Tunable distributed feedback color center laser using stabilized F_2^{+**} color centers in LiF crystal

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ABSTRACT

The first room temperature stable tunable color center (CC) distributed feedback (DFB) laser is described. The laser utilizes stabilized F_2^{+**} centers in LiF (LiF:F_2^{+**}) as a gain medium. Tunable DFB lasing was achieved in the near IR region (882 - 962 nm) with a lasing linewidth of less than 0.2 cm^{-1}. The lasing threshold was found to be 1.2 mJ, while the slope efficiency with respect to pump energy was found to be as high as 3%.

Keywords: color center laser, distributed feedback laser, LiF:F_2^+ color center crystals.

1. INTRODUCTION

Distributed feedback (DFB) lasers are mirror-less sources of coherent radiation utilizing backward Bragg scattering from periodic modulations of their refractive index[1,2]. First introduced by Kogelnik and Shank in the early 70's[1,3], DFB lasers have attracted considerable attention due to their ease of construction, precise tuning, and good mode selection. Tunable operation of DFB lasers throughout the UV-visible range has been realized using different organic dyes[4-9] and crystalline impurity doped laser materials[2]. LiF color center crystals (CCCs) are known to be promising laser media for high energy tunable lasing[10] and are also promising active media for DFB tunable solid state lasers in a broad visible - middle infrared spectral range. The construction of DFB lasers using F_A(II) and N_2 CCs in KCl and F_2 CCs in LiF crystals was reported by G.C. Bjorklund[11] and Kurobori et al[12, 13]. However, poor thermo- and photo- stability were limiting factors in these crystals, and thus the lifetime of these lasers was short. In fact, the laser operation in[11,12] required liquid nitrogen cooling of the KCL gain medium and the LiF:F_2 crystal in[13], although being thermo-stable at room temperature, degraded after 500 pumping pulses due to the poor photo-stability of active F_2 CCs.

Due to their low hygroscopicity and a unique combination of operational (high photo-thermo stability), spectroscopic, and laser characteristics[10], LiF crystals are the most exceptional of all the alkali-halides. Some of the latest improvements in CCCs have produced LiF with stabilized F_2^{+**} CCs (LiF:F_2^{+**}), crystals which combine the thermal- and photo-stability of impurity doped laser crystals with the high absorption and emission cross-sections of laser dyes[14,15]. The F_2^{+**} CCs constitute pairs of adjacent anion vacancies with one captured electron (F_2^+ center) further perturbed by neighboring anion impurities, cation impurities, and cation vacancies[15]. Efficient room temperature (RT) stable lasing tunable over a 0.80-1.22 μm spectral range was demonstrated in[14]. The following reports our experimental results on a first tunable room temperature stable LiF:F_2^{+**} DFB laser.

2. EXPERIMENTAL SETUP

The 19.3×7.4×8.3 mm^3 crystal studied was grown by the Kyropulos method and doped with LiOH, LiO_2, and MgF_2 in order to provide thermal and photo stabilization of the positively charged CCs. To obtain a high concentration of F_2^{+**} centers and a low concentration of colloids and parasitic aggregate CCs, a multi-step technique in which the crystals were γ-irradiated by a ^{60}Co source was used[14]. Next the two largest parallel faces (19.3×8.3 mm^3) were polished and the other four sides cleaved. The absorption spectrum of the studied LiF:F_2^{+**} CCC is shown in Fig.1. The absorption coefficient of the studied crystal at room temperature was found to be k=3.5 cm^{-1} at 610 nm, but

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it should be noted that the maximum absorption coefficient of LiF:F_2^{+*} CCCs at a given wavelength can be as high as 7.5 cm^{-1}.

