Multicolor lasers using birefringent filters: experimental demonstration with Cr:Nd:GSGG and Cr:LiSAF

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Abstract: In this study, we numerically and experimentally investigate application of birefringent filters (BRFs) as frequency selective elements in multicolor lasers. A BRF plate made out of crystalline quartz with an arbitrarily oriented optical axis has been explored. Simulation results have shown that compared to regular BRFs where the optical axis lies in the plane of the plates surface, a BRF with an optical axis pointing out of its surface enables design flexibility in filter parameters, providing access to a wider set of free spectral range and bandwidth values. As a result, multicolor operation could be obtained in many wavelength pairs using a single BRF plate. In the experiments a 3-mm thick quartz BRF with an optical axis 45° to the surface plane has been used. With Cr:Nd:GSGG as a laser medium two-color and three-color cw laser operation has been demonstrated in 11 and 3 different transition combinations, respectively. Moreover, two-color laser operation has been demonstrated in 10 different wavelength pairs in Cr:LiSAF. To our knowledge, this study is the first detailed investigation and experimental demonstration of BRFs with tilted optical axis for multicolor operation of solid-state lasers. Compared to other methods, BRFs enable a rich selection of transition pairs and also the ratio of the power in each line could be regulated by fine adjustment of the rotation angle. Implementation of tilted-axis BRFs should boost development of efficient and low-cost multicolor lasers in other gain media as well.

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1. Introduction

Dual-wavelength and tri-wavelength (multicolor) operation of solid-state lasers in continuous-wave, Q-switched and mode-locked regimes has been attracting great deal of attention [1]. This is due to the need for such sources in application like generation of coherent terahertz (THz) waves [2–4], generation of ultrahigh pulse repetition rates by optical beating [5], optical communication [6,7], remote sensing [8], digital holographic microscopy [9], laser ranging [10], and coherent anti-Stokes Raman scattering microscopy [11]. Simultaneous dual/tri-wavelength laser operation have been shown in many solid state laser gain media including Nd:YAG [1,12], Nd:CNGG [13], Nd:CLTGG [14], Nd:YVO4 [15], Nd:GdVO4 [16], Nd:GGG [17], Nd:YAlO3 [18], Nd:NGAB [19], Yb:YAG [20], Tm:YAP [21], Cr:LiCAF [22], Cr:LiSAF [23], Alexandrite [24], Tm:CaYAlO4 [25], Tm:Ho:Er:YAG [1], and Ti:Sapphire [26]. Most of these systems report dual/triple wavelength operation in a few pairs of lines. Also, the ratio of the power in each line varies with external factors such as pump power, and could not be controlled easily. Moreover, variation of the output coupler percentage also creates shift of multicolor laser wavelengths [27]. These drawbacks are due to the method used for frequency selection, where operating in multi-wavelength regime require specially coated cavity optics and/or coupled cavities, which can usually be optimized for a single transition pair at a fixed pump power and output coupling.

Regular birefringent filters where the optical axis lies in the plane of the plate have been recently used in generation of dual-wavelength radiation from cw Yb:KGW lasers [27]. However, the free-spectral range of regular birefringent filters does not vary a lot with the rotation angle of the plate, limiting the set of THz frequencies that can be achieved in [27]. For example, a frequency difference of 7.57 THz (1014.6 nm and 1041.3 nm) has been demonstrated using a 4-mm-thick BR filter in [27], and accessing other different frequency values required use of BR filters with different thicknesses. A multiple-plate BRF was also employed to obtain dual-wavelength cw operation in Ti:Sapphire [28, 29]. In our experiments, a 3-mm-thick quartz crystal birefringent filter with an optical axis tilted 45° with respect to the plate’s surface has been used for spectral selection. Compared to regular BRFs where the optical axis lies in the plane of the plate, a BRF with an optical axis pointing out of its surface enables access to a wider set of free spectral range and filter bandwidths [30–35]. This fact eliminates the need to change the thickness of BR filter to access different multicolor wavelength pairs. In the experiments we have investigated multicolor laser operation with our BRF using Cr:Nd:GSGG and Cr:LiSAF gain media. In continuous-wave laser experiments with Cr:Nd:GSGG, we have achieved quite stable lasing in 11 different line pairs in dual-wavelength operation, and in 3 different groups of triple lines in tri-wavelength operation. Obtaining stable multicolor laser operation with Cr:LiSAF was more challenging due to the broadband nature of the gain, but as it was also recently demonstrated by Akbari et al in [27] with Yb, the method was still applicable and high-quality two-color cw output has been demonstrated in 10 different lines. Simple rotation of the BRF plate enabled adjustment of the power in each line. To our knowledge, this is the first report of multi-wavelength operation in a Cr:Nd:GSGG laser. Moreover, to our knowledge such diversity in wavelength selection has not been achieved before from any Nd-based system. Results with Cr:LiSAF confirm that the method can also be applied to broadband solid-state gain media. These experiments verify the advantages of BRFs with an optical axis pointing out of its surface as frequency selective elements in multicolor lasers. We believe that multicolor lasers systems based on birefringent filters may work quite well for other laser concepts as well.

