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

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We report a room temperature tunable color center distributed feedback (DFB) laser using stabilized $F_2^{+}{**}$ centers in LiF (LiF:$F_2^{+}{**}$) as a gain medium. Tunable oscillation of LiF:$F_2^{+}{**}$ DFB lasing was achieved in the near infrared region (882–962 nm) with a lasing linewidth of less than 0.2 cm^{-1}. Also the lasing threshold and slope efficiency with respect to pump energy were found to be 1.2 mJ and up to 3%, respectively.
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Since first introduced by Kogelnik and Shank in the early 1970s[1,2] distributed feedback (DFB) lasers have attracted considerable attention due to simplicity of construction, easy tuning, and good mode selection. Tunable operation of the DFB lasers in the UV–visible spectral range was demonstrated by using different organic dyes[3–8] and crystalline impurity doped laser materials (e.g., Ce-doped LiSAF[9]). Color center crystals (CCCs) are also promising active media for the DFB tunable solid state lasers in a broad visible–middle infrared spectral range. Realizations of DFB lasers using F_A(II) and N_2 CCs in KCl and F_2 CCs in LiF crystals were reported by Bjorklund[10] and Kurobori *et al.*[11,12] However, poor thermo- and photostability were limiting factors for extensive usage of CCCs until recently. The laser operation in Bjorklund *et al.*[10] and Kurobori *et al.*[11] required liquid nitrogen cooling of the KCL gain medium and the LiF:F_2 crystal in Kurobori *et al.*[12] being thermostable at RT degraded after 500 pumping pulses due to the poor photostability of active F_2 CCs.

LiF crystals are the most outstanding among alkali-halides for their low hygroscopicity and a unique combination of operational (high photo–thermo stability), spectroscopic, and laser characteristics.[13] Recent advancements in CCCs have yielded LiF with stabilized $F_2^{+}{**}$ CC (LiF:$F_2^{+}{**}$) crystals, which combine the thermal- and photostability 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 RT stable lasing tunable over a 0.80–1.22 μm spectral range was demonstrated in Dergachev *et al.*[14] In this letter we report our experimental results on a tunable room temperature stable LiF:$F_2^{+}{**}$ DFB laser.

The LiF crystal was grown by the Kyropulos method and doped with LiOH, LiO_2, and MgF_2 to provide thermal- and photostabilization of the positively charged CCs. In order to obtain a high concentration of $F_2^{+}{**}$ centers and a low concentration of colloids and parasitic aggregate CCs, a multistep technique in which the crystals were γ irradiated by a ^{60}Co source was used.[14] 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. However, the maximum absorption coefficient of LiF:$F_2^{+}{*}$ CCCs at a given wavelength can be as high as 7.5 cm^{-1}.

Development of the dynamic grating in the crystal was achieved using the interference of two equal laser beams of a single longitudinal mode Nd:YAG GCR 230 laser operated in the second harmonic at a wavelength of 532 nm with a 12 ns pulse duration at a 10 Hz repetition rate. The experimental setup is depicted in Fig. 2. The laser beam was directed through a cylindrical lens ($f = 50$ cm), split into nearly equal parts by a beam splitter, and directed to the crystal slab (19 mm×7 mm×7 mm) by two adjustable mirrors ($R \approx 99\%$). The focused beams produced an approximately 0.5-mm-wide and 10-mm-long DFB laser grating. The mirror M3 was used for additional feedback and to provide the DFB laser output in one direction. 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 following relationship:

$$\Lambda = \frac{\lambda_p}{2 \sin \theta}, \tag{1}$$

where Λ is the period, λ_p the pumping wavelength, and θ the

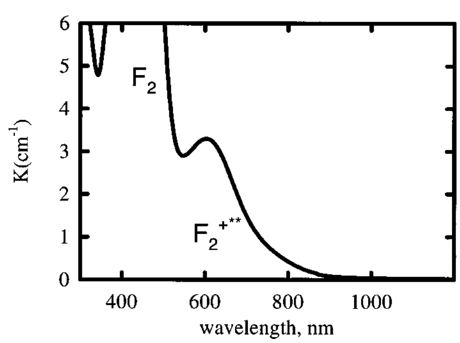

FIG. 1. Absorption spectrum of LiF:$F_2^{+}{**}$ color center crystal.