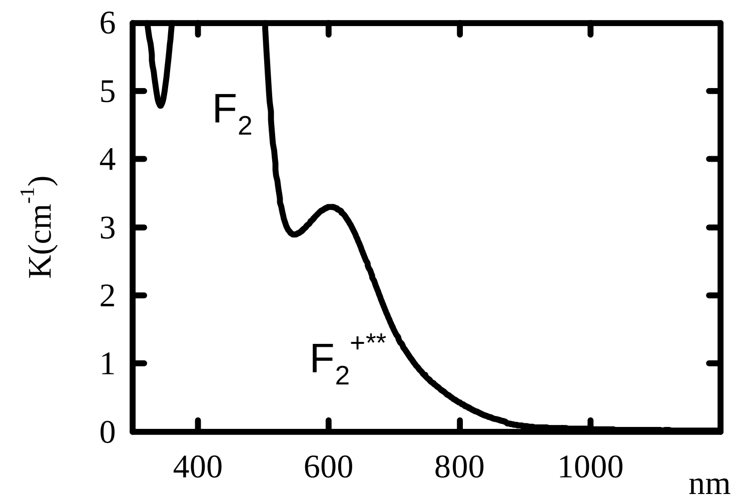

Fig.1. Absorption spectrum of LiF:F_2^{+**} Color Center Crystal

The interference of two equal laser beams, and the resulting fringe they create, was used for development of the dynamic grating in the crystal. The experimental setup is shown in Fig. 2. A single longitudinal mode "SpectraPhysics" Nd:YAG GCR 230 laser was used as a pumping source. It was operated in the second harmonic at a wavelength of 532 nm with 12 ns pulse duration at a 10 Hz repetition rate.

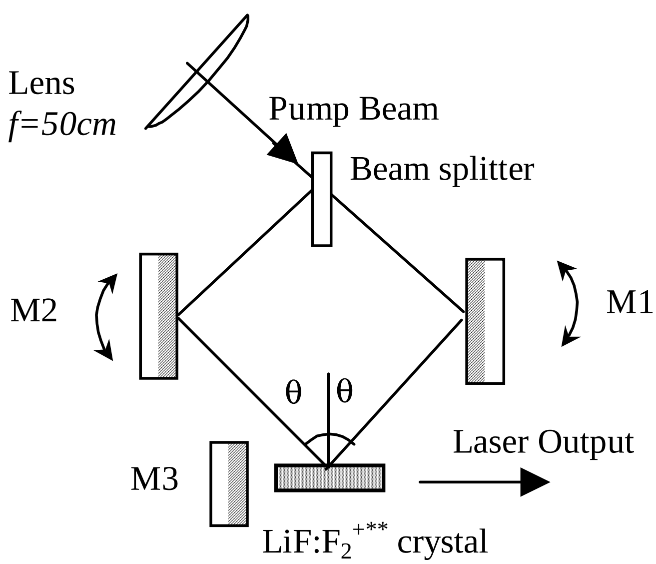

Fig.2. Experimental setup of LiF:F_2^{+**} DFB laser.

The pump beam was first focused by a cylindrical lens (*f*=50 cm) to obtain high intensity interference fringes. Next it was split into nearly equal parts by a beam splitter and directed to the crystal by two adjustable mirrors (R≈99%). The focused beams produced a DFB laser grating approximately 0.5 mm wide and 10 mm long. To provide additional feedback and to concentrate the laser output in one direction, the mirror M3 was placed perpendicular to the crystal slab. The oscillation of the DFB laser was detected by a spectrograph (Acton Research 150) with a 0.5 nm resolution equipped with CCD camera. The period of the interference fringe was controlled by adjusting the angle θ between the interfering beams according to the relationship:

$$\Lambda = \frac{\lambda_p}{2\sin\theta}, \qquad \textbf{(I)}$$

where Λ-period, λ_p-pumping wavelength, and θ-interference beam incident angle measured from the normal to the crystal surface. The DFB lasing wavelength can be adjusted by adjusting the period of the interference fringe (and thus the grating) which follows the Bragg condition:

$$\Lambda = \frac{m\times\lambda_l}{2n}, \qquad \textbf{(II)}$$

where m-order of diffraction (our setup uses 1st order), λ_l-lasing wavelength, and n-index of refraction (1.38 for LiF[10]).

Thus, following the previous equations, tuning of the DFB laser is achieved by changing the incident angle of the pumping beams. For the first order of diffraction the incident angle of our pumping beams was in the 50-57 degrees range. Remarkably, this is close to the Brewster angle of LiF crystal (54°) and, hence, pumping losses are minimized for our experimental arrangement.

3. EXPERIMENTAL RESULTS

The emission spectrum of the DFB lasing was detected by a 0.5 nm resolution spectrograph-CCD combination. The broadband lasing in Fig. 3 was attained by pumping the crystal at high power with one shoulder of the interfering beams blocked. Broadband oscillation in this scheme occurred in a nonselective cavity with positive feedback due to mirror M3 and Fresnel reflection from the crystal's facet (R≈2.5%). However, once both shoulders of the pumping scheme were opened the laser switched to the narrowband regime of DFB oscillation. The DFB tuning over the 882-962 nm spectral range is depicted in Fig. 3 and was provided by changing the angle θ of the interfering beams with the normal to the crystals surface. The gain profile of LiF:F_2^{+**} under 532 nm excitation is centered at 930 nm. Thus when the setup was adjusted to lase near the center wavelength only narrowband DFB oscillation occurred. However, when the setup was adjusted outside this spectrum a coupled cavity scheme occurred accompanied by a competition between DFB and typical broadband lasing.