2. Theoretical background and simulation results

In this part, with our numerical simulation results, we would like to present filtering properties of laser resonators that contain a uniaxial birefringent plate with an arbitrary optical axis. In particular, we show that the usually employed birefringent filters which have its crystal axis oriented within the surface of the plate can provide a limited range of filter
parameters (such as free spectral range and bandwidth). On the other hand, if the crystal axis is chosen correctly, a single birefringent plate could offer a rich range of filter parameters from a single-element filter. Basically, as the BRF is rotated about an axis normal to the surface, one can attain different values of free spectral range and bandwidth from the BRF. Then accessing different filter parameters only requires adjustment of the plate’s rotation angle correctly. As a result from a single BRF, one can obtain many different filter parameters, rendering these filters quite useful for many applications such as broadband cw and femtosecond tuning as well as multicolor laser operation, which will be the focus of this paper.

Fig. 1. (a) An X-type laser cavity that contains the laser crystal and a single birefringent plate tilted at Brewster’s angle. (b) Light beam incident on a uniaxial birefringent plate at Brewster’s angle. The orientation of the plate’s crystal axis is arbitrary. \( \mathbf{c} \) : orientation of the crystal, \( \mathbf{s} \) : direction of beam propagation, \( \beta \) : internal Brewster’s angle, \( \rho \) : rotation angle of the plate, \( \sigma \) : angle between the optical axis and the surface normal.

As a starting point, Fig. 1(a) shows the particular situation that we would like to investigate here. We assume that our cavity contains a birefringent tuning plate (BR plate) that is placed at Brewster’s angle inside the cavity. The cavity also contains a laser crystal that is inserted at Brewster’s angle as well (this is not necessary and a flat-flat crystal with antireflective coatings could also be used, but a Brewster-cut crystal helps to increase the selectivity of the birefringent filter by increasing the modulation depth). The birefringent filter will transform the incident TM polarized light into some elliptical polarization that will contain both TM and TE modes. The Brewster surfaces of the laser crystal and the birefringent plate will create loss for the TE polarized part of the beam. Figure 1(b) shows a detailed view of the birefringent filter, where we have followed the notation that was introduced in [32]. The incident ray, the light’s path inside the crystal and the orientation of the crystal (\( \mathbf{c} \)) are all shown. Note that the axis of the birefringent plate (\( \mathbf{c} \)) is arbitrarily oriented and does not lie in the plane of the plate’s surface. In Fig. 1(b), \( t \) is the thickness of the plate, \( \beta \) is the internal Brewster’s angle (around 33° in quartz around a wavelength of 1 \( \mu \)m), \( \mathbf{s} \) is the direction of beam propagation in the plate, \( \rho \) is the rotation angle of the plate, \( \gamma \) is the angle between the crystals axis and the beam propagation direction and \( \sigma \) is the angle between the optical axis and the surface normal (when \( \sigma = 90^\circ \), the optical axis lies on the surface of the plate, which is what is typically employed in birefringent filters). As we have mentioned, the BR plate will change the polarization of the intracavity laser beam, creating a wavelength dependent loss. Besides the wavelength (\( \lambda \)), this loss will also depend on the thickness of the birefringent plate (\( t \)), the rotation angle of the birefringent filter \( \rho \), as well as well as the angle between the optical axis and the surface normal (\( \sigma \)). Theoretical details of transmission characteristics of such laser systems containing birefringent filters have been studied in detail earlier [30–35] and will not be repeated here. In the following, we will present numerical simulation results that are based on Jones matrix analysis of the entire cavity. We will mostly elaborate on the importance of the orientation of the plate optical axis.
in determining filtering characteristics of the system especially for multicolor laser operation applications.

