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Toward the development of direct emission yellow fiber lasers for biomedical applications

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ABSTRACT

The paper presents the design and preliminary experimental validation of a fiber laser with direct emission in the yellow. The active material is a Dy-doped custom-made phosphate fiber, which is pumped by high-power blue diode lasers emitting at 450 nm. A suitable model has been developed to optimize the laser behavior and validated with a low-power version of the laser cavity with femtosecond written Bragg grating mirrors.

Keywords: Yellow lasers, Fiber lasers, Ophthalmological lasers, Phosphate fibers.

1. INTRODUCTION

Visible lasers are finding an increasing number of applications in the biomedical field; for instance, treatments with yellow emitting lasers (∼565 nm to 590 nm) are emerging as the elective choice for many ophthalmologic and dermatologic diseases because of the good combination of the absorption values of the main tissue components (Fig. 1). In particular, yellow light at 577 nm is considered to be the best choice for the macular retinopathy treatment by photocoagulation because of the lower absorption by the retinal and foveal pigments and the higher absorption of oxyhemoglobin and the lower scattering by the eye tissue. This opens the way to central macular edema treatments free of foveal damages, thus allowing the successful treatment of pathologies with less risks of affecting the fovea, which is the portion of the eye responsible for accurate vision.[1–4]

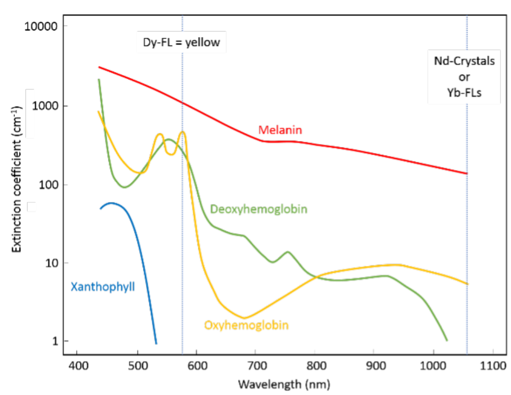

Figure 1. Laser wavelength and effective light absorption.

Originally green lasers (532 nm) were used but switching to yellow lasers has paved the way toward new treatments for these frail retinal areas. Experimental investigations on animals and humans, but also numerical analyses, have confirmed that yellow light is the most suitable for retinopathies because it is effective with lower power, preventing thermal damage to neighboring areas.[5] However, developing a yellow laser source is quite challenging. Indeed, the currently commercially available sources are mainly based on second harmonic

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generation, starting from different types of infrared emitting lasers, such as rare-earth-doped (Nd, Yb) crystals or fibers and optically pumped semiconductors. However, frequency up-conversion methods require nonlinear crystals and free-space alignments, and this leads to low efficiency, complexity, reliability issues and high costs. In contrast, the direct generation of yellow light using Fiber Lasers (FLs) would lead to efficient, simpler and less expensive sources, with the additional advantages of higher brightness, better stability, and alignment-free and mechanically robust layouts. Besides, the native light fiber delivery would be advantageous in some surgical procedures for the minimal invasive impact. Nevertheless, the use of fibers to develop direct emission lasers has not been exploited so far because of the lack of robust active fibers for visible emission and of efficient pump sources. Therefore, to achieve the goal, first a suitable rare-earth doped fiber has to be developed.

The most promising rare-earth candidate as dopant material is the trivalent dysprosium ion, in which the transition from $^4F_{9/2}$ to $^6h_{15/2}$ can be exploited for laser emission in the yellow, as sketched in Fig. 2. This choice for the rare-earth doped has the additional advantage that Dy^{3+} ion exhibits a high absorption peak at 450 nm wavelength, where high-power and high-brilliance fiber coupled laser diodes have recently become available to be used for pumping.[6,7] These recent progresses in the field of GaN based blue laser diode are offering new scopes to optically pump rare-earth ions.

So far Dy-doped fibers used for emission in the yellow are based on fluoride glasses, which however present severe limitations in terms of chemical resistance and spectroscopy. To overcome these issues an ad-hoc designed phosphate fibers has been developed.

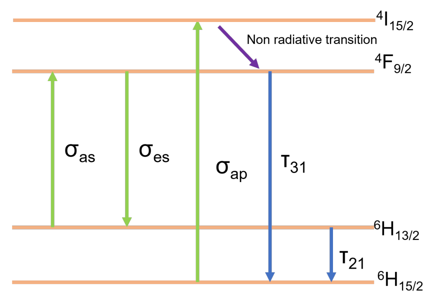

Figure 2. Simplified energy scheme for trivalent Dy^{3+} ion.

This paper reports on the fabrication of a Dy-doped phosphate fiber, the preliminary characterization of its emission properties, and the design and numerical analysis of the predicted laser behavior.

