Session	**D1-1-High Power Diode Pumped Solid State Lasers**	
Date	**Tuesday, 9 Dec 08**	
Time	**14:00 - 15:30 hrs**	
Session Chair	Horst **Weber**	
Room	**Executive Seminar Room 4.2**	
D1-1-01 - Invited 14:00 - 14:30 hrs (conf196a34)	**High Power Yb-doped Thin-disc Lasers** *Rigo* ***Peters,*** *Christian* ***Kränkel,*** *Susanne* ***Fredrich-Thornton****, Christian* ***Hirt****,* *Klaus* ***Petermann,*** *Günter* ***Huber***	**109**
D1-1-02 - Oral 14:30 - 14:45 hrs *(conf196a18)*	**Spectroscopy and Lasing of Cryogenically Cooled Yb,Na:CaF3** *W. J.* ***Lai,*** *A.* ***Pugžlys,*** *D.* ***Sidorov****, A.* ***Irshad****, L.* ***Giniūnas,*** *R.* ***Danielius,*** *P. B.* ***Phua****, L.* ***Su,*** *J.* ***Xu****, R.* ***Li****, A.* ***Baltuška***	**109**
D1-1-03 - Oral 14:45 - 15:00 hrs *(conf196a20)*	**Tunable, Continuous-Wave, Solid-State Source for the Blue** *G. K.* ***Samanta,*** *M.* ***Ebrahim-Zadeh***	**109**
D1-1-04 - Invited 15:00 - 15:30 hrs *(conf196a36)*	**High-power Diode-pumped Single-frequency Nd:YLF Lasers with Intracavity SHG to the Red Range** *Jean-Jacques* ***Zondy***	**110**
15:30 – 16:00	**Tea Break**	

Session	**D1-2-Ceramics Laser and Nonlinear Optical Crystals**	
Date	**Tuesday, 9 Dec 08**	
Time	**16:00 - 17:30 hrs**	
Session Chair	Ebrahim Zadeh **Majid**	
Room	**Executive Seminar Room 4.2**	
D1-2-01 – Invited 16:00 – 16:30 hrs	**Current and Future Status of Ceramic Lasers** *Akio* ***Ikesue***	**110**
D1-2-02 – Invited 16:30 – 17:00 hrs *(conf196a32)*	**Nonlinear Cascaded Lasing in Crystals and Ceramics** *Alexander A.* ***Kaminskii***	**110**
D1-2-03 – Invited 17:00 – 17:30 hrs	**High Efficiency Nonlinear Optical Crystals For Mid-Infrared Frequency Conversion** *Peter* ***Schunemann***	**110**

Spectroscopy and Lasing of Cryogenically Cooled Yb,Na:CaF2

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***Abstract*-Absorption, photoluminescence spectra and cw lasing parameters of an Yb^{3+}- and Na^{+}-codoped CaF_2 laser crystal are measured in the temperature range from 5 K to 290 K. The crystal appears to be a promising host for broadband multi-mJ kHz cw-pumped regenerative amplification.**

I. INTRODUCTION

Ti:sapphire femtosecond amplifiers operating at kHz repetition rates rarely exceed the energy level of a few milli-Joules and the average power of several Watts because of the thermal management and/or optical damage problems. In comparison with Ti:sapphire, the Yb^{3+} materials offer a very low quantum defect and can be pumped directly by laser diodes, making it very easy to attain high average powers in Yb oscillators. Although Yb crystals generally have a very long fluorescence lifetime, frequently longer than 1 ms, obtaining high gain is very challenging because their emission cross-section is 20—30 times lower than that of Nd and Ti:sapphire. Very high laser saturation and pump saturation intensities (e.g. for Yb:KGW and Yb:YAG ~10 kW/cm^2 and ~30 kW/cm^2, respectively) require an exceptionally tight diameter of the pump and cavity modes. The tight mode size becomes a problem for mJ-class chirped-pulse amplifiers, especially for Yb:YAG and Yb:KGW/KYW, the materials most established to date for regenerative and multi-pass amplification of femtosecond pulses. This is caused by high linear and nonlinear refractive indices; narrow gain linewidth (Yb:YAG); high Raman susceptibility (KGW/KYW).

