Spatial- spectral transformation of the laser radiation

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ABSTRACT

This paper is focused on a design of flexible laser systems capable to provide spatial transformation of the pump radiation into the spectral domain of the output laser oscillation using specially designed “spatially dispersive” laser cavity. These systems also provide ultrabroadband or controlled spectral linewidth of the output laser oscillation. The theoretical analysis based on gaussian approximation for the designed laser cavities with “spatial dispersion” was used to provide maximum spatial resolution of the spatial-spectral transformation. The transformations of the spatial distribution of the pump radiation into the spectral domain of the output laser oscillation were experimentally demonstrated in the gain-switched LiF:F\textsuperscript{2+} and LiF:F\textsuperscript{2-} lasers with total efficiencies of up to 20% and output pulse spectrum width wider than 140 nm, centered at 0.96 \( \mu \)m and 1.14 \( \mu \)m, correspondingly. As a result of the optimization of the angular dispersion of the output radiation, the simultaneous phase-matching for second harmonic generation in the single nonlinear crystal was realized for the whole oscillation spectral range. This technique allows to use a nonlinear frequency conversion for nonlinear transformation of the beam spatial distribution. Due to this, the ultra broadband (>100 nm) or multiline (20 lines) second harmonic and sum frequency oscillations were demonstrated in a LiIO\textsubscript{3} nonlinear crystal with an overall efficiencies of up to 12%.

Keywords: spatial-spectral transformation, spatially dispersive cavity, broadband/ multiline laser oscillation, color center laser

1. INTRODUCTION

In this paper the analysis and experimental results of “spatially dispersive” laser system providing spatial- spectral transformation of the laser beam are presented. This approach is successful for the design of ultrabroadband laser sources operating in near IR, visible, and UV spectral regions and allows utilization of a variety of active media, including crystals, glasses, dyes, as well as single broad stripe, multistripe diode chips, and diode arrays\textsuperscript{1-11}.

Usually, the competition of modes in the active element narrows the output radiation spectrum. In “spatially dispersive” laser cavities, the lasing modes with different wavelengths propagate in different parts of the active element, which removes the competition between the modes and provides ultrabroadband oscillation. The technology of spatially-dispersive cavities was known since 70’s\textsuperscript{12}. It was proposed basically for narrow and tunable oscillation, where tuning was achieved simply by scannable pumping beams without tuning of intracavity dispersive elements. In 1989 Danailov and Christov\textsuperscript{1} proposed to utilize the principle of spatially dispersive cavity for the generation of radiation of laser radiation with ultrabroadband spectrum in dye lasers. Another laser scheme of spatially dispersive cavity was introduced in early 90’s by Basiev, et.al\textsuperscript{6}. This cavity was utilized for realization of first solid-state ultrabroadband lasers\textsuperscript{6,10}.

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Technology of spatially dispersive cavities provides another important spatial to spectral transformation realized in nonlinear crystal. This idea relates to a novel principle of obtaining nonlinear mixing of super broadband radiation in a single nonlinear crystal. This principle is based on a simultaneous realization of phase matching conditions for all oscillating wavelengths by means of compensation of phase-matching angular dispersion in the nonlinear crystal with spatial angular dispersion of different wavelengths forming output super broadband continuum.

To realize the spatial-spectral transformation of the laser beam in the "spatially dispersive" laser systems the active media with broad luminescence bands are required. Recent progress in LiF color center crystals stimulates design of effective room temperature stable color center lasers tunable in the near-IR spectral region\textsuperscript{13-17}. F\textsubscript{2}++ CC laser (LiF:F\textsubscript{2}++) exhibits excellent photo and thermostable operation at room temperature when pumped by an alexandrite laser and can provide efficient high power lasing tunable in 800-1200 nm spectral range. Other widely used color center in LiF crystal is F\textsubscript{2}– (LiF:F\textsubscript{2}–). They are used as passive Q-switchers of resonators of neodymium lasers and as active elements of near IR tunable lasers. LiF:F\textsubscript{2}– crystals feature wide near-IR absorption (0.85-1.1) and emission bands (1.0-1.3 \(\mu\)m) and a high (~50\%) quantum efficiency of fluorescence at room temperature.

In this paper we studied theoretically and experimentally the transformation of the spatial shaping of the pumping beam into spectral domain of the output oscillation in the gain-switched LiF:F\textsubscript{2}++ and LiF:F\textsubscript{2}– color center lasers. Also, transformation of the spatial autocorrelation function of the pumping beam into the spectral domain was demonstrated using nonlinear mixing of the ultrabroadband oscillation.

2. SPATIAL-SPECTRAL TRANSFORMATION OF THE PUMPING RADIATION

2.1 Principles of operation

To provide spectral mode suppression the laser cavity is design as a set of independent micro-cavities, which are laterally shifted in the gain media and operate at different wavelengths. One of the possible configurations of these cavities are shown in the Fig. 1. It consists of input coupler \(M_1\), active element, intracavity lens \(L_1\), aperture \(A\) installed in the lens focal plane, and a diffraction grating \(G\) operating in the Littrow mount scheme. The laser operates as follows\textsuperscript{8,9}: the beams propagating in the active element parallel to the optical axis of the system are focused by lens 3, while the beams that propagate at a distance from the optical axis are incident on the diffraction grating (after passing through the lens) at different angles \(\theta\). As a result, the autocollimation condition for each beam is satisfied at different radiation wavelengths, which are determined by the relation

\[
 k\lambda_i = 2t \sin(\theta_i),
\]

where \(t\) is the grating period; \(k\) is the diffraction order; \(\theta_i\) is the autocollimation angle; \(\lambda\) is the oscillation wavelength. The zero order of the diffraction serves for laser output. The aperture suppresses the radiation propagating in the active element at an angle to the optical axis. Using (1) one can find that the oscillation channel located at a distance \(x\) from the optical axis (Fig.1) generates its own wavelength \(\lambda_i\) determined as:

![Figure 1: Optical scheme of the spatially dispersive cavity](image-url)
\[ \lambda_i = 2t \sin \left( \arcsin \left[ \frac{\lambda_0 k}{2T} \right] + \frac{x_i}{T} \right), \]  

where \( \lambda_0 \) is a oscillation wavelength central channel and \( f \) is the focal length of the focusing lens.

In a regime of quasi-stationary lasing for pump intensities much higher then the threshold level the intensity of output radiation can be defined as follows:

\[ I_{osc}(\lambda) = \left( \frac{T}{T + L} \right) \eta_{abs} \eta_{ST} I_{pump}, \]  

where the first term describes pump utilization efficiency, \( \eta_{ST} = \lambda_{pump}/\lambda_{osc} \) - is a Stokes factor or quantum efficiency, which represents the ratio of photon energy at oscillation and pump wavelengths, \( T \) - is transmission of the output coupler, \( L \) represents cavity losses and \( I_{pump} \) is intensity of the pump radiation. Equations (2,3) demonstrate a direct relationship between the spatial distribution of the pump radiation and spectral distribution of the output oscillation in this spatially dispersive cavity. In another words, spatial distribution of the pump radiation is transformed in the cavity in the spectral distribution of the laser oscillation:

\[ I_{pump}(x) \rightarrow I_{osc}(\lambda), \]  

where

\[ \lambda = \lambda_0 + \frac{x}{f} \sqrt{4t^2 - \lambda_0^2}, \]  

Using equation (2) the dispersion \( d\lambda/dx \) of the wavelengths in the active element can be written as:

\[ \frac{d\lambda}{dx} = \sqrt{\frac{2t}{k} \lambda_0^2 - \lambda_0^2} \frac{1}{f}. \]  

In the framework of Gaussian beams approximation the cavities of each channel can be considered as a cavity consisting of two plane mirrors, intracavity lens and a gain medium. According to this model the diffraction grating operating in autocollimation regime is equivalent to a plane mirror. The matrix of the equivalent resonator is calculated as follows:

\[ M = \left( \begin{array}{cc} 1 & 1 \\ 0 & 1 \end{array} \right) \left( \begin{array}{cc} 1 & d_{eff} \\ -\frac{1}{f} & 1 \end{array} \right) = \left( \begin{array}{cc} g_1 & L \\ \frac{g_1 g_2 - 1}{L} & g_2 \end{array} \right), \]  

where \( d_{eff} = z + d_0/n + d_1 \) is the effective distance between mirror \( M_j \) and the lens \( L_j \), \( z \) is the separation between the mirror and the rear facet of the crystal, \( d_0 \) is the length of the crystal, \( d_1 \) is the distance from the output facet of the crystal to the lens and \( n \) is the refraction index of the active medium.

The resonator effective length \( L \) is given by

\[ L = d_{eff} + l - \frac{ld_{eff}}{f}, \]  

where \( l \) is the separation between lens \( L_j \) and grating \( G \), and \( f \) is the focal length of the lens. The parameters \( g_1 = 1 - l/f \) and \( g_2 = 1 - d_{eff} / f \) are the stability parameters of the resonator.

An unstable cavity configuration leads to a strong overlapping and coupling among different channels. Therefore, we consider only stable cavity configurations for which the following stability condition is satisfied:

\[ 0 < g_1 g_2 < 1 \]  

The beam radii of TEM\(_{00}\) modes for individual channels at the mirror \( w_m \), the diffraction grating \( w_G \), output crystal facet \( w_c \), and the aperture \( w_a \) are calculated via the ABCD law for the appropriate cavity unit cells:

\[ w_m^2 = \left( \frac{L \lambda}{\pi} \right) \sqrt{\frac{g_2}{g_1(1 - g_1 g_2)}}, \]  

\[ w_G^2 = w_m^2 g_1/g_2, \]  

\[ w_c^2 = w_m^2 + \frac{\lambda^2(z + d_0/n)}{\pi w_m^2}, \]  

\[ w_a = \frac{\lambda}{\pi w_m}, \]  

where a beam radius is defined as the radius where intensity of the mode is decreased to 1/e\(^2\) of its maximum.
In order to avoid crosstalk the channels should not overlap in the active medium. The minimum channel’s overlapping and maximum amount of oscillation lines can be realized by minimizing beam radius on the output facet of the laser crystal \( w_c \). It follows from (11) that the minimum beam radius is achieved with \( z=0 \) and:

\[
w_c^2 = 2w_m^2 = \frac{2\lambda d_i}{n\pi}
\]  

(12)

The maximum number of oscillation channels can be estimated as the ratio of the crystal width to the beam diameter on the output facet of the crystal \( N = \Delta x / 2w_c \). The spectral separation of the channels is found using (2.3), where \( \Delta x \) is replaced by the spatial separation of the channels, which, in turn, equals the channels diameters on the output facet of the crystal:

\[
\delta \lambda_{ch} = \frac{4\pi w_c}{f} \cos(\beta),
\]

(13)

In order to avoid channel’s crosstalk the diffraction grating must provide spectral resolution better than or equal to that given by (13). The diffraction grating resolution is determined by the number of illuminated grooves \( M \) and can be calculated in terms of the beam diameter on the grating \( 2w_m / \cos(\beta) \):

\[
\delta \lambda_G = \frac{\lambda}{M} = \frac{\lambda f}{2w_G} \cos(\beta)
\]

(14)

The requirement on the diffraction grating resolution \( \delta \lambda_G \leq \delta \lambda_{ch} \) leads to the following condition on the minimum mode diameter on the diffraction grating:

\[
w_G \geq \frac{\lambda f}{8w_c}
\]

(15)

The requirements on the laser cavity parameters discussed above can be conveniently summarized in three expressions in terms of the cavity stability parameters \( g_1 \) and \( g_2 \) as follows.

The requirement of the cavity stability (9):

\[
g_1 < \frac{1}{g_2}
\]

(16)

The requirement of the minimum resolution of the diffraction grating (15):

\[
g_1 \leq g_2 \frac{\pi^2}{128A^2}
\]

(17)

The requirement of the maximum number of channels (3.10) and (3.8):

\[
g_1 = \frac{g_2}{g_2^2 + A^2},
\]

(18)

where \( A = d_i / (\eta f) \). Figure 2 shows a stability diagram for the LiF:F2 and LiF:F2** CC lasers. In our calculations we used 4 cm long LiF:F2** crystals, 1200 grooves/mm holographic grating, and 5 cm focal length of the intracavity lens.
The range of \( g_1, g_2 \) acceptable values is bounded by stability region of the cavity (curve a)) and condition (15 - curve c). Curve b) shows \( g_1=f(g_2) \) dependence for optimal waist on the mirror \( M_1, w_m \). As it is seen from Fig.2 both \( g_1 \) and \( g_2 \) parameter should be within \((-2,0)\) and \((-0.87,0)\) intervals correspondingly. This places limits on \( d_{eff} \) and \( l \) values (\( 3f < d_{eff} < sf \) and \( 1.87f < d_{eff} < sf \)). Some cavity parameters calculated of the LiF:F\(_2\)- and LiF:F\(_2\)^{++} CC lasers are shown in the table 1.