2. CUSTOM ACTIVE PHOSPHATE OPTICAL FIBER

The first step to develop the ad-hoc phosphate fiber is to synthesize the new glasses that will constitute the core and the cladding. Such glasses must be suitable for the fabrication of both active and passive versions of the fiber. Fluoride glasses, specifically ZBLAN glasses, have historically been the medium of choice for visible FLs exploiting up-conversion processes in rare-earth ions thanks to their low phonon energy, but this property presents several drawbacks when considering down-conversion processes by pumping rare-earth ions at a wavelength shorter than the laser emission wavelength. In particular, excited state absorption and energy transfer towards high energy levels impair the efficiency of radiative process through down-conversion; a long lifetime of the termination laser level which induces reabsorption of the laser emission for 4-level laser systems like Dy^{3+}. On the other hand, in terms of thermo-mechanical properties, silica glass matrix is beyond any doubt the material of choice and, as a mature technology, silica fibers also offer an unrivaled ease of integration. However, rare-earth ions clustering and photodarkening phenomena limit its versatility as a host for rare-earth ions and its range of operation at visible wavelengths, respectively. Phosphate glass system appears therefore the ideal host for the development of visible FLs. Moreover, the involvement of a high phonon energy matrix such as phosphate glass with enhanced thermo-mechanical properties with respect to ZBLAN glass would ease the integration process of the laser cavity and eventually allow to reach high power level.

The Dy^{3+}-doped phosphate glass optical fiber was manufactured by preform drawing, with the preform being obtained by the rod-in-tube technique. The first step has been the melting of the glass constituents in a furnace at 1080 °C for 1 h in a mix of O_2/N_2 gases to minimize the hydroxyl ions (OH^-) content. The melt has then been cast into a cylindrical mold to form a rod, whereas the cladding glass tube has been shaped by extrusion technique using an in-house-developed equipment. A Dy^{3+} concentration of 3×10^{19} ions/cm^3 has been added in the core. The cast glasses were immediately annealed at a temperature near their respective transition temperature for 5 h to relieve internal stresses and finally cooled down slowly to room temperature. The glass has then been characterized to evaluate the active parameters: the emission lifetime has been evaluated using a pulsed pump illumination, while the cross sections from spectral measurements using the McCumber theory.

Although high-power FLs make use of double-cladding fibers, the first demonstration of the new direct emitting yellow laser is done with a single-core fiber for simplicity. Therefore, to improve the launching efficiency of the pump directly into the doped core, slightly larger diameters than those of most common fibers have been selected. In the first realization the rod-in-tube preform has then been drawn into a fiber of core and cladding diameters of 14 µm and 150 µm, respectively. The fiber propagation loss turned out to be pretty high, but ongoing improvements in the fabrication should give better values.

3. MODELING AND PRELIMINARY VALIDATION

A reliable numerical method for predicting the experimental behaviors of the doped-fiber without having to run many fabrications is fundamental, especially considering all the limitations that come from the in -house development of a prototypal fiber. Different commercial simulation softwares exist, like for example RP Fiber Power;[8] however, developing a custom software gives the possibility to integrate it into optimization routines that can be used to recover difficult, or impossible, to measure laser parameters from experimental data. Following this approach a laser is fabricated with a piece of the active fiber with some unknown parameters and fully characterized (e.g., output power versus pump power, residual pump power, etc.); then, the model is used to find the parameters best fitting the measurement data. Therefore, a numerical model based on Forward-Time, Centered-Space explicit finite difference method, has been implemented to simultaneously solve propagation and rate equations. First the model has been validated against published similar results using the cited RP Fiber Power software.[9–11] Then it has been used to design a fist realization of a laser that uses as the active medium the fiber under development. The active fiber has been modeled as a four level system, with the structural and physical parameters in Tab. 1, where σ_{abp} is the absorption cross section at the pump wavelength λ_{p}, σ_{abs} and σ_{ems} are the absorption and emission cross sections at the signal wavelength λ_{s}, and τ_{32}, and τ_{21}, τ_{30}, and τ_{10} are the energy level lifetimes.

Table 1. Parameters of the investigated Dy^{3+}-doped fiber.