Yb-doped fluorides represent an interesting alternative because of their transparency in a wide wavelength region from the VUV to the IR; low linear and nonlinear refractive indices and low nonradiative relaxation between adjacent energy levels. Among different fluoride hosts, CaF_2, one of the first host materials since the early 1960s [1,2], has one of the lowest phonon frequencies (328 cm^{-1}) and a high thermal conductivity (10 $Wm^{-1}K^{-1}$). Recently, a modified host, Yb^{3+},Na^{+}:CaF_2 was introduced, where Na^{+} acts as a charge compensator in CaF_2 [3,4]. As was shown in Ref. [3], codoping with Na^{+} leads to significant modifications of the spectroscopic properties, especially to an increase of the radiative lifetime.

In this contribution, we are examining optical and lasing properties of the new Yb,Na:CaF_2 host at temperatures ranging from room temperature (RT) to 5 K and present latest developments of Yb fiber laser seeded, cw pumped, cryogenically cooled regenerative amplifier (RA). Previously, several LN2-cooled Yb regenerative amplifiers at 10 Hz were developed by Yamakawa and coworkers [5]. The interest in the cryogenically cooled Yb amplifier [6] is determined by the following key advantages expected at low temperatures: a) disappearance of the ground state absorption (GSA) above 1000 nm, b) increase of the emission cross-section, i.e., higher single-pass gain and decreased saturation fluence; c) increase of thermal conductivity leading to an improved parasitic heat transport, lower thermal lens, increased thermal fracture threshold and decreased thermally induced birefringence; d) greater radiative lifetime; e) decreased pump saturation intensity.

II. Results

A. Spectroscopy

Spectroscopic properties of pure Yb:CaF_2 at cryogenic and room temperature and at various dopant concentrations were examined in detail by V. Petit et al. [7]. Hexameric clusters of Yb^{3+} ions were named as lasing centers of Yb:CaF_2 at the concentrations of Yb^{+3} above 0.1at. % [7]. Here we concentrate on the comparison of the optical properties of pure and Na^{+} co-doped Yb:CaF_2 crystals.

The overview of the measured absorption spectra for a 2% $Yb^{3+}CaF_2$ crystals with and without 3% Na^{+} cooled to different temperatures is presented in Fig. 1. For the measurements slabs of Yb:CaF_2 and Yb,Na:CaF_2 with the length of ~4 mm and height of 1.2 mm were mounted to a copper heat sink which was placed inside an LHe continuous flow cryostat (Oxford research, MicrostatHe). Luminescence was measured by exciting the crystals by a single emitter 980-nm laser diode.

General feature for both, pure and Na^{+} co-doped Yb:CaF_2 crystals, is that at cryogenic temperatures a significant increase of absorption (Fig.1), especially in the vicinity of zero phonon line (ZPL), and disappearance of GSA on the red side of the spectrum is observed. The main influence of Na^{+} co-doping on the shape of emission and absorption spectra is observed also in the vicinity of ZPL: co-doping of Yb:CaF_2 with Na^{+} leads to a substantial broadening of ZPL width which increases with Na^{+} concentration. This makes Yb,Na:CaF_2 advantageous with respect to other broadband

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Yb crystalline hosts by means of non-critical pumping, i.e., this permits pumping Yb,Na:CaF_2 into ZPL with conventional laser diode stacks without Bragg grating wavelength stabilization even at 80 K temperature (Fig.2), paving the way to a technologically simple and economical way for kHz-repetition-rate fs pulse energy scaling.