As one can see for used crystal grating, and 7 cm focal length intracavity lens were utilized. In the case of the studied cavity spatial to spectral transformation \( I_{pump}(\lambda) \rightarrow I_{osc}(\lambda) \) will be defined by the following relationship:

\[
\lambda = \lambda_0 + 19\frac{nm}{mm} \times x[mm],
\]

As it is seen from Eq. (12) the optimal size of the beam waist on the mirror is defined by the length and index of refraction of the used crystal, as well as the oscillation wavelength. For the used crystal the beam waist radius calculated from this equals to \( w_m=94 \) µm. Spectral resolution in this situation defined by Eq. (13) is \( \Delta\lambda_{ch}=4.9 \) nm. It is noteworthy, that the spectral resolution determines the minimum spectral separation between two adjacent channels, while the width of oscillation spectrum of individual channel can be smaller then spectral resolution. In this case, when many individual channels are simultaneously excited the output oscillation spectrum will be comprised from the separate lines with the spectral separation between adjacent lines equal to spectral resolution. Full width of the LiF:F\(_2\)^{++} gain spectrum is \( \Delta\lambda\approx400 \) nm (800-1200 nm), hence, utilization of this crystal in the described spatially dispersive cavity should result in \( I_{pump}(\lambda) \rightarrow I_{osc}(\lambda) \) transformation with a quality factor of \( N=\Delta\lambda/\delta\lambda=82 \) and spatial range \( \Delta x=21.9 \) mm.

### 2.2 Experimental results

Laser experiments of pump beam transformation were realized on gain switched LiF:F\(_2\)^{++} and LiF:F\(_2\)- CC lasers. The schematic of this laser is similar to described above shown in Fig. 1. Cylindrical lenses with focal lengths \( f=30 \) or \( 50 \) mm were used as the intracavity lens. The 1200gr/mm diffraction grating with 20-50% reflectivity was utilized as a dispersive element. The input dichroic mirror \( M_1 \) transmitted \( \geq 80\% \) at pumping wavelength and reflected \( \geq 95\% \) in the oscillation range. The active elements used in the experiments were LiF crystals 4-cm long cut at the Brewster angle. To produce high concentration of stable laser-active F\(_2\)- and F\(_2\)^{++} color centers in LiF crystals were \( \gamma \)-irradiated using a \( \alpha \)-Co source. The LiF:F\(_2\)^{++} active elements had 2.5-3 cm\(^3\) coefficient of absorption at 610 nm. The absorption coefficient of the LiF:F\(_2\)- crystal at 1047 nm wavelength was 0.7 cm\(^-1\). Due to a wide absorption band of CC’s the number of solid-state lasers can be used as a pump source. A pumping beam expanded to a diameter of 10 mm and was further reshaped into elliptical profile with cylindrical lens. In order to demonstrate spatial-spectral transformation the pump beam was modulated by the spatial masks. Laser spectra of single output pulses were measured with a CCD camera coupled to an imaging grating spectrograph. The averaged lasing spectra were recorded with a spectrometer, a photodiode, and a Boxcar integrator. The oscillation of LiF:F\(_2\)^{++} laser was obtained using SHG of Nd\(^3\):YAG laser or Alexandrite laser radiations as a pump source.

### Table 1. Cavity parameters of the LiF:F\(_2\)- and LiF:F\(_2\)^{++} CC lasers calculated according to equations (12-14) for 1200 grooves/mm diffraction grating.

