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Solar pumping of solid state lasers for space mission: a novel approach

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Abstract—Solar pumped laser (SPL) can find wide applications in space missions, especially for long lasting ones. In this paper a new technological approach for the realization of a SPL based on fiber laser technology is proposed. We present a preliminary study, focused on the active material performance evaluation, towards the realization of a Nd³⁺-doped fiber laser made of phosphate glass materials, emitting at 1.06 μm. For this research several Nd³⁺-doped phosphate glass samples were fabricated, with concentration of Nd³⁺ up to 10 mol%. Physical and thermal properties of the glasses were measured and their spectroscopic properties are described. The effect of Nd³⁺ doping concentration on emission spectra and lifetimes was investigated in order to study the concentration quenching effect on luminescence performance.

Keywords—solar energy; solar pumping; laser glass; phosphate glasses; fiber laser; space mission.

I. INTRODUCTION

On-board lasers have had an increasing role in the engineering phase of space systems in the last decade: indeed, several current and planned missions include instruments for space exploration relying on lasers for monitoring, sensing or measuring purposes. The range of applications of these systems is wide, and, besides telemetry, it encompasses altimetry for the investigation of the topography of the planetary surface, on-site spectrometric analysis of soil samples, LIDAR (light detection and ranging) applications for atmospheric investigations, precision interferometry and optical communications [1].

Although the numerous applications require different laser architectures and working parameters, almost all space lasers are based on the same technology: diode pumped solid state lasers based on YAG crystal doped with Nd³⁺ ions. Owing to the use of a diode pump source, this technology presents several limitations in terms of lifetime, need of electricity, power consumption, mass, operating temperatures, mechanical stability, resistance to ionizing radiation and overall reliability. All these drawbacks reduce the effective laser employment in space and limit technical and economic feasibility of missions planned to last many years.

A very promising concept able to overcome current laser technology limitations is the solar pumped laser (SPL). Compared to the traditional use of sunlight for producing

electricity through photovoltaic cells, which in turn produces the pump signal through pump diodes, direct solar pumping of solid state lasers avoids two energy conversion steps. This approach is therefore potentially more efficient, simpler and more reliable [2] and in principle it would also provide a limitless operative lifetime. These characteristics make it particularly attractive for space applications, in which long lifetimes are required and where efficiency, compactness and reliability are critical issues.

In order to design an efficient SPL, several aspects have to be taken into account, such as: the solar light collection system, the pumping scheme, the active material and the laser layout. Different solutions have been proposed during the long history of the SPL concept, since the idea of directly converting incoherent broad-band solar radiation into narrow-band and coherent laser light, is almost as old as the laser itself.

The very first SPL was obtained using Dy³⁺ ions as active element in a CaF₂ matrix [3]. Soon after, a 1 W emission from a sun pumped continuous wave Nd³⁺:YAG laser was reported [4]. From then on, the choice of Nd³⁺ as emitting ion became practically a standard because it presents a very strong absorption band where the sun spectral density is almost at its maximum.

After these first reports, several improvements have been reported. Among them, we can mention the highest output power of 500 W achieved in 1993 by side-pumping a Nd³⁺:YAG rod with light concentrated from a 660 m² collecting mirror system [5]. However, in this work the collection efficiency, i.e. the ratio of laser power to primary mirror area, was very low, around 0.76 W/m². The record collection efficiency reported with a Nd³⁺:YAG rod was 6.7 W/m² [2]. In recent years a further increase of solar laser power efficiency was obtained using an alternative solar power collection means, i.e. a Fresnel lens tracking automatically the sun trajectory, and by using as active medium a chromium (Cr³⁺) co-doped Nd³⁺:YAG ceramic in order to enhance the absorption of solar radiation [6,7].

II. A NEW TECHNOLOGICAL APPROACH

Despite the successful and very promising concept demonstration, in order to spread the SPL technology worldwide, reliability, cost/performance and optical-to-optical

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conversion efficiency of the system must still be improved considerably. This can be achieved with a new technological approach based on fiber laser technology, a mature and well spread technology with unmatched performance, especially in terms of beam management and quality [8].