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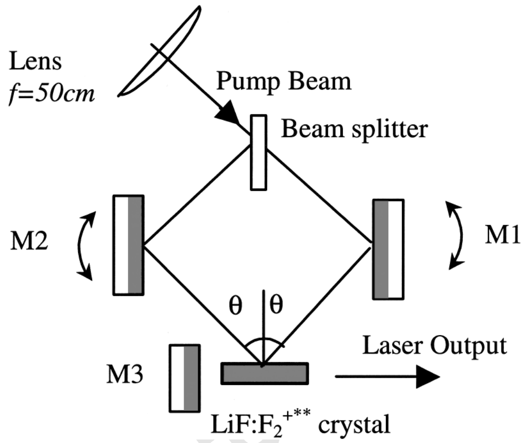

FIG. 2. Experimental setup of LiF:F_2^{+}** DFB laser.

interference beam incident angle measured from the normal to the crystal surface. Adjusting the period of the fringe (and thus the grating) correspondingly adjusts the DFB lasing wavelength according to the Bragg condition:

$$\Lambda = \frac{m\lambda_l}{2n}, \tag{2}$$

where m is the order of diffraction (our setup uses first order), λ_l the lasing wavelength, and n the index of refraction (1.38 for LiF[13]).

Wavelength tuning of the DFB laser was achieved by changing the incident angle of the pumping beams. Remarkably, for the first order of diffraction the incident angle of pumping beams was in the 50°–57° range. This is close to the Brewster angle of LiF crystal (54°) and, hence, pumping losses are minimized for our experimental arrangement. Figure 3 demonstrates tuning of DFB laser (curves 1–8). We have obtained narrowline ($\sim$0.2 cm^{-1}) laser oscillation tunable over the 882–962 nm spectral range. In the absence of a dynamic grating when one pumping beam is blocked a nonselective oscillation was observed with a full width at half maximum (FWHM) of about 20 nm centered at 925 nm. This oscillation is due to lasing in a nonselective cavity formed by mirror M3 and Fresnel reflection ($\sim$2.5%) from the facet of the LiF crystal (curve 9).

The output energy of the LiF:F_2^{+}** DFB laser is depicted in Fig. 4. 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 h of continuous operation at a 10 Hz repetition rate.

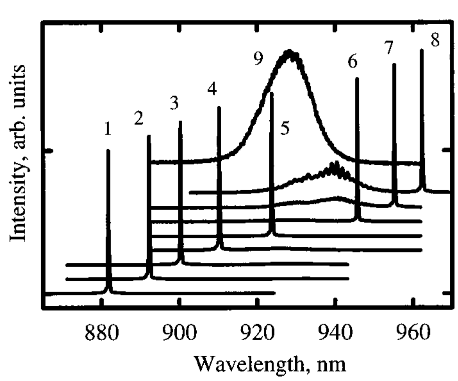

FIG. 3. Tunable operation of LiF:F_2^{+}** distributed feedback laser (curves 1–8). The broad band at 925 nm corresponds to laser emission in nonselective cavity (curve 9). All spectra were scaled for convenience.

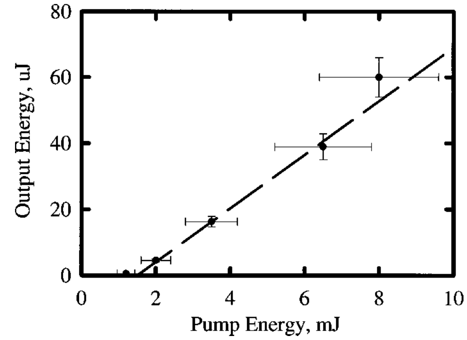

FIG. 4. The output energy of LiF:F_2^{+}** DFB laser vs pump pulse energy.

The time delay between pumping pulse and DFB laser oscillation was measured by a fast photodetector (Newport, 818-bb-20) with a rise time less than 200 ps. As one can see in 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 laser pulses going together with a narrow line 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.

The linewidth of DFB laser oscillation was measured by an etalon with a 1 cm^{-1} free spectral range as shown in Fig. 6. The FWHM of the DFB laser oscillation at 920 nm was 0.2 cm^{-1}. The maximum etalon resolution was equal to 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.[9] The substitution of $L = 2$ cm and $\lambda = 920$ nm gives the laser linewidth equal to $\Delta\nu \approx 0.18$ cm^{-1}. As one can see, the estimation of laser linewidth provides good correlation with experimental data.