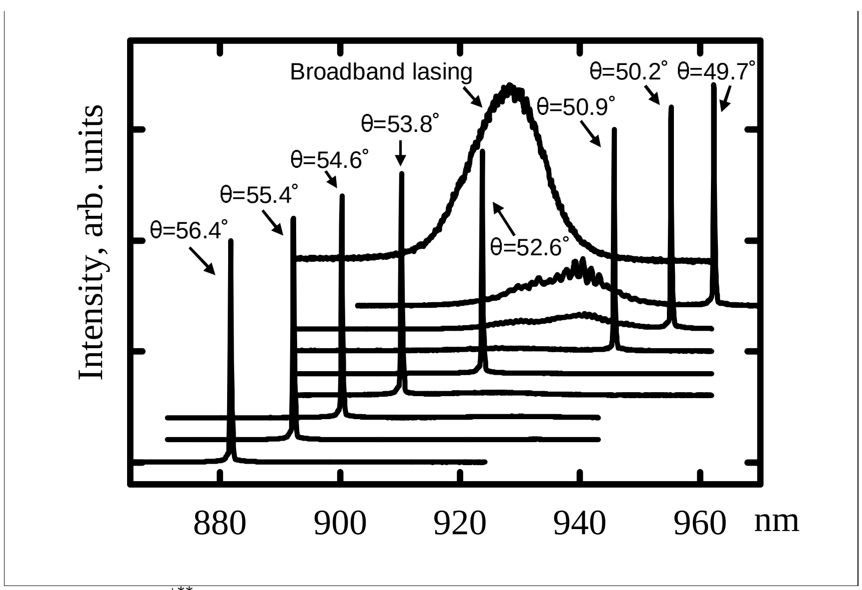

Fig.3. Tunable operation of LiF:F_2^{+**} distributed feedback laser. The broad band at 925 nm corresponds to laser emission in nonselective cavity. All spectra were scaled for convenience.

Fig. 4 depicts the output-input characteristic of the laser. The DFB lasing threshold was observed at total incident pump energy of 1.2 mJ. The maximum conversion efficiency of 3% was achieved at 920 nm at 10 mJ of pump energy. We believe this obtained value of conversion efficiency is far from the potentially achievable efficiency (tens of %) and could be explained by a low coupling efficiency of the Bragg scattering due to a poor spatial coherence of the pump radiation. There was no noticeable decrease in output energy of the DFB laser during 5 hours of continuous operation at a 10 Hz repetition rate.

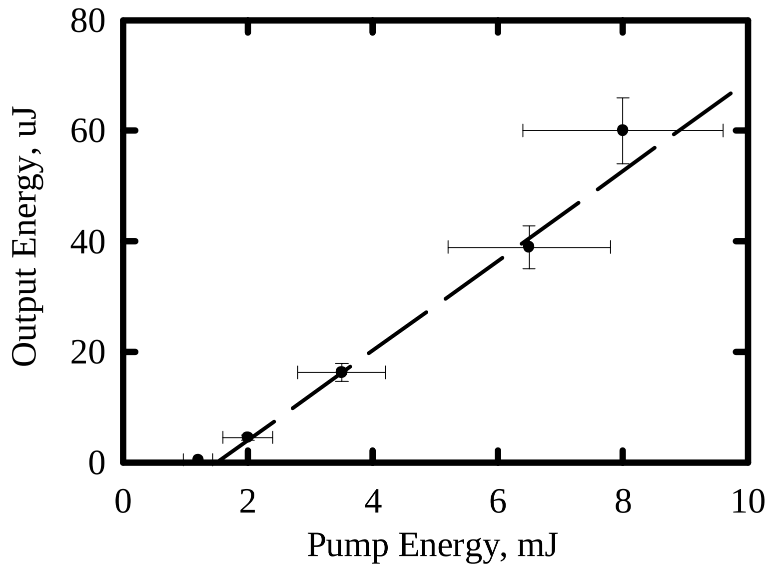

Fig.4. The output energy of LiF:F_2^{+**} DFB laser versus pump pulse energy.

Because our distributed feedback is due to a dynamic grating, proof of the existence of DFB can be obtained by blocking one shoulder during DFB lasing. If one shoulder is blocked, the interference fringe must disappear and in turn so must any lasing due to DFB. Once the shoulder is reopened the DFB lasing peak should reappear. Next, the other shoulder is blocked. If this action also eliminates the peak in question, it is reasonable to assume that the peak in question is due to DFB. This method was employed in all cases in which DFB occurred.