Optical fiber lasers have several key advantages for space applications, such as simplified thermal management system, light weight, minimum footprint and flexible remote delivery. Moreover, the new technological approach is extremely versatile and could be customized to suit the different laser applications in space in terms of output power, beam quality and dimension, spectral properties, output stability, etc.

Another key advantage of this new technological approach is the possibility of developing the whole laser resonator using only fiber components (*all-fiber setup*), so avoiding the use of free-space optics, which can be critical in space missions due to mechanical vibrations and large temperature variations. In addition, a pulsed regime, requested in the majority of current space applications, can be achieved by a technique known as passive Q-switching, i.e. a method that does not require drivers and electrical power supply, thus making it a simple and reliable device. Till now, passive Q-switching of Nd³⁺:YAG lasers pumped by either non-solar or solar light has been successfully obtained using a Cr⁴⁺:YAG crystal saturable absorber [9,10]. A similar approach in fiber configuration will allow the realization of an all fiber pulsed SPL, eliminating the use of optical discrete components and thus resulting in higher laser reliability.

Very recently the demonstration of a first solar pumped fiber made of fluoride glass has been reported [11], however with a very low output power of less than 1 mW and with a host glass that suffers from poor chemical durability and temperature stability and require stringent manufacturing process to avoid crystallization.

In this work we present a preliminary study towards the development of a Nd³⁺-doped side pumped fiber laser made of phosphate glass material, emitting at 1.06 μm. The focus of the activity is on the evaluation of active material performances: the phosphate glass host, the emitter ion and its fluorescence properties under laser and broadband light excitation.

The phosphate glass system has been chosen because it displays a large glass formation region, a high solubility for rare earth oxides, good thermo-mechanical and chemical properties and no evidence of photodarkening even at high population inversion [12]. All these features makes phosphate glass a suitable host material for compact high-power and single-frequency fiber lasers. As a matter of fact, phosphate glass is the material of choice for the development of ultra-high-power laser systems, such as that in the United States laser fusion program [13].

Concerning the doping ion, the choice of Nd³⁺ as has been driven by the overlapping ratio between the standard solar spectrum and the ion absorption bands that was calculated to be 0.14 [14]. Moreover Nd³⁺ is one of the most important RE activators for crystalline and bulk glass lasers because of the power and efficiency available from the transition around 1064 nm. A Nd³⁺-doped laser operated at this wavelength behaves

like a four-level laser system, so a positive internal gain is possible even for very small pump power and, therefore, a very low threshold can be achieved.

Another novelty of the proposed solar laser system is the side pumping of the optical fiber by concentrated solar light. An optical fiber is very thin and flexible, thus it can be coiled in a desired area. In this way a perfect match between solar concentrator image in the focal plan and pumping absorbing area could be achieved thus resulting in an higher conversion efficiency (see Fig. 1).

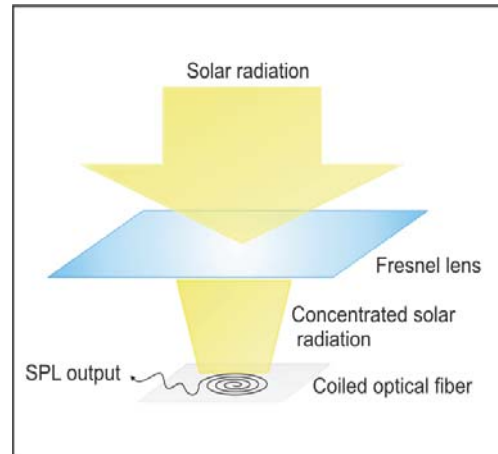


Figure 1. Schematic of a side pumped solar pumped laser concept.

III. EXPERIMENTAL

Glass samples (30g batch) used in this research were prepared by conventional melt-quenching technique using chemicals of 99+% purity. Molar % composition of the fabricated samples were as follows: 65P₂O₅:17Li₂O:3Al₂O₃:4B₂O₃:5BaO:(6-x)La₂O₃:xNd₂O₃ (with x = 0.05, 0.5, 1, 2, 3, 5). The samples were named as Nd01 ÷ Nd06 for short. The host composition was ad hoc developed for this research in order to have the glass stable, robust, able to incorporate high amount of RE and suitable for fiber drawing. After weighting and mixing, the batched chemicals were melted within a chamber furnace at a temperature of 1500°C, under dried air atmosphere with a water level lower than 2 ppmv. The melt was cast into a brass mould preheated at 480 °C and annealed at the same temperature for 10 h. The obtained glasses were cut and optically polished with a diamond paste to 2 mm thick samples for different optical and spectroscopic characterization.