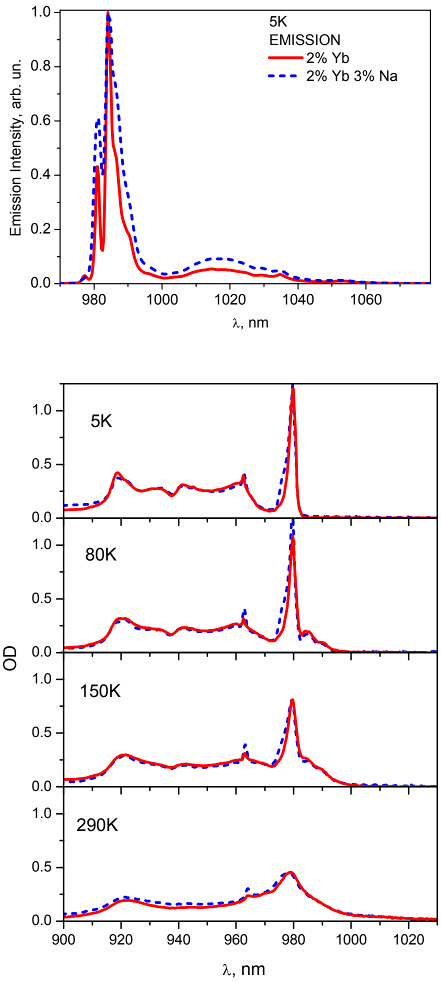

Fig.1. Emission (top panel) and absorption (bottom panels) spectra of 2%YbCaF2 (solid lines) and 2%Yb3%NaCaF2 (dashed lines) at various temperatures (indicated in the panels).

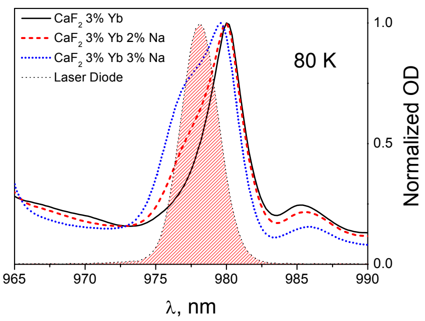

Fig.2. Comparison of the ZPL linewidth at 80 K in Yb:CaF2 and Yb,Na:CaF2 at two Na^{+} concentrations

From the measured absorption and luminescence spectra emission cross-sections of Yb,Na:CaF2 were recovered by using the method described in [8]. Calculated gain crossections (Fig. 3) reveal that at low temperatures, unlike Yb:KGW and even another fluoride host YLF [9], the gain cross-section of Yb,Na:CaF2 remains remarkably smooth and broadband, making it a promising host for cryogenic regenerative amplification (RA) of sub-100-fs pulses.

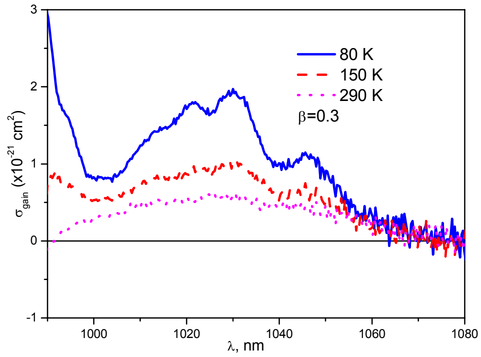

Fig 3. Gain cross-sections at different temperatures (indicated) at population inversion rate 0.3

B. *Lasing*

The lasing properties of Yb,Na:CaF2 were tested in a short cavity consisting of two high reflectors. Reflections off the uncoated cryostat windows provide an effective ~28% output coupler (OC) for the intracavity energy. The slope efficiencies and the threshold pump powers obtained in the case of effective OC of 28% at various temperatures are depicted in Fig. 4. The emission wavelength of the diode was selected such that the crystal absorption practically stayed invariant with temperature. Note that for the selected range of pump powers no lasing was obtained above 210 K because the losses due to GSA are too high.

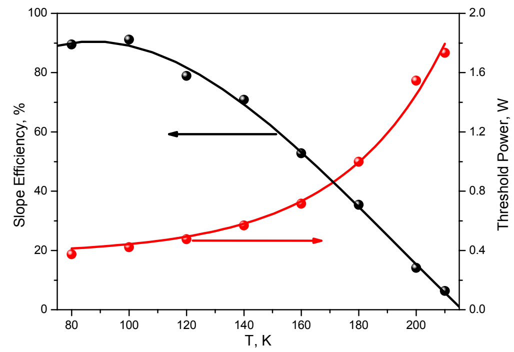

Fig. 4. Dependence of slope efficiency and lasing threshold dependence on the temperature.