<table>
<thead>
<tr>
<th>Gain Media</th>
<th>( \lambda_0, \mu m )</th>
<th>( \Delta\lambda, \mu m )</th>
<th>( w_m, \mu m )</th>
<th>( f, mm )</th>
<th>( d\lambda/dx, nm/mm )</th>
<th>( \Delta x, mm )</th>
<th>( \delta\lambda_{ch}, nm )</th>
<th>( N )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiF:F(_2)-</td>
<td>0.96</td>
<td>0.3</td>
<td>102</td>
<td>30</td>
<td>39</td>
<td>7.7</td>
<td>11.2</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>23</td>
<td>12.8</td>
<td>6.7</td>
<td>44</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>16.7</td>
<td>19.6</td>
<td>4.8</td>
<td>62</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LiF:F(_2)^{++}</td>
<td>1.14</td>
<td>0.4</td>
<td>94</td>
<td>30</td>
<td>43</td>
<td>9.4</td>
<td>11.3</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>26</td>
<td>15.6</td>
<td>6.8</td>
<td>59</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>19</td>
<td>21.9</td>
<td>4.9</td>
<td>82</td>
<td></td>
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</tr>
</tbody>
</table>
For experimental demonstrations of the spatial-spectral relationships, the pump-beam shape in front of the input mirror was modulated by the spatial masks. Fig. 3 demonstrates spatial-spectral pump-output transformations with a two-aperture spatial filter arrangement into the output radiation of the broadband LiF:F$_2^{+}$** laser. When these spatial filters with circular apertures of 0.5 mm diameter separated by distances 0.86, 2 and 2.8 mm (Fig. 3 B,C,D, respectively) were used to reshape the pump beam it resulted in 2 line spectral output of LiF:F$_2^{+}$** laser with a variable spectral separation between two lines, increasing from 20 to 60 nm. As one can see from Fig. 3 B-D we experimentally realized spatial-spectral transformation with a coefficient of transformation $\Delta\lambda/\Delta x=19$ nm/mm, which is in a good agreement with theoretical value defined by Eq. (5). The narrow-line oscillation was realized by utilization of spatial filter - metal plate with 0.5 mm aperture placed in front of the input mirror (see Fig. 3 A). Tuning of the narrow-line oscillation wavelength was realized by a parallel moving of the aperture across the pump beam without any tuning of the laser cavity components. Experimentally measured range of tunability was from 900 to 1150 nm. Figure 3E presents another variant of spatial-spectral transformation. It demonstrates a fragment of an experimental LiF:F$_2^{+}$** output
spectrum obtained when a spatial periodic structure (7 rectangular shape holes) with a shadow width of 100 µm and a period of 400 µm was installed into the pump beam. In this case spectral output consisted of 7 narrow lines separated by ∼ 18 nm with a linewidth of each line as narrow as 0.5-0.6 nm was realized. In this particular experiment 30 mm focal length intracavity lens was utilized.

For LiF:F₂ CC laser the maximum number of equidistant lines obtained with this mask was 15, covering the spectral range from 1.095 to 1.23 µm (see Fig. 3F). It is noteworthy that the intensity envelope of the pumping beam defines the envelope of the output spectrum. The maximum efficiency of the LiF:F₂ laser equals to 16 %, was reached using Nd³⁺:YLF pump laser at a pump energy equalled to $E = 25$ mJ and oscillation threshold equalled to 3mJ.

The infrared output radiation has high divergence in the horizontal plane determined by autocollimation condition. In the absence of any collimating optics, its divergence is approximately 10 deg for the whole oscillation spectra from 1.08 to 1.23 µm. But the divergence of each channel is low and can be determined by the laser mode structure. By using additional cylindrical lenses, we were able to compensate for the angular divergence of these beams and to collimate the output radiation to a single beam with a divergence of about 1 mrad. The maximum efficiency of the broadband LiF:F₂ laser equaled to 20 % was obtained at $E = 9$ mJ pump energy.

3. Utilization of the nonlinear frequency mixing for transformation of the spatial distribution of the radiation into the spectral domain

Technology of spatially dispersive cavities provides another important spatial to spectral transformation realized in nonlinear crystal. This idea relates to a novel principle of obtaining second (and similarly fourth) harmonic generation (SHG) of superbroadband radiation in a single nonlinear crystal. The principle is based on a simultaneous realization of phase matching conditions for all oscillating wavelengths by means of compensation of phase-matching angular dispersion in nonlinear crystal with spatial angular dispersion of different wavelengths forming output ultrabroadband continuum. In other words proper shaping of the superbroadband laser output beam can provide simultaneous phase matching conditions for frequency up- and even down-conversion processes.