Density of samples was measured by Archimedes method using distilled water as immersion fluid. The Nd³⁺ ion concentrations were calculated from measured sample densities and their initial compositions. Thermal analysis was performed on fabricated glasses using a Perkin Elmer DSC-7 differential scanning calorimeter up to 550°C under Ar flow with a heat rate of 10°C /min in sealed Al pans using typically 30 mg samples. Thermal analysis was carried out in order to measure the characteristic temperatures T_g (glass transition temperature) and T_x (onset crystallization temperature). Their measurement allowed assessing the corresponding glass stability parameter ΔT = T_x-T_g that is an estimation of the fiber

drawing ability of the glasses. In fact larger ΔT , for a glass host, means larger working range during sample fiber drawing. An error of $\pm 3^\circ\text{C}$ was observed in measuring the characteristic temperatures. The refractive index of the glasses was measured at 5 different wavelengths by prism coupling technique (Metricon, model 2010). Five scans were used for each measurement. Estimated error of the measurement was ± 0.001 .

The absorption spectra were measured at room temperature for wavelengths ranging from 350 to 3000 nm using a double beam scanning spectrophotometer (Varian Cary 500). Fluorescence spectra of samples were acquired using a Jobin Yvon iHR320 spectrometer equipped with a Thorlabs PDA10CS and standard lock-in technique. Emission spectra were obtained by exciting the samples with two different excitation sources: first a monochromatic light at the wavelengths of 785 nm, emitted by a single mode fiber pigtailed laser diode (Axcel B1-785-1400-15A); then a broadband visible light emitted by a supercontinuum source (Coheras SuperK Extreme), in order to simulate the broadband solar light. The fluorescence lifetime of $\text{Nd}^{3+}:^4\text{F}_{3/2}$ level was obtained by exciting the samples with light pulses of 785 nm single mode fiber pigtailed laser diode, recording the signal by a digital oscilloscope (Tektronix TDS350) and fitting the decay traces by single exponential. Fluorescence spectra and lifetime measurements were collected in both wavelength regions by exciting the samples at the very edge in order to minimize reabsorption.

All measurements were performed at room temperature.

IV. RESULTS AND DISCUSSIONS

A. Physical and thermal properties

Typical physical properties values of the manufactured glass samples are reported in Table 1.

The measured characteristic temperatures indicate good thermal properties of the glasses. The stability parameter is around 207°C , a value that demonstrates that these glasses are very stable against crystallization and suitable for fiber drawing.

Concerning the linear thermal expansion coefficient, the obtained value is fairly low, making these glasses resistant to thermal shock.

TABLE I. TYPICAL PHYSICAL PROPERTIES VALUES OF THE MANUFACTURED GLASS SAMPLES

density	$2.88 \pm 0.05 \text{ g/cm}^3$
glass transition temperature (T_g)	$495 \pm 3^\circ\text{C}$
crystallization temperature (T_x)	$702 \pm 3^\circ\text{C}$
glass stability parameter ($\Delta T = T_x - T_g$)	$207 \pm 6^\circ\text{C}$
coefficient of thermal expansion	$10 \text{ E-}6 \text{ }^\circ\text{C}^{-1}$
refractive index @ 633nm	1.551 ± 0.001

B. Absorption spectra

UV-VIS-NIR spectroscopy was carried out on all prepared samples and absorption spectra were recorded. Absorption cross-section σ_a was calculated from experimental data using the following formula:

$$\sigma_a = (2.303 \log(I_0/I)) / (NL) \quad (1)$$

where $\log(I_0/I)$ is the absorbance, L the glass sample thickness in cm and N is the concentration of the Nd^{3+} ions per cm^3 .