To independently confirm that we can reach sufficient gain for constructing a cw-pumped RA, we measured single-pass gain by seeding the Yb,Na:CaF2 crystal with a cw fiber laser emitting at 1030 nm. Single-pass small signal gain in excess of 1.5 at 150 K (corresponding to the temperature of a recirculating cooler available in our lab) was readily obtained with the absorbed pump power of 10 W.

C. Regenerative amplifier

Considering the above-mentioned spectroscopic and lasing properties of Yb,Na:CaF2 we have designed a Yb fiber laser seeded Yb,Na:CaF2 regenerative amplifier (RA). The layout of the RA cavity is presented in Fig. 5. An AR-coated 2%Yb^{3+}3%$Na^{+}CaF_2$ slab with the length of ~4 mm and height of 1.2 mm is mounted to a copper heatsink with a layer of In on both sides of the slab. The crystal assembly is mounted inside a cryogenic chamber cooled to a temperature of 110K by a closed-loop refrigerator (CryoTiger). The crystal is pumped in a double-pass configuration by two 60-W laser bars (DILAS) lensed with a set of microoptics (Light Conversion, Ltd.). The small quantum defect of Yb^{3+} leads to only modest increase of crystal temperature (to ~140 K) while pumping with the full pump power. The temperature of the diode bars was set to match the ZPL of the laser crystal. The dichroic mirror DM in the cavity was installed in order to suppress lasing at ~1000 nm.

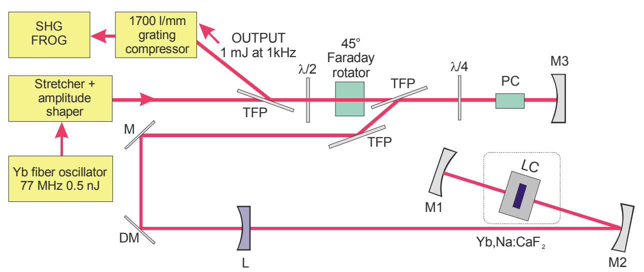

Fig. 5. Schematics of cryogenically cooled $Yb^{3+}Na^{+}CaF_2$ RA. M1-M3 curved mirrors, LC- cryogenically cooled laser crystal chamber, L – negative lens, DM- dichroic mirror, M – folding mirror, TFP – thin film polarizers, PC – Pockels cell, λ/2 and λ/4 – half- an d quarter-waveplates

The configuration of the cavity is essential for optimal RA operation: although cw lasing at the level of ~14 W an be easily achieved when pumping with ~ 60W (total output power of LD's) c, the mode size on the laser crystal appears rather small which, because of AR coating photo-damage, prevents operation in the Q-switched regime above 1 mJ level. Adjustment of the cavity configuration mainly by choosing an appropriate focal length and position in the cavity of the lens L leads to a larger mode size on the crystal and prevents AR coating damage up to 3 mJ energy of ns Q-switched pulses at 1kHz repetition rate.

As it is shown in Fig.6 the cw output of the RA is spectrally unstable: slightest changes in pump power or output coupling (by slightly rotating λ/4 plate in the cavity) causes variation of the output spectrum from 1029 nm to 1033 nm. This suggests a large variety of lasing sites in the 2%Yb^{3+}3%$Na^{+}CaF_2$ crystal. The behavior was not observed in the case of $Yb^{3+}CaF_2$ crystal without Na^{+} co-doping.

In the ps operation mode, the RA was seeded by the output of a femtosecond Yb fiber laser stretched to ~300 ps. The positive dispersion stretcher is based on a single transmission grating (1700 l/mm, WasatchPhotonics) and an R=-600 mm spherical mirror.