As an example, Fig. 2(a) shows the calculated transmission properties of a Cr:Nd:GSGG laser operating around 1 μm that contains a 3-mm-thick crystal quartz birefringent plate with an optical axis tilted 45° with respect to the plate’s surface (σ = 45°). The graph is separated into two for easier viewing.

![Fig. 2](image1)

Fig. 2. Calculated transmission characteristics of a Cr:Nd:GSGG laser cavity around 1 μm, as a function of wavelength for different values of birefringent plates rotation angle (for ρ in the range from 15° to 115°, see differently colored graphs). The calculation has been performed for a 3-mm-thick crystal quartz birefringent plate with an optical axis tilted 45° with respect to the plate’s surface (σ = 45°). The graph is separated into two for easier viewing.

As an example, Fig. 2(a) shows the calculated transmission properties of a Cr:Nd:GSGG laser operating around 1 μm that contains a 3-mm-thick crystal quartz birefringent plate with an optical axis tilted 45° with respect to the plate’s surface (the angle is chosen as σ = 45° here, since such a BRF filter was available to us and therefore used in the experiments). Both the birefringent plate and the gain medium were assumed to be inserted at Brewster’s angle. The transmission is calculated for several different rotation angles ρ of the birefringent plate in the range from 15° to 115°. In the experiments, changing ρ refers to rotation of the BRF about an axis normal to the surface, as shown in Fig. 1(b). Also, the results are symmetric for ρ values of 0°-180° and 180°-360°; hence, we will focus only on the 0°-180° range here. Note from Fig. 2 that as the plate’s rotation angle is varied, the filter properties such as modulation depth, free spectral range and full-width-half-maximum (FWHM) of the transmission peaks change considerably. As an example, when ρ = 15°, the filter has a FWHM of 75 nm and a modulation depth of around 45%. On the other hand, ρ = 115° provides a similar modulation depth but has a FWHM of around 5 nm. Hence, when its optical axis is not oriented parallel to its surface, the same filter could provide quite different filter functions at different values
of rotation. For comparison, Fig. 3 shows the calculated transmission in the same wavelength region for a regular birefringent plate with an optical axis on the surface of the plate ($\sigma = 90^\circ$, all the other parameters are same as Fig. 2). Note that for this case, the free spectral range and the full-width-half-maximum of the filter stay nearly the same and are not strong functions of the rotation angle $\rho$. Hence, such a filter offers limited flexibility compared to an BRF with an optical axis pointing out of its surface.

As we have discussed above using Fig. 2 and Fig. 3, compared to a regular BRF plate, a BRF plate with an optical axis pointing out of plate’s surface provides a wider range of filter parameters. This observation can also be seen from Fig. 4 which plots the variation of free-spectral range (FSR), FWHM and modulation depth as a function of plates rotation angle $\rho$ around the 1 $\mu$m region for the plate with an optical axis tilted 45$^\circ$ with respect to the plate’s surface ($\sigma = 45^\circ$). First of all, consistent with the observations from Fig. 2, there are two regions where the modulation depth is high, which is necessary for the plate to be useful for many of the tuning applications (one narrow band region around $\rho = 15^\circ$ and another broadband region around $\rho = 115^\circ$). As may be seen from Fig. 4, around 15$^\circ$ one can attain FSR values above 500 nm and FWHM values around 75 nm. On the other hand, at rotation angles around 115$^\circ$, one can obtain FSR values in the 40-80 nm range and FWHM values between 6 nm and 15 nm (again in accordance with Fig. 2).

