's core region. To avoid that, we are currently working on an alternative design that allows extraction of the whole spectrum from a single core.

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