## Research report –Short term mobility of Jiang Li in CNR

Period: December 16 - 23, 2016 (6 working days)

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**A. Introduction**

The visit was aimed to set up a common research activity on the subject of transparent ceramics for laser applications, as a basis for the organization of future research projects.

Focused research activities have been set up during the visit, allowing the individuation of the most promising research lines, and aimed to the preparation of joint publications.

The research is focused on novel mixed garnet ceramics, with composition Yb:$(Y,Gd,Lu)_3(Al,Sc,Ga)_5$ doped with Yb, with a broad fluorescence band in the near infrared, enabling the generation of broadband tunable laser emission and ultrashort laser pulses. Various formulations will be addressed, to establish the impact of the mixed structure on the spectroscopic and laser properties. The impact of different fabrication procedures on the optical properties (uniformity, defects) which can affect the laser performances will also be evaluated.

For the activities in the period of my visit, samples fabricated in SICCAS with formulations Yb:$(Lu_{0.5},Y_{0.5})_3Al_5O_{12}$ with Yb doping of 5%, 10% and 20%, were brougth in the INO-CNR laboratories in Sesto Fiorentino, and subjected to experimental research as described in details in the following parts.

**B. Research activities**

### 1. Microstructural and spectroscopic characterization of the ceramic samples

The samples used in the experiment were fabricated by a solid-state reactive sintering method [**Errore. L'origine riferimento non è stata trovata.**] at 1800°C for 30h under vacuum using high-purity $Lu_2O_3$, $Y_2O_3$, $Al_2O_3$ and $Yb_2O_3$ powders as raw materials. Figure 1 report the FESEM micrographs of the thermally etched surfaces of the samples with different dopings and the fractural surface of the 10at.% doping sample. It can be seen that the grain size decreases with increasing the doping concentration of Yb3+, indicating that the high concentration of dopant inhibits the grain growth. The grain boundaries of all samples are very clean and there are almost no micropores at the grain boundaries or inside grains.

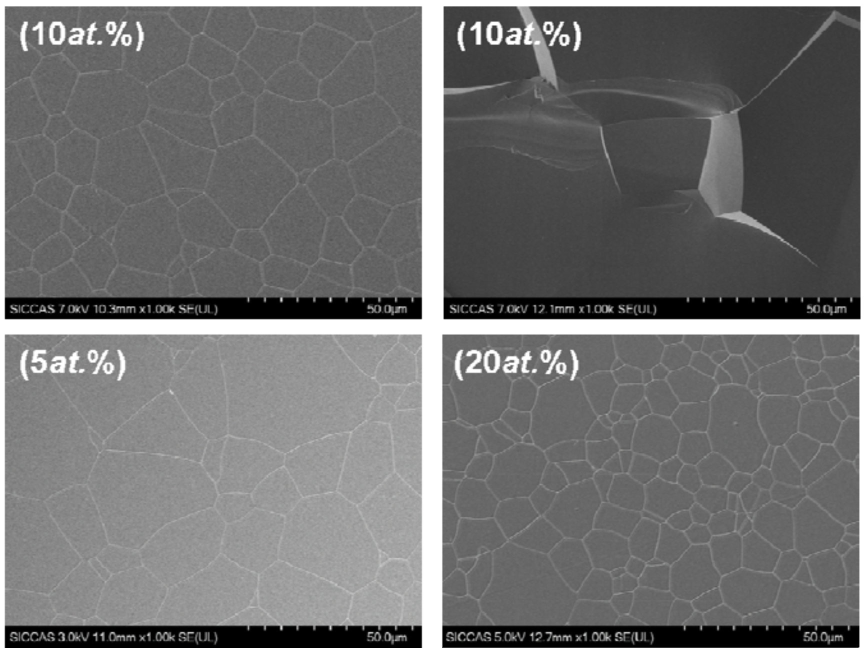


Fig. 1. FESEM micrographs of the thermally etched surface of 5at%, 10at.% and 20at% $Yb:(Lu_{0.5}Y_{0.5})_3Al_5O_{12}$ transparent ceramics and the fractural surface of the 10at% doping sample.