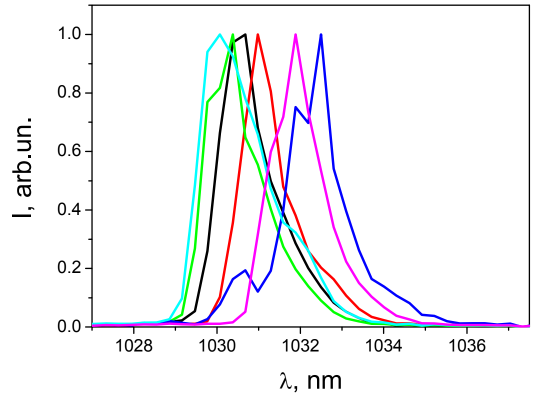

Fig. 6. Different time integrated cw spectra measured while slightly perturbing the RA cavity.

Since the amplification bandwidth of the RA is substantially narrower than the output spectrum of the fiber laser, in order to avoid using optical components of extra-large dimensions while ensuring sufficiently long seed pulses, the stretcher was designed to transmit only part of the fiber laser spectrum which was centered around 1030 nm, i.e., maximum of the amplification. The regenerative amplifier, if seeded with the unperturbed spectrum, supports ~ 5 nm bandwidth centered at 1031 nm (Fig. 7).

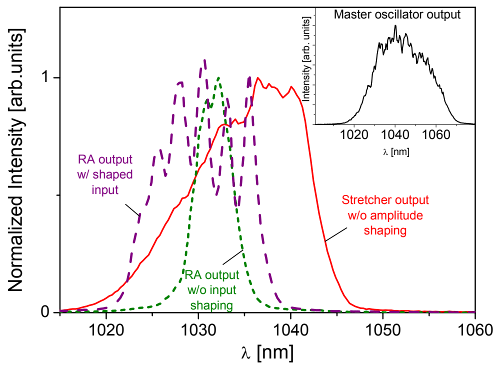

Fig. 7. Overview of input and output spectra: Seed spectrum (solid), amplified spectrum without shaping (short dashed) and amplified spectra with heavy spectral amplitude shaping (dashed). Inset: output spectrum of the Yb fiber seed laser.

By installing in the Fourier plane of the stretcher an amplitude shaper consisting of a series of mechanical adjusters to suppress spectral components in the central part of the amplification spectrum, we were able to broaden the spectrum of the RA output to 12 nm FWHM (dashed curve in Fig.7). As the result, 1-mJ pulses with the spectrum supporting 90-fs FWHM pulse duration were generated. The incident pump power on the crystal was about 20W (~10 W from each diode). It is important to mention that neither pulse train saturation nor bi-stable behavior of the pulse train, which is common for Yb:KGW RA, was observed at 1-mJ energy. Further amplification was not possible because of optical damage of the AR coatings of the crystal. Examination the crystal revealed that only optical damage of the AR coating was taking place, no optical damage in the volume was found.

Finally we would like to point out an excellent spatial quality of the RA cavity output in the case of all three, cw, Q-switched and picosecond, operation regimes. As it is shown in Fig.8, the beam profile is ideally Gaussian in both vertical and horizontal cross-sections with M^2 being very close to one (M^2 of 1.05 was measured in the case of picosecond operation).

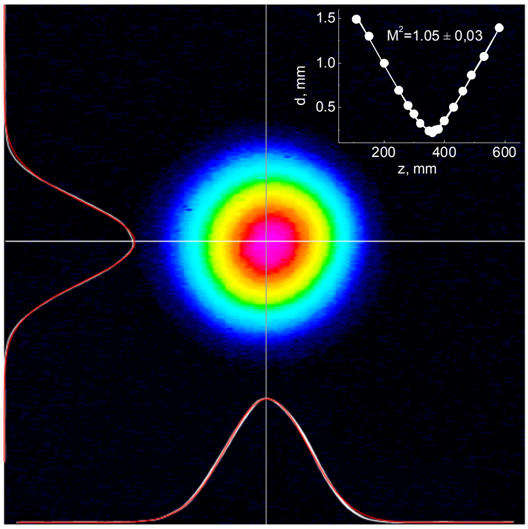

Fig.8. Far field output beam profile at 1 mJ 1-kHz. Red lines: vertical and horizontal beam profile cross-sections. White lines: Gaussian fits. An M^2 measurement (M^2 =1.05±0.03) is shown in the top right corner.

In conclusion, we have explored the lasing and spectroscopic properties of the novel Yb host, CaF_2 codoped with Na^+, which, despite being a low gain cross-section material, presents considerable interest for cw-pumped RA of multi-mJ (sub-)100-fs pulses with repetition rates approaching 1 kHz at cryogenic temperatures. Particular advantages of the cryogenic scheme with this crystal lie in the possibility to pump it into the ZPL, which reduces the quantum defect to about 5%, with conventional polarization-combined laser diodes without wavelength stabilization. Stronger emission and absorption at low temperatures in principle allows one to lower the Yb concentration, thus further increasing the crystal fracture limit. Finally, by merging Yb fiber laser master oscillator technology and cryogenically cooled DPSS Yb,Na:CaF_2 regenerative amplifier technology we have generated 1-mJ pulses at 1 kHz repetition rate with the spectral bandwidth of 12 nm. Amplification substantially beyond 1 mJ should become feasible in the very near future by improving the quality of surface polishing and AR coatings, as well as by further optimizing the RA cavity design. Spectral shaping of the seed appears to be crucial for amplification of broad spectra and shows potential for attaining sub-90-fs pulses with an appropriately matched (blue-shifted) spectrum from the master oscillator.

REFERENCES

[1] P. Sorokin, M. Stevenson,"Stimulated Infrared Emission from Trivalent Uranium", Phys. Rev. Lett. 5, 557-559 (1960).

[2] G. Boyd, R. Collins, S. Porto, A. Yariv, W. Hargreaves, "Excitation, Relaxation, and Continuous Maser Action in the 2.613-Micron Transition of CaF_2:U^{3+}", Phys. Rev. Lett. 8, 269-272 (1962).

[3] L. Su, J. Xu, H. Li, L. Wen, Y. Zhu, Z. Zhao, Y. Dong, G. Zhou, J. Si, "Sites structure and spectroscopic properties of Yb-doped and Yb, Na-codoped CaF2 laser crystals", :Chem. Phys. Lett. 406, 254-258 (2005).

[4] L. Su, J. Xun, H. Li, W. Yang, Z. Zhao, J. Si, Y. Dong, G. Zhou, "Codoping Na+ to modulate the spectroscopy and photoluminescence properties of Yb^{3+} in CaF2 laser crystal", Opt. Lett. 30, 1003-1005 (2005).

[5] J. Kawanaka, K. Yamakawa, H. Nishioka, and K.-I. Ueda, "30-mJ, diode-pumped, chirped-pulse Yb:YLF regenerative amplifier" Opt. Lett. 28, 2121-2123 (2003).

[6] D.C. Brown, "The promise of cryogenic solid-state lasers", IEEE J. Sel. Top. Quantum Electron. 11, 587-599 (2005).

[7] V. Petit. PCamy, J-L. Doualan, X. Portier and R. Moncorge, "Spectroscopy of Yb^{3+}:CaF_2: from isolated centers to clusters", Phys. Rev. B 78, 085131-1 – 08531-12 (2008) and references therein.

[8] P.-H. Haumesser, R. Gaumé, B. Viana, and D. Vivien, "Determination of laser parameters of ytterbium-. doped oxide crystalline materials", J. Opt. Soc. Am. B, 19, 2365-2375 (2002).

[9] J. Kawanaka, K. Yamakawa, H. Nishioka, K. Ueda, "Improved high-field laser characteristics of a diode-pumped YB:LIYF4 crystal at low temperature", Opt. Express 10, 455-460 (2002) "30-mJ, diode-pumped, chirped-pulse Yb:YLF regenerative amplifier", Opt. Lett. 28, 2121-2123 (2003).