![Graph showing variation of FSR, FWHM, and Modulation Depth vs. Plate Rotation Angle](image)

Fig. 4. Calculated variation of free spectral range (FSR), FWHM and modulation depth for a Cr:Nd:GSGG laser cavity operating around a wavelength of 1 $\mu$m, as a function of rotation angle $\rho$ of the birefringent plate. The calculation has been performed for an optical axis orientation 45$^\circ$. The crystal quartz birefringent plate was assumed to have a thickness of 3 mm.

From an alternative perspective, Fig. 5 shows the calculated transmission of the system at a fixed wavelength of 1061 nm (coinciding with the gain peak of Cr:Nd:GSGG) as a function of plate’s rotation angle. The transmission is calculated for two different $\sigma$ angles: (a) 45$^\circ$ and (b) 90$^\circ$. We would like to remind here that $\sigma$ is the angle between the optical axis and the surface normal and $\sigma = 90^\circ$ refers to a typical birefringent plate with an optical axis that lies on the surface of the plate. Note that as the birefringent plate is rotated, the incident wave at 1061 nm sees several transmission maxima (where the birefringent plate does not change the incident polarization state). Note that, for the plate with a $\sigma$ of 45$^\circ$ [Fig. 5(a)], around each of this transmission maxima (27 different orders), the filter characteristics are different and one can attain different FWHM and FSR values. On the other side, for the typical birefringent plate with an optical axis that lies on the surface [$\sigma = 90^\circ$, Fig. 5(b)], there are lower number of orders (20), and transmission maxima are distributed quite evenly (similar FSR) with each order having a similar width (FWHM).
Fig. 5. Calculated variation of transmission at a wavelength of 1061 nm as a function of birefringent plate rotation angle $\rho$ for a Cr:Nd:GSGG laser cavity that contains a 3-mm-thick crystal quartz birefringent plate. The plate’s optical axis is tilted at an angle $\sigma$ of (a) 45° and (b) 90° with respect to the plate’s surface.

Fig. 6. Calculated variation of free spectral range (left) and modulation depth (right) for a Cr:Nd:GSGG laser cavity around 1 $\mu$m, as a function of birefringent plate rotation angle. The calculation has been performed for different optical axis orientation values $\sigma$ ranging between 0° and 90° (see differently colored graphs). The crystal quartz birefringent plate was assumed to have a thickness of 3 mm.

To elaborate on this issue further, Fig. 6 shows the calculated variation of filter free spectral range and modulation depth as a function of filter rotation angle $\rho$. The calculation has been performed for several different optical axis orientations $\sigma$ in the range from 0° and 90°. When $\sigma = 0°$, the plate’s crystal axis is perpendicular to the plate surface, and hence the BR plate does not change the polarization state of the incident beam at all, yielding a modulation depth of 0 and the calculated free spectral range does not have any physical significance. As mentioned when $\sigma = 90°$, the plate’s crystal axis lies on the surface of the plate, and as can be seen the free spectral range value varies in a narrow range (30-45 nm). On the other hand, when $\sigma = 45°$, the FSR varies in a much wider range between 35 and 725 nm, and this makes the filter useful for a broader array of applications. We note here that, as we mentioned earlier, all the values of this FSR might not be accessible, since the modulation depth might be too low for some cases. Lastly, as $\sigma$ gets closer to $\beta$ (the internal Brewster’s angle), the direction of beam propagation $\vec{s}$ gets closer to the direction of crystals c axis ($\vec{c}$), $\gamma$ approaches an angle of 0° and one can attain very large free spectral range values. However, in such a case the FWHM of the filter is also very large, which might not be optimum for tuning applications.