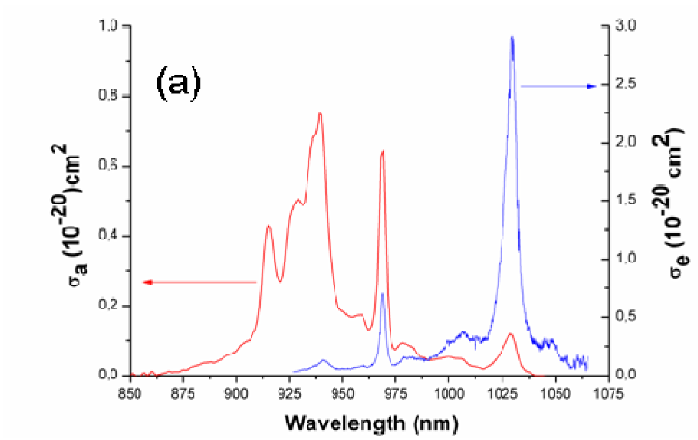


Fig. 2. Absorption ($\sigma_a$) and emission ($\sigma_e$) cross sections spectra of the $Yb^{3+}$ 4f-4f transition for 5*at.*% ceramics.

For all the samples, the transmission in the near infrared was very close to the theoretical limit set by the Fresnel reflections. Figure 2 shows the absorption and emission cross sections spectra at room temperature of the Yb laser transition. The absorption spectrum was acquired by means of a Shimadzu spectrometer 3101PC. The structured absorption lines of $Yb^{3+}$ in the near infrared region related to transitions within $^2F_{7/2}$–$^2F_{5/2}$ multiples include an intense band suitable for diode-laser pumping and a well-defined peak at 968 nm (zero-phonon absorption line). The fluorescence spectrum was recorded by a grating spectrometer equipped with a CCD array. To avoid reabsorption effects the samples were excited (using a pulsed laser diode at 936 nm) in a small spot very near to a lateral edge of the sample; the fluorescence was collected at 90° with respect to the pump beam direction by a converging lens and sent to the spectrometer. The lifetime of the $^2F_{5/2}$ state of Yb was measured by the pinhole technique in order to avoid radiation trapping effects. We found $\tau$=935μs (5at.%), $\tau$=940μs (10at.%), $\tau$=873μs (15at.%) and $\tau$=826μs (20at.%), respectively. The emission cross section spectrum was calculated with the $\beta$-$\tau$ method using the lifetime value of 935 μs (*i.e.* the one resulting from the less doped sample) for the calculation. The emission cross section spectra (see Fig. 2) were found substantially independent from the doping level.

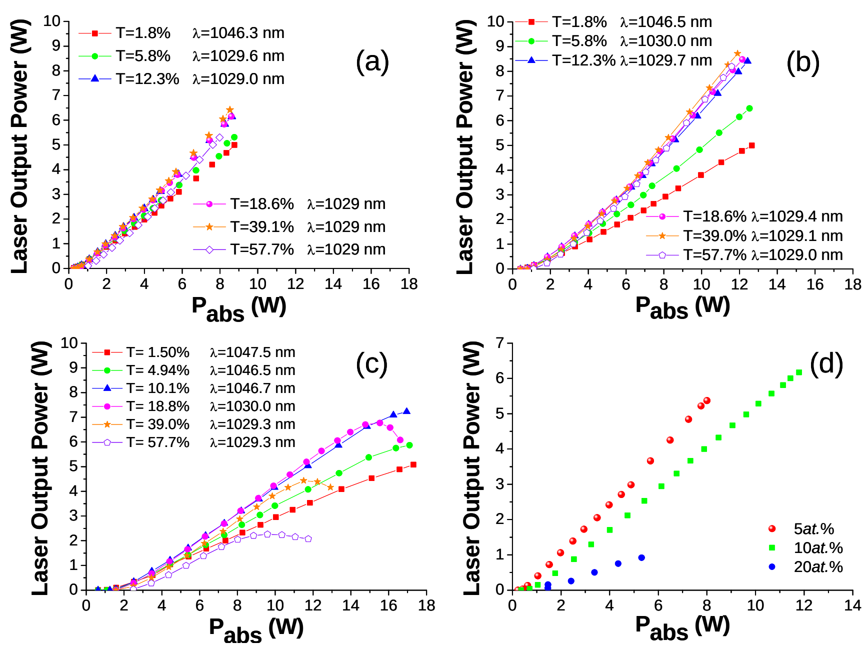


Fig. 3. Laser output power versus absorption pump power of the different ceramic samples: (a), 5at.%, (b) 10at.%(b) and (c) 20at.%, QCW; (d) CW laser output power versus absorption pump for the different samples.