Parameters	Value
λ_{p}	450 nm
λ_{s}	577 nm
d_{cor}	14 µm
Numerical aperture NA	0.14
Doping concentration	$3 \cdot 10^{25}\,\mathrm{m}^{-3}$
Propagation loss	4 dB/m
HR mirror reflectivity	$\simeq 0$ @ λ_{p}; 0.95 @ λ_{s}
OC mirror reflectivity	0.95 @ λ_{p}; 0.5-0.7 @ λ_{s}
σ_{abp}	$0.64 \times 10^{-25}\ \mathrm{m}^2$
σ_{abs}	$0.70 \times 10^{-25}\,\mathrm{m}^2$
σ_{emp}	~ 0
σ_{ems}	$0.90 \times 10^{-25}\ \mathrm{m}^2$
τ_{32}	100×10^{6} ms (estimated)
τ_{21}	1×10^{-3} ms
τ_{30}	~ 0 ms (estimated)
τ_{10}	500×10^{-6} ms (estimated)

The considered laser layout is an adaptation of the classical well-known scheme for high-power fiber laser[12] in which in the preliminary experimental setup all the mirrors are considered to be discrete components (Fig. 3). With reference to Fig. 3, the symbols have the following meaning: P_{in} is the coupled pump power; P_{res} is the residual pump power after two passes; P_{out} the generated output power; HR is the high-reflectivity mirror at the signal wavelength; OC is the "output coupler", which exhibits a high reflectivity at the pump wavelength and reflectivity lower than that of the HR at the signal wavelength.

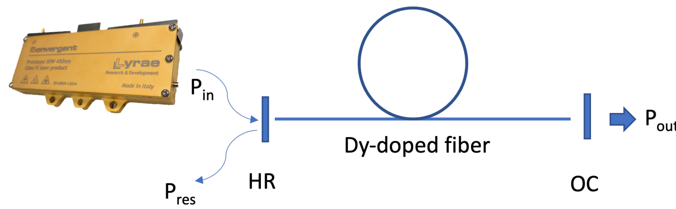

Figure 3. Schematic layout of the considered fiber laser prototype.

The pump comes from a high-power blue emitting laser diode coupled to a 100 µm fiber.[7] Given the large mismatch between the diode pump fiber and the active fiber core and the high propagation loss, to ensure the lasing in the prototype, a double pass pump scheme and an output coupler with the high reflectivity have been considered. Fig. 4 reports the output power versus the coupled pump power for an OC reflectivity of 55% and different fiber lengths, which must be quite short for the already mentioned propagation loss limitations. Fig. 4 reports the output power versus the coupled pump power for different reflectivity values of the output coupler and a fixed fiber length of 0.75 m.

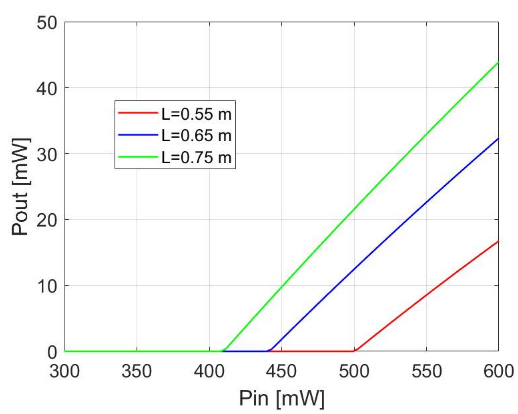

Figure 4. Output power versus the coupled pump power for different fiber lengths.

Based on the simulation results, a first prototype of fiber laser made with ~ 0.70 m of the new active fiber has been realized using discrete mirrors for the cavity. The OC reflectivity was $\sim 50\%$ at the signal wavelength and almost 99% at the pump wavelength. The preliminary characterization has been done by collecting the emitted power by a photodiode through a yellow-centered bandpass filter because the yellow wavelength is outside the operating range of the at-the-time available optical spectrum analyzer. For an estimated coupled power of 450 mW, an output power slightly larger than 1 mW has been measured, which is lower that what expected from the simulations. This might be due to a poorer coupling of the pump and to an underestimation of actual losses.

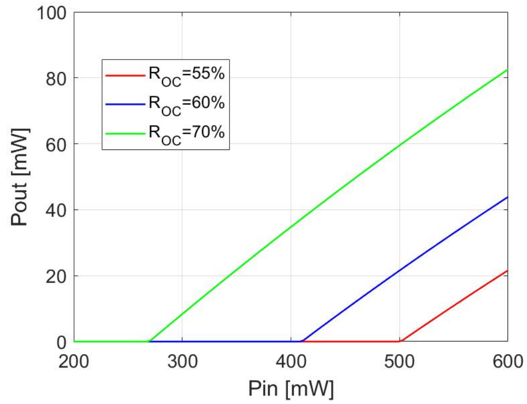

Figure 5. Output power versus the coupled pump power for different reflectivity values of the output coupler.

4. CONCLUSIONS

The fabrication of a Dy-doped custom-made phosphate fiber suitable for the realization of a blue diode laser pumped FL with direct emission in the yellow has been presented. The fiber has been characterized to find the optical parameters, which have then been used to model the laser. The design demonstrated the feasibility of the approach, although preliminary experimental results showed the generation of lower power than what expected because of the limitations in the pump coupling and the pretty high propagation loss.

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