For example, due to nonlinear dependence of the second harmonic generation (SHG) intensity on incident radiation intensity ($I_{osc}$), the total transformation of the pump beam after frequency doubling can be written as follows:

$$I_{pump}(x)^2 \sim I_{osc}(\nu)^2 \sim I_{shg}(2\nu)$$

(20)

Sum frequency generation (SFG) process provides possibility for even wider class of transformations. In this case the transformation of the pump beam is proportional to the spatial autocorrelation function of the pumping beam and can be presented as follows:

$$\int I(x)I(x-x_0) dx \sim \int I_{osc}(\nu)I_{osc}(\nu - \nu) d\nu \sim I_{sfg}(\nu)$$

(21)

To realize these transformations it is necessary to provide phase-matching conditions for all the oscillating wavelengths. Due to a small spectral and angular acceptance bandwidth in the crystal the nonlinear frequency conversion is a difficult problem. The feasibility of SHG of broadband laser radiation with a spectral width of 10 nm was demonstrated in 19. The spectral width of the output radiation from the LiF:F₂ and LiF:F₂ color center lasers can exceed 300 nm. One of the possible ways for SHG of such an ultrabroadband radiation is matching of the angular dispersion of the output radiation with angular dispersion of the phase-matching angle by means of additional lens (Fig. 4).

The angular distribution of oscillating wavelengths of the CC laser output radiation after the grating is described by Eq. (2):

$$\theta_g(\lambda) = \arcsin\left(\frac{\lambda k}{2t}\right) - \arcsin\left(\frac{\lambda k}{2t}\right)$$

(22)

From the other hand, the required angular dependence for nonlinear conversion could be written as:

$$\theta_{nc}(\lambda) = \arcsin\left(\frac{\sin(\theta_c - \theta_{pm}(\lambda))}{n(\lambda)}\right)$$

(23)

where, $\theta_c$ - angle between the crystal axis and input facet of the nonlinear crystal, $n$ –the refractive index at an incident wavelength, $\theta_{pm}$ - phase-matching angle of the nonlinear frequency conversion.
In the linear approximation, the required angular magnification of the optical system is given by the expression

\[ \Gamma = \frac{d\theta_{nc}/d\lambda}{d\theta_{g}/d\lambda} \]  

(see Fig. 4)

This scheme operates efficiently only in crystals with phase-matching of the ooe or eeo type. The optimal nonlinear crystal can be selected by calculating the spectral dependence of the phase-matching angles for different crystals. It is assumed that the crystal is cut for the normal incidence of radiation at a wavelength corresponding to the middle of the spectral range of lasing (at 0.965 nm for the LiF:F2** laser and at 1.14 um for the LiF:F2 laser). Fig. 5 presents the calculated dispersion curves for the angle of incidence of the radiation from broadband LiF:F2** and LiF:F2 lasers on the nonlinear crystal (solid curves) and the phase-matching angles in KDP, BBO, LiNbO3, and LiIO3 crystals recalculated with allowance for the optimal angular magnification \( \Gamma \).

Among the nonlinear crystals considered, LiNbO3 has the largest nonlinearity coefficient \( D_{eff} = 5.32 \times 10^{-12} \).
This crystal exhibits a strong nonlinear dependence of the phase-matching angle on the wavelength, which makes it possible to obtain 90° phase-matching by decreasing the wavelength to 1.05 µm. Hence, this crystal is suitable only for output frequency doubling of the LiF:F2⁺⁺⁺ laser. However, the strong nonlinearity leads to a substantial discrepancy between the angular matching curves and the wavelength dependence of the angle of incidence of the radiation from a broadband laser on the nonlinear crystal (angular mismatch). The dispersion dependence of the phase-matching angle of the KDP crystal has a flat maximum around 1.05 µm. As a result, a strong angular mismatch was observed for the LiF:F2⁺⁺⁺ laser. The KDP crystal has the smallest nonlinearity coefficient ($D_{\text{eff}} = 0.29 \times 10^{-12} \text{ m V}^{-1}$) among the suggested crystals. The spectral dependences of the phase-matching angles for the LiIO3 and BBO crystals are similar (Fig. 5) when the angular magnifications $\Gamma$ are optimal ($\Gamma_{\text{BBO}} = 0.8$ and $\Gamma_{\text{LiIO3}} = 1.8$ for the 0.87-1.1-µm range, and $\Gamma_{\text{BBO}} = 0.4$ and $\Gamma_{\text{LiIO3}} = 1$ for the 1.1-1.25-µm range). The LiIO3 crystal has a somewhat better angular matching and a larger nonlinearity coefficient ($D_{\text{eff}} = 2.75 \times 10^{-12} \text{ m V}^{-1}$) compared to the BBO crystal ($D_{\text{eff}} = 1.69 \times 10^{-12} \text{ m V}^{-1}$). Thus, among the crystals we examined the LiIO3 crystal proved to be the best for frequency doubling of the infrared radiation emitted by a broadband laser.