In summary, we have realized room temperature stable and broadly tunable DFB CC lasing using LiF:F_2^{+}** CCs as a gain medium. Distributed feedback was based on a peri-

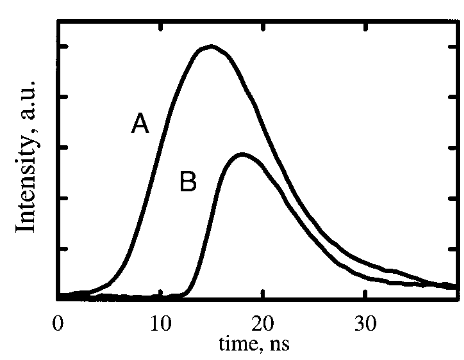

FIG. 5. Temporal delay of LiF:F_2^{+}** DFB laser emission (b) with respect to pumping pulse (a).

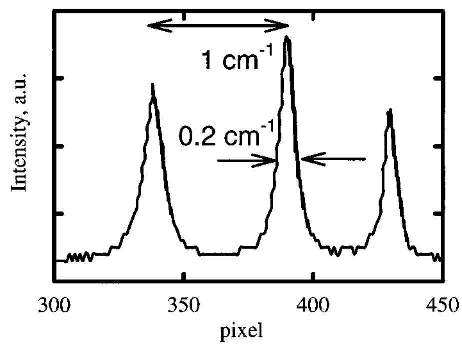

FIG. 6. LiF:F_2^{+**} DFB laser linewidth measurements.

odic gain modulation. The incident angle of the pumping beams was close to the Brewster angle providing minimum losses of pump energy. The laser was tunable over a 882–962 nm spectral range with an emission linewidth less than 0.2 cm^{-1}. Pump threshold at 920 nm was measured to be ~1 mJ and maximum efficiency reached was 3%.

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[1] H. Kogelnik and C. V. Shank, J. Appl. Phys. **43**, 2327 (1972).
[2] C. V. Shark, J. E. Bjorkholm, and H. Kogelnik, Appl. Phys. Lett. **18**, 395 (1971).
[3] V. M. Katarkevich, A. N. Rubinovich, S. A. Ryzhechkin, and T. Sh. Efendiev, Quantum Electron. **24**, 871 (1994).
[4] W. J. Wadworth, I. T. McKinnie, A. D. Woolhouse, and T. G. Haskell, Appl. Phys. B: Lasers Opt. **69**, 163 (1999).
[5] X. L. Zhu, S. K. Lam, and D. Lo, Appl. Opt. **39**, 3104 (2000).
[6] K. P. Kretsch, W. J. Blau, V. Dumarcher, L. Rocha, C. Fiorini, J. M. Nunzi, S. Pfeiffer, H. Tillman, and H. H. Hornold, Appl. Phys. Lett. **76**, 2149 (2000).
[7] C. Ye, K. S. Lam, K. P. Chik, D. Lo, and K. H. Wong, Appl. Phys. Lett. **69**, 3800 (1996).
[8] K. S. Lam and D. Lo, Appl. Phys. B: Lasers Opt. **66**, 427 (1998).
[9] J. F. Pinto and L. Esterowitz, Appl. Phys. Lett. **71**, 205 (1997).
[10] G. C. Bjorklund, L. F. Mollenauer, and W. J. Tomlinson, Appl. Phys. Lett. **29**, 116 (1976).
[11] T. Kurobori, H. Hinino, Y. Q. Chen, and K. Inabe, Jpn. J. Appl. Phys., Part 2 **34**, L894 (1995).
[12] T. Kurobori, K. Inabe, and N. Takeuchi, Jpn. J. Appl. Phys., Part 2 **16**, L121 (1983).
[13] T. T. Basiev and S. B. Mirov, *Room Temperature Tunable Color Center Lasers* (Harwood Academic, Chur, Switzerland, 1994)
[14] A. Yu Dergachev and S. B. Mirov, Opt. Commun. **147**, 107 (1998).
[15] N. W. Jenkins, S. B. Mirov, and V. V. Fedorov, J. Lumin. **91**, 147 (2000).