Fig. 2 shows the absorption cross-section values obtained for glass sample Nd04. The inhomogeneously broadened bands are assigned to the transitions from the ground state $^4\text{I}_{9/2}$ to the excited states of Nd^{3+} ions (see for reference Fig. 3).

In Fig. 2, for reference, the solar spectral irradiance at sea level is also reported. As previously mentioned, Nd^{3+} presents several strong absorption bands in the visible, where the sun has its maximum emission, making it a suitable doping ion for the development of a SPL.

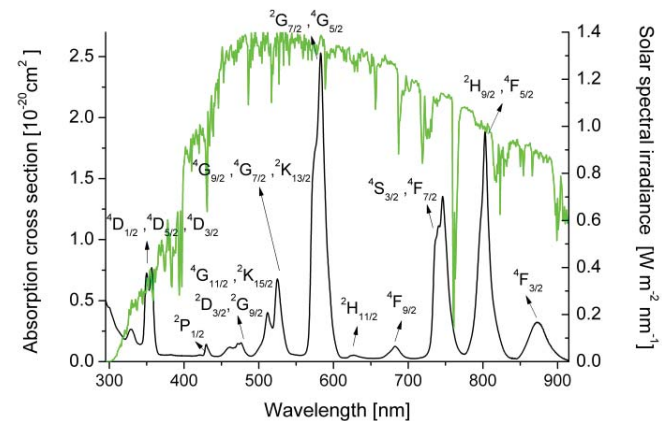


Figure 2. Absorption cross-section spectrum for sample Nd04. The main Nd^{3+} levels are labeled, considering absorption from the ground state $^4\text{I}_{9/2}$. In green, for reference, the solar spectral irradiance at sea level is reported (ASTM G173-03).

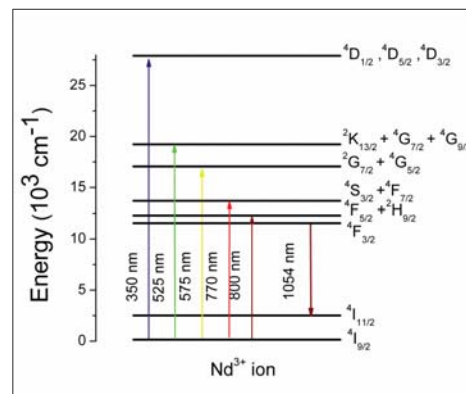


Figure 3. Schematic energy level diagram of Nd^{3+} ion.

C. Fluorescence emission spectra

Fig. 4 illustrates the fluorescence spectra of the glass Nd05 (6 mol% Nd³⁺ concentration) in the wavelength range 1010÷1110 nm under 785 nm excitation and broadband visible light. The broad 1.06 μm emission is assigned to the ⁴F_{3/2}→⁴I_{11/2} transition. Similar spectra were recorded for the other manufactured glass samples.

It is important to underline that the emission spectrum in the case of monochromatic and polychromatic excitation light pump is the same, although the excitation process of the ion is completely different. This mean that it is possible to use as excitation light the single frequency source, that is easier to handle and extend all the results also to the case of a polychromatic pump source, like the sun.

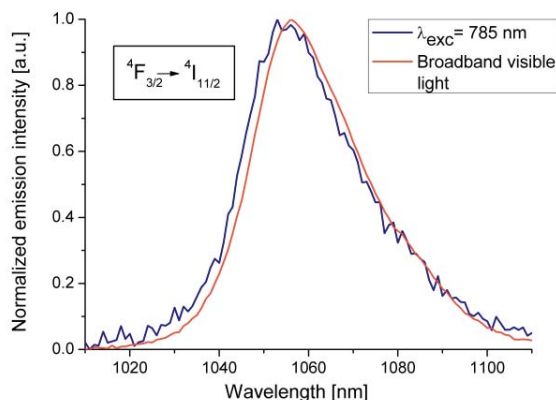


Figure 4. Emission spectra of the ⁴F_{3/2}→⁴I_{11/2} transition of Nd³⁺ upon 785 nm excitation and broadband visible light for the sample Nd05 (6 mol% Nd³⁺ concentration).

D. Fluorescence lifetime

Another experimental parameter required to characterize the emission properties of RE ions in a host medium, and therefore its suitability for active optical devices, is the fluorescence lifetime. Moreover, the fluorescence lifetime is one of the requested parameter for laser design.