In this work, we are interested in use of birefringent filters in multicolor laser operation applications. For example, assume one wants to obtain a two-color Cr:Nd:GSGG laser operating at the wavelengths of 1058 nm and 1061 nm. Looking at the emission spectrum, the line of Cr:Nd:GSGG around 1061 nm is stronger than the line at 1058 nm. Hence one needs to create some loss at 1061 nm to push the laser to operate at two colors simultaneously (to
roughly equalize the net gain at both transitions). Moreover, one may want to fine tune the net gain in each wavelength to adjust the laser power in each lasing line. Hence, ideally one needs a filter that potentially could enable a wide range of loss modulation. In that respect, since the birefringent filters with optical axis pointing out of the surface enables access to a wider selection of filter parameters such as free spectral range and filter bandwidth, they are better suited for multicolor laser operation applications. A wider set of filter parameters from a single BR plate: (i) enables multicolor operation in many different wavelength pairs, (ii) permits better adjustment of power at each wavelength in multicolor operation, and (iii) in some cases might improve the stability of the multicolor laser. In the following, we will present experimental data taken with Cr:Nd:GSGG and Cr:LiSAF lasers that confirm the expectations of our simulation results.

3. Experimental setup

Figure 7 shows a schematic of the Cr:Nd:GSGG and Cr:LiSAF lasers that were used to demonstrate the potential of birefringent filters with a c-axis pointing out of plane in obtaining cw multicolor laser operation. The lasers were pumped by four 665 nm, linearly-polarized 1.8-W single-emitter multi-mode diodes (MMD-1 to MMD-4). The output of the multimode diode lasers were first collected and collimated with aspheric lenses of a focal length of $f = 4.5$ mm and then focused inside the laser crystals to a spot size of around $25 \times 70 \, \mu m^2$ using 100 mm focal length achromatic doublets. An astigmatically compensated X-type cavity consisting of two curved pump mirrors (M1 and M2, $R = 75$ mm), a flat end mirror (M3) and output coupler (OC) were employed for both lasers. The cavity mirrors (M1-M3) for Cr:Nd:GSGG had a reflectivity bandwidth extending from 845 nm to 1120 nm and a transmission of $\sim 97\%$ at the pumping band. The cavity mirrors (M1-M3) for Cr:LiSAF had a reflectivity bandwidth extending from 730 nm to 1030 nm and a transmission of $\sim 98\%$ at the pumping band. Short and long cavity arm lengths were 25 cm and 30 cm, respectively. As the gain media, we have used (a) a 8.15 mm long, 0.25% Cr and 0.015% Nd-doped Cr:Nd:GSGG crystal and (b) a 20-mm-long, 0.8% Cr-doped Cr:LiSAF crystal. The Cr content in Cr:Nd:GSGG enables pumping by visible red diodes, whereas the Nd content enables laser emission in the well-known emission wavelengths of the Nd ion. Both crystals were Brewster-cut to minimize laser reflection for the TM polarized intracavity laser beam. The Cr:Nd:GSGG sample absorbed 98.5% and 65% of the incident TM and TE polarized pump light, respectively (34% of the incident pump power was lost due to Fresnel reflections for TE polarization). The Cr:LiSAF crystal absorbed about 98% and 86% of the incident TM and TE polarized pump light, respectively (10% is lost for TE). The laser crystal holders were cooled to 15 °C with a circulating water chiller. For multicolor laser operation a 3-mm-thick crystal
quartz birefringent filter (BRF) with an optical axis 45° to the plate’s surface plane has been used for both gain media. The birefringent filter was inserted at Brewster’s angle into the cavity. During the experiments, the BRF was rotated about an axis normal to the surface to optimize its filtering properties for the desired operation regime.

4. Experimental results

4.1 Multicolor laser operation with Cr:Nd:GSGG

In this section we present our multicolor laser operation results taken with the Cr:Nd:GSGG gain material. We will start this section with the regular continuous-wave laser results, meaning laser data taken in the usual single-wavelength operation regime. Figure 8(a) shows sample cw laser efficiency curves taken using 1%, 3% and 5.4% transmitting output couplers. As an inset, laser slope efficiencies obtained with respect to absorbed pump power were also indicated for each output coupler. The best laser performance was attained using the 5.4% output coupler, where we have obtained cw powers as high as 738 mW at an absorbed pump power of 4.6 W. On the other hand, to demonstrate tuning at more wavelengths or wavelength pairs, we have used the 3% transmitting output coupler in tuning experiments. With this output coupler, we have measured a laser threshold of 62 mW, and acquired a slope efficiency of 16.2%. The laser produced up to 496 mW of cw laser output at an absorbed pump power of 4.6 W. The free running laser wavelength was 1061 nm (with free running we mean for the cavity without the BR plate). When the BR plate was inserted into the cavity, the laser power at 1061 nm decreased to 455 mW due to the additional losses associated with the BR plate. By adjusting the rotation angle of the filter, we could attain lasing at 7 other wavelengths. Figure 8(b) shows sample spectra obtained from the single-wavelength cw Cr:Nd:GSGG laser. The cw output powers obtained at each transition are also indicated in the figure. Laser powers at the 1058 nm and 1061 nm lines are relatively high, as expected from the observed strength of these lines in the emission spectrum.
Figure 9 summarizes the multicolor cw laser operation results obtained with Cr:Nd:GSGG. By adjusting the rotation angle of the BRF plate to the desired position, dual-wavelength (two-color) cw operation has been obtained at 11 different transition pairs: 1051 & 1058 nm, 1051 & 1061 nm, 1051 & 1103 nm, 1058 & 1061 nm, 1058 & 1068 nm, 1061 & 1068 nm, 1061 & 1103 nm, 1065 & 1068 nm, 1068 & 1072 nm, 1068 & 1111 nm, 1071 & 1111 nm, respectively. In Fig. 9, the data are plotted starting from the spectrum with the shortest lasing wavelength and the order of the graphs is not correlated with the rotation angle of the BRF plate. Output power levels are also indicated in the figure. In cw two-color laser operation, for most of the transition pairs, the laser was quite stable and by fine adjusting the rotation angle of the BRF, it was possible to vary the power in each transition. The frequency differences between the pairs range roughly between 0.7 THz and 13.5 THz, which potentially facilitates efficient THz generation at a wide spectral range. An interesting point to note here is that, even though the minimum free spectral range that can be provided by the BRF was around 30-40 nm for our case [Fig. 4], we could still obtain two-color laser operation with wavelength separations as low as 3 nm. This finding shows that, as mentioned earlier, for multicolor laser operation one needs to equalize net gain for the oscillating modes by introducing the correct filter function and this does not necessitate use of a BRF with an FSR value that matches the wavelength separation. Moreover, a birefringent filter with an optical axis on the plate's surface can also be used for multicolor operation but it cannot provide the richness of wavelength pairs that we have obtained using an off-axis BRF in this study. With the BRF filter it was also possible to obtain three-color cw laser operation with Cr:Nd:GSGG at the 1051 & 1058 & 1061 nm, 1061 & 1065 & 1068 nm, and 1061 & 1068 & 1072 nm wavelength groups [Fig. 9(b)]. However, as expected, unlike two-color laser operation the adjustment of the BRF filter angle does not allow free variation of lasers power in each line in this setting since this requires two independent inputs and we have only one. Still, as seen from Fig. 9(b), by fine adjustment of the filter angle, it was possible to almost equalize the power in each line for the 1051 & 1058 & 1061 nm and 1061 & 1065 & 1068 nm wavelength operation.
Table 1. Review of dual and tri-wavelength Nd-based solid state lasers