## 2. Laser emission measurements

The sample is longitudinally pumped by a fiber coupled laser diode at 936 nm in *quasi*-CW (10Hz, 20% duty factor) and CW pumping regime. The pump spot in the sample has an almost Gaussian intensity distribution with a spot radius around 150 µm at $1/e^2$. The thickness of the samples are 1.4 mm (5at.%), 1.7 mm, (10at.%) and 1.4 mm (20%at.), with a pump absorption of 46.8%, 58.1% and 89.2%, respectively. The resonator is V-shaped, with a total cavity length of 260 mm, with the sample near to the pump coupling mirror. The $TEM_{00}$ mode radius at the sample is about 40 µm. The sample is soldered with indium on a copper heat sink water-cooled at 18°C. The tunability is obtained by inserting a ZnSe prism (apex angle 41.8°) near to the output coupler mirror. The laser wavelength is measured by a 60 cm focal length spectrometer equipped with a multichannel detector, with spectral resolution of 0.4 nm. Figure 3 reports the laser output power as a function of the absorbed pump power, $P_{abs}$, measured with several output coupler mirrors with different transmission T (from 1.5% to 57.7%). Free running laser emission occurred either near 1030 m or near 1046nm, as shown in the figure legends: longer wavelengths are obtained with transmission below T=5%. The highest slope efficiency is achieved by the 10at.% sample which delivers Pout=8.2W at 1029 nm. The samples with the lowest and highest doping provide 6.4W with ηs=86.5% (T=39.1%) and 7.2W with ηs=47.4% (T=10.1%), respectively. The 20at.% ceramic shows a different laser behavior depending on the excitation density of Yb involved in the laser action as well as on the pump level. With an output coupler transmission up to T=18.8%, the laser efficiency increases by increasing the pump power. With T= 10.1% we measured a maximum output power of 7.2W with a slope of 47.4% at 1046.7 nm. With T≥18.8% and absorbed pump levels above 14.7W, a rapid decrease of the output power is observed. The power roll-over takes place at lower pump levels by increasing the output coupler transmission.

## 3. Conclusions

We obtain the first laser oscillations of 5*at.*%, 10*at.*% and 20*at.*% Yb doped LuYAG ceramic samples and their spectroscopic characterizations. The maximum output power, 8.2W at 1029 nm, is achieved by 10*at.*% sample while the highest slope efficiency, 86.5%, is obtained from both the 5*at.*% and 10*at.*% doped samples. To the best of our knowledge, these are the highest laser slope efficiencies obtained so far for Yb doped LuYAG ceramics. With the 20*at.*% doped ceramic a decrease of the output power is observed for absorbed pump power higher than 15.6 W, probably due to the appearance of a non-linear loss mechanism. Its maximum output power was 7.2W at 1047.6 nm with a corresponding slope of 47.4%.

**C. Lecturing activities**

The seminar for CNR audience was given under the title **"Advanced Laser Ceramics Developed in Shanghai Institute of Ceramics, Chinese Academy of Sciences".**

**D. Communication and collaboration activities**

During the visit, a meeting was organized with Dr. Antonio Lapucci in the Florence site of National Institute of Optics, CNR.. Discussion addressed new ceramic lasers media, and we will start our collaboration on the characterizations of Nd doped multicomponent garnet transparent ceramics.

**E. Conference activities**

I went to Pisa together with Dr. Guido Toci and Dr. Matteo Vannini for participating as observer to the 2$^{nd}$ Progress Meeting of the Laser Design and Optimization WorkPackage (WP4), in the framework of the European Project EUPRAXIA. The meeting has been held at the National Institute of Optics, CNR, on December 19. The participation was useful to get a direct contact and a deeper insight with the laser development projects ongoing at INO.

In Sesto Fiorentino, Italy, December 23, 2016

Jiang Li

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The proposer of the Short Term Mobility Visit

Matteo Vannini

Matteo Vannini