Lifetime is the expected time before the excited state electron returns to a lower energy state by photon emission. In particular for a Nd³⁺-doped laser operated at 1.06 μm, the important parameter is the ⁴F_{3/2} lifetime: the longer the lifetime, the higher the population inversion between this level and the ⁴I_{11/2} one.

The decay curves of the ⁴F_{3/2} were measured upon 785 nm excitation for all glass samples and the results are reported in Table 2.

Lifetime decreases with increasing doping concentration, because of the unwanted energy transfer between ions at high concentration level, implying a reduction of the luminescence performance. This effect, referred to as concentration quenching, is described by the following empirical formula that relates the measured lifetime (τ) and Nd³⁺ ion concentration (N):

$$\tau = \tau_0 / [1 + 9/2\pi(N/N_0)] \quad (2)$$

where τ₀ is the lifetime in the limit of “zero” concentration, i.e. the radiative lifetime, and N₀ is the quenching concentration [16]. By fitting the experimental data with the above formula, the following characteristic values were obtained: τ₀ = 367 μs and N₀ = 8.47 E+20 ions/cm³.

TABLE II. EXCITED STATE LIFETIME VALUES FOR Nd³⁺ DOPED SAMPLES UNDER LASER EXCITATION AT 785 NM.

Glass samples	Nd ³⁺ concentration [mol%]	Nd ³⁺ concentration [x 10 ²⁰ ions/cm ³]	Nd ³⁺ : ⁴ F _{3/2} lifetime [μs] ±15μs
Nd01	0.1	0.134	365
Nd02	1	1.32	358
Nd03	2	2.66	327
Nd04	4	5.33	212
Nd05	6	7.72	177
Nd06	10	13.3	92

The results are in line with values reported in literature [17-18]. Graphical presentation of experimental data and curve fit are shown in Fig. 5.

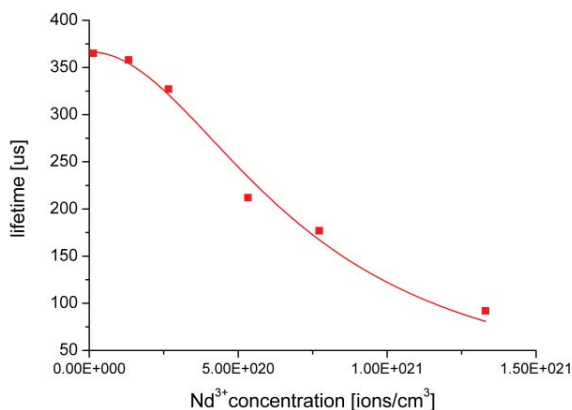


Figure 5. Correlation between ⁴F_{3/2} lifetime and Nd³⁺ ion concentration.

V. CONCLUSION AND FUTURE DEVELOPMENTS

This paper presents physical and optical properties of a novel Nd³⁺ doped phosphate glass system proposed for the development of a solar pumped fiber laser. All prepared glass samples were homogeneous and presented a good thermal stability and thus are suitable for fiber drawing. A strong emission at 1.06 μm was measured for each glass sample by using two different excitation sources: a laser at 785 nm and a polychromatic light, confirming the possibility to pump these glasses by concentrated sunlight.

The effect of Nd³⁺ doping concentration on optical properties was investigated in order to study the concentration quenching effect on luminescence performance. No changes in

the shape of the fluorescence spectrum were found with increasing the Nd³⁺ doping level. Lifetimes of the Nd³⁺:⁴F_{3/2} were found to decrease with increasing Nd³⁺ concentration. The following characteristic values parameters were obtained: radiative lifetime $\tau_0 = 367 \mu\text{s}$ and quenching concentration $N_0 = 8.47 \text{ E}+20 \text{ ions/cm}^3$.

The next step in this research will be the design, based on these preliminary results, of the optical fiber to be pumped with concentrated solar light. The choice of the most suitable Nd³⁺ doping level will be driven not only by the concentration quenching effect, but also by the maximum energy available for the pumping. Thus, it will depend on the dimension and efficiency of the solar element collection system and the optical pumping scheme.

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