An additional opportunity to match angular dispersions is to use non-paraxial approximation of beam propagation. In this case, the additional parameters (such as: lens thickness, lens tilt, off axial lens shift and radii of curvatures of the lens surfaces) permit to obtain better matching. For example, curves (4) in Fig. 5 show the differences between the angular dependence of the nonlinear phase matching in LiIO3 crystal and output radiation of the broadband laser calculated using ray tracing for non-paraxial approximation. The curve (4) in Fig. 5B was calculated using following parameters: focal lengths = 50 mm, lens thickness = 10 mm, off axial lens shift = 10 mm, lens tilt = 4°. As one can see from the Fig. 5 this approximation demonstrates essentially better results than geometry optics for the same crystal (curve 2).

The broadband radiation produced in the visible region can be converted into the UV range by doubling its frequency once more. After the frequency doubling in a nonlinear crystal with the ooe phase-matching, the polarization of the second-harmonic radiation lies in the diffraction plane of the grating. So, for further conversion of the radiation to the fourth harmonic, one should use eeo interaction. Unordinary, the positive nonlinear crystals operating in the UV region are not available now. Other way to obtain broadband UV radiation is to rotate the polarization of the second harmonic of the broadband on 90° degree (for example, an optically active quartz crystal) and to use negative nonlinear crystal. Among available nonlinear crystals the BBO is the most efficient nonlinear crystal for generating the fourth harmonic from a broadband laser.

For frequency doubling of the broadband lasing, a 20-mm long LiIO3 nonlinear crystal was used. The crystal was cut for wavelength frequency doubling at 1.064 µm. Matching of the angular synchronism dispersion and the spectral dependence of the angle of incidence of radiation on the nonlinear crystal was achieved using the spherical lens with a focal length equal to 50 mm. Selection of the proper angular magnification of the lens provided a 12% overall conversion efficiency of broadband infrared radiation to the second harmonic for LiF:F2⁺⁺⁺ and LiF:F2 CC lasers. The emission spectrum of the second harmonic in the visible (green-yellow-red) spectral range (0.545-0.615 µm) and

![Figure 6: Sum frequency generation spectra of LiF:F2 CC laser demonstrate spatial- spectral (A) and spatial autocorrelation transformation (B) into the of the pump radiation](image-url)
green-blue spectral range (0.45-0.51 \(\mu m\)) were obtained. Due to using cylindrical inracavity and spherical collimated lenses the waist of the beams and spatial channels intersection were located at different points at optical axis. The shift of the nonlinear crystal into the second position provided not only the efficient frequency doubling but also generation of the sum frequencies from various spectral regions of multifrequency lasing, which doubled the number of lines in the second-harmonic lasing spectrum (Fig. 6).

For FHG of broadband visible radiation the BBO (5x7x10 mm) nonlinear crystal was used. Polarization of the visible radiation from SHG of LiF:F\(_2^+\) laser was rotated by a broadband \(\lambda/2\) quartz plate. The visible radiation was focused into nonlinear crystal using a spherical lens with a focal distance \(f = 70\) cm. The filter installed behind nonlinear crystal blocked visible radiation and transmitted FHG in UV. Under the same pumping conditions the maximum conversion efficiency of FHG was obtained using BBO crystal and was measured to be about 7% with respect to visible SHG radiation.

4. CONCLUSIONS

The theoretical analysis based on gaussian approximation for the designed laser cavities with “spatial dispersion” was used to provide maximum spatial resolution of the spatial-spectral transformation. The transformations of the spatial distribution of the pump radiation into the spectral domain of the output laser oscillation were experimentally demonstrated in the gain-switched LiF:F\(_2^+\) and LiF:F\(_2^-\) lasers with total efficiencies of up to 20% and output pulse spectrum width wider than 140 nm, centered at 0.96 \(\mu m\) and 1.14 \(\mu m\), correspondingly. As a result of the optimization of the angular dispersion of the output radiation, the simultaneous phase-matching for second harmonic generation in the single nonlinear crystal was realized for the whole oscillation spectral range. This technique allows to use a nonlinear frequency conversion for nonlinear transformation of the beam spatial distribution. Due to this, the ultra broadband (>100 nm) or multiline (20 lines) second harmonic and sum frequency oscillations were demonstrated in a LiIO\(_3\) nonlinear crystal with an overall efficiencies of up to 12%.

REFERENCES