| Wavelengths (nm) | Gain Medium | Operating Regime | Method for multicolor operation | Reference |
|------------------|-------------|------------------|---------------------------------|-----------|
| 938.5 & 946      | Nd:YAG      | CW               | -                               | [36]      |
| 1079.5 & 1341.4  | Nd:YAlO₃    | QS               | Specially designed cavity mirrors| [18]      |
| 932.9 & 936.5    | Nd:GGG      | QS               | -                               | [17]      |
| 1075.8 & 1078.1  | Nd:LYSO     | ML               | -                               | [37]      |
| 1075.5 & 1076.8 & 1078.2 | Nd:SYO | ML | - | [38] |
| 946 & 1064       | Nd:YAG      | CW               | -                               | [18]      |
| 1075.5 & 1076.8 & 1078.2 | Nd:SYO | ML | - | [38] |
| 1064.5 & 1085.5  | Nd:YVO₄    | CW               | Specially designed cavity mirrors| [40]      |
| 1064 & 1342      | Nd:YVO₄    | CW               | Coupled cavity (two OCs)        | [15]      |
| 1064 & 1342 & 593 | Nd:YVO₄ | QS | Coupled cavity (two OCs) | [41] |
| 1064.1 & 1085.3  | Nd:YVO₄    | CW               | Specially designed cavity mirrors| [42]      |
| 1096.1 & 1098.5  | Nd:YVO₄    | CW               | Coupled cavity                  | [43]      |
| 1063 & 1065      | Nd:YVO₄    | CW               | Coupled cavity                  | [44]      |
| 1064 & 1064      | Nd:YVO₄    | CW               | Dual-crystal                    | [45]      |
| 1319 & 1338 & 1356 | Nd:YAG | CW | Specially designed cavity mirrors | [46] |
| 1063 & 1342      | Nd:YVO₄    | CW, QS           | Coupled cavity (two OCs)        | [16]      |
| 1064 & 1064      | Nd:YAG     | CW               | Specially designed cavity mirrors| [47]      |
| 1066.6 & 1067.1  | Nd:LGGGG    | ML               | Fabry-Perot band-pass filter    | [48]      |
| 1064 & 1074      | Nd:YAG     | CW               | -                               | [49]      |
| 1058.9 & 1060.3 & 1062.1 | Nd:YGG | QS | - | [50] |
| 1064 & 1319 & 1338 | Nd:YAG | CW | Specially designed cavity mirrors | [12] |
| 1052 & 1064      | Nd:YAG     | QS               | Cr:YAG saturable absorber       | [51]      |
| 1059 & 1061      | Nd:CGGG    | QS               | -                               | [52]      |
| 1059.35 & 1061.7 | Nd:CGGG    | ML               | -                               | [53]      |
| 1320 & 1338 & 1353 | Nd:GdLuAG | QS | - | [54] |
| 1063 & 1064      | Nd:YVO₄    | ML               | Dual-crystal                    | [55,56]   |
| 1059 & 1061      | Nd:CLTGG   | ML               | -                               | [57]      |
| 1060.9 & 1062.7  | Nd:LGGGG   | ML               | -                               | [58]      |

*Denotes the results obtained in this work.

To finalize this section, we would like to compare the multicolor laser operation results obtained with Cr:Nd:GSGG in this study with the other Nd-based laser results in the literature (Table 1). Our aim is to show the advantage of using BRFs with tilted optical axis in multicolor operation compared to other methods. In Table 1, for each summarized result from the literature, the gain medium, the multicolor laser wavelengths, the laser operation regime and the method used for multicolor operation are indicated. Note that most of the studies
report multicolor operation in a few pairs of transitions, whereas in our study we have obtained multicolor operation in 14 different wavelength groups. As indicated before, this is the advantage of using the BRF filter with a c-axis out of the crystals surface, which provides a rich range of filter parameters from a single device. Other approaches such as specially coated cavity mirrors, coupled cavities or two different laser crystals only provide multicolor operation at a few (if not one) wavelength pair. Moreover, the technique that is used in this paper allows easy adjustment of laser power in each line by adjustment of the BRF filter angle. This option is not always available relying on other techniques. Lastly, our setup is flexible to variation in pump power or output coupling, since again the fine adjustment of BRF angle provides a feedback mechanism to cancel out any undesired fluctuations. The results presented here were taken with Cr:Nd:GSGG which was available at the laboratory during the experiments. However the method we present is general and can be applied to any Nd-based gain media as well as other rare earth element doped gain media such as Er, Yb, Ho and Tm.

4.2 Multicolor laser operation with Cr:LiSAF

In the previous section, we have presented laser operation results taken with the Nd-based material Cr:Nd:GSGG. In multicolor laser operation, rare earth element doped gain media with sharp laser lines have advantage since the filter parameters should be optimized for two or three fixed known wavelengths. On the other hand, for the transition metal doped gain media such as Cr:LiSAF, laser operation over a broad wavelength range is feasible and multicolor operation requires a more subtle optimization. To test the feasibility of a BRF plate in multicolor operation in transition metal-doped gain media, we have performed detailed experiments with Cr:LiSAF as well.

![Optical spectra obtained in dual-wavelength operation of the continuous-wave Cr:LiSAF laser. Obtained output powers are also indicated for each case. The data were taken at an absorbed pump power of 1500 mW.](image)

Single-wavelength cw operation results of a multimode diode pumped Cr:LiSAF laser has recently been presented in [59], and here only the new results involving multicolor laser operation will be presented. In the experiments, the free running Cr:LiSAF laser was producing around 500 mW of cw output around 860 nm at an absorbed pump power of 1.5 W using a 1% transmitting output coupler (while pumping only with one of the multimode diodes). With the insertion of the BR plate, the output powers around 860 nm decreased to the 450 mW level. In single wavelength operation, the laser could be tuned continuously from 770 nm to 1110 nm. It requires two different highly reflective mirror sets to cover all this region [59].

Figure 10 shows the dual-wavelength operation results obtained with the Cr:LiSAF laser in cw mode. Obtained power levels from the Cr:LiSAF laser are indicated in the figure as...
well (at an absorbed pump power of 1.5 W). The Cr:LiSAF laser could be operated in dual wavelength operation quite stably at 10 different laser wavelength pairs: 848 & 870 nm, 847 & 877 nm, 846 & 884 nm, 839 & 888 nm, 838 & 892 nm, 816 & 899 nm, 814 & 920 nm, 814 & 936 nm, 800 & 947 nm, and 789 & 869 nm, respectively. In Fig. 10, the spectra are depicted starting with lasing wavelength pairs with minimum separation and the order of the plots is not correlated with the rotation angle of the BRF plate. Note that the center of the lasing lines are located around 860 nm, which is where the gain of Cr:LiSAF maximizes. Besides the 10 wavelength pairs shown in Fig. 10, multicolor laser operation could also be obtained at many other pairs; the Cr:LiSAF laser, however, was not very stable at these other transition pairs and they will not be presented here. This we believe is due to the broad FWHM gain bandwidth of Cr:LiSAF of approximately 200 nm, which makes stabilization of two-color laser operation more challenging compared to narrow and discrete line gain media such as Cr:Nd:GSGG. First of all, unlike Cr:Nd:GSGG, it was not possible to adjust the wavelengths in multicolor operation: the laser optimizes itself and works at a wavelength pair that cannot be controlled. For example, we have obtained stable two-color laser operation at the 848 nm & 870 nm wavelength pair and obtained an output power of 350 mW. As mentioned the wavelengths are determined by the properties of the BRF, the specific optics used and the laser materials gain properties and therefore, they cannot be adjusted freely. Moreover, with Cr:LiSAF it was harder to adjust the power level in each line during two-color operation again due to the above mentioned difficulty of broadband gain. However, as the results in Fig. 10 shows the method still works in Cr:LiSAF for many different wavelength pairs. Different BRF designs could potentially be used to attain two-color laser operation at other transition pairs in Cr:LiSAF.

Note from Fig. 10 that the wavelength differences between the operating wavelength pairs are in the 22 nm to 80 nm range. This corresponds to a frequency difference ranging from around 9 THz to 70 THz. Moreover, the average power levels that are indicated in Fig. 10 are the results obtained while pumping the Cr:LiSAF laser with only one multimode-diode, and could be scaled up 3-4 times by applying all the available pump power from the diodes (i.e. to above 1.5 W level) [59]. We also believe that, using this BRF plate, multicolor laser operation is also feasible with ultrashort pulses in either Kerr lens mode-locked or Saturable Bragg mirror mode-locked laser cavities [60, 61]. Lastly, dual-wavelength cw operation has been demonstrated in Cr:LiSAF before using grating controlled coupled cavities [23]. However, the power levels reported were in the order of 10 mW only.

5. Conclusions

In summary, we have explored the application of birefringent filters as frequency selective elements in multicolor lasers. Our simulation results predicted that birefringent filters with an optical axis pointing out of its surface provide design flexibility in filter parameters and offer access to a very wide set of filter parameters. In the experiments, we have obtained cw multicolor laser operation in many laser line pairs in Cr:Nd:GSGG and Cr:LiSAF materials, in accord with the simulation results. We believe that tilted-axis BRFs should provide efficient and low-cost multicolor laser operation with other laser gain media as well.

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