The temporal profile of pumping pulse versus output pulse was also measured and is displayed in Fig. 5. Graph A is the initial pumping pulse while graph B is the resulting DFB output pulse. A fast photodetector (Newport, 818-bb-20) with a rise time less then 200 ps was used to measure the time delay between the pumping pulse and the corresponding DFB laser oscillation. As can be seen in the Fig. 5, the rise-time of laser oscillations is a few nanoseconds and it is accompanied by a good temporal overlap of pump and laser emission pulses. Good temporal overlap of the pump and DFB output laser pulses accompanied by a narrow line DFB generation are important factors for realization of efficient up- and down- conversion by means of frequency mixing (sum and difference frequency generation) of the pump and DFB beams.

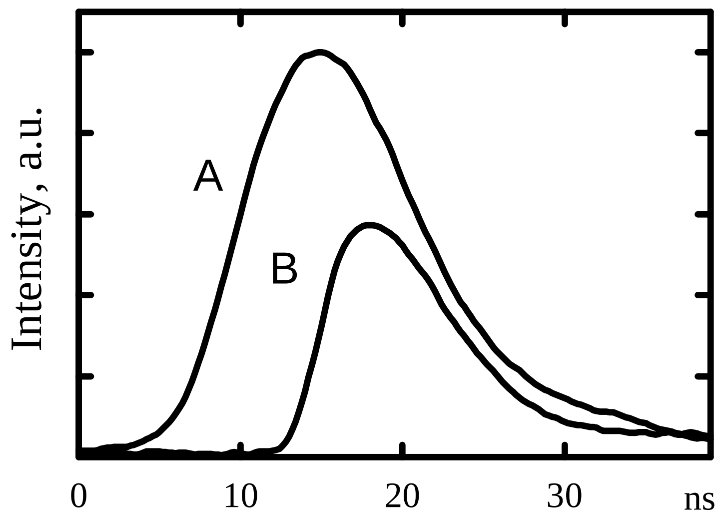

Fig.5. Temporal delay of LiF:F_2^{+**} DFB laser emission (B) with respect to pumping pulse (A).

An etalon with a 1 cm^{-1} free spectral range was used to measure the linewidth of DFB laser oscillation (shown in Fig.6). The FWHM of the DFB laser oscillation at 920 nm was 0.2 cm^{-1}. The maximum etalon resolution was 0.1 cm^{-1}. A simple estimation of the spectral laser line ($\Delta\nu$) of the DFB laser may be obtained by using the equation for the spectral resolution of a grating given by $\nu/\Delta\nu_{cav} \approx L/\Lambda$, where L is the interaction length[2]. Substituting L=2 cm and λ=920 nm gives the laser linewidth equal to $\Delta\nu \approx 0.18$ cm^{-1}. This estimation of laser linewidth is in good correlation with the experimental data.

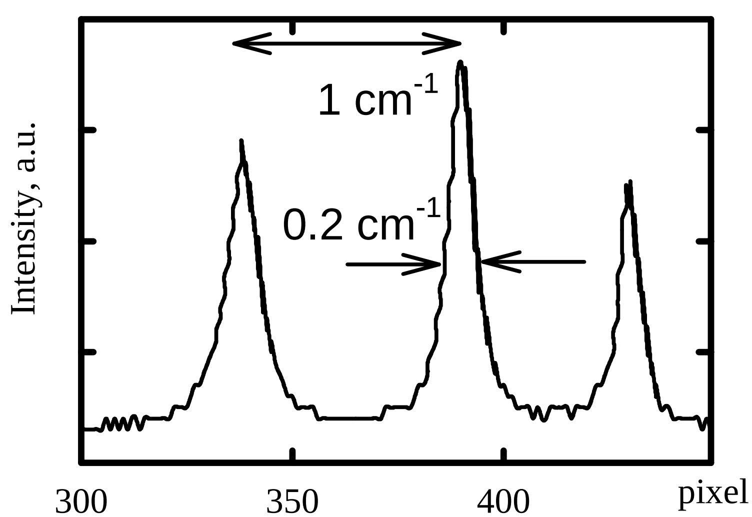

Fig.6. LiF:F_2^{+**} DFB laser linewidth measurements.

4. CONCLUSIONS

We have obtained the first tunable room temperature stable DFB lasing with LiF:F_2^{+**}. A dynamic grating with adjustable period was constructed using the interference of two laser beams of equal intensity. Our selection of LiF:F_2^{+**} as a lasing medium affords the benefit of stable laser operation, something previously impossible with color center DFB lasers. Our laser is fully tunable from 882 to 962 nm, and we believe this range can grow considerably. A linear relationship between pumping power and output power has been determined. Also the optical threshold of lasing was determined to be 1.2 mJ.

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