Solid-state lasers emitting at red, green and orange wavelengths for projection applications

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ABSTRACT

Lasers will bring a further step in terms of compactness and efficiency for projection systems. However, the availability of suitable green laser sources limits the advent of laser projection. Blue diode pumped solid-state lasers are presented here as one promising way to realize green, red and orange lasers that are specifically suited for projection applications.

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Introduction

Lasers will bring a further step in terms of compactness and efficiency for projection systems. Both factors are of major importance for the currently emerging portable applications of personal projection and micro-projection. These portable applications are possible with devices that allow for quickly sharing data or pictures, devices that connect to any kind of electronic companions like cell phones or cameras or are even embedded in these electronic devices. Lasers emitting at red, green and blue primary wavelengths are a nearly ideal light source for this type of portable projection applications. Especially the excellent collimation of lasers leads to a breakthrough in luminous efficacy for projection systems. However, the availability of suitable visible laser sources limits the advent of laser projection. Figure 1 shows a comparison of the power conversion efficiency of laser diodes emitting at different wavelengths in the visible, together with the normalized responsivity curve of the human eye. The laser diode efficiency is plotted on a logarithmic scale. On this scale, the steep drop of the laser diode efficiency towards wavelengths where the human eye is more sensitive is clearly seen. Laser diodes with an emission wavelength between 535 and 620nm do not exist at all.

In this contribution we will present results from our work on blue diode pumped solid-state lasers as one promising way to realize green, red and orange lasers that are specifically suited for projection applications. These lasers are an attractive alternative to frequency-doubled systems, since they make use of the mature blue laser diodes as pump sources for green, red and also orange emitting solid-state lasers. Especially the green and the orange laser presented here are useful to fill the gap between 500 and 620nm in Figure 1, where diode lasers are either quite inefficient (green) or do not exist at all (orange). Based on blue diode pumped solid-state lasers quite efficient RGB-lightsources for display applications can be realized.

Projection requirements

The requirements for the projection light source depend on the application as well as on the specific projection technology used. For portable, battery-powered applications only small to intermediate screen sizes have to be illuminated and a luminous flux of at least 20lm on the screen is sufficient to realize an acceptable picture quality [1]. Such a luminous flux can be realized with three lasers emitting only about 50mW of power in each primary color red, green and blue. From bigger, standalone devices that connect to different types of electronic equipment, like digital cameras or portable computers, larger screen sizes and an accordingly higher light flux of about 100lm is expected. This in turn requires lasers of about 200mW power in every primary color [2].

Different projection display technologies can be used in combination with lasers. The most straightforward way is using the 2d-lightvalves well-known from front projectors, like digital mirror devices or Liquid Crystal Displays and illuminate these with laser light. Compared to the so-called flying-spot technique [3], the use of 2d-lightvalves has the advantage that laser safety regulations are met even at higher light levels. Furthermore, the requirements on laser beam quality and on the modulation frequency of the laser are much lower for the case of 2d-lightvalve projectors than for flying-spot projectors. Therefore we decided to limit our work to laser sources for 2d-lightvalve projection systems.
Just like the various projection technologies available, there exist also different laser technologies to generate laser radiation at visible wavelengths. We decided to focus our work on blue diode pumped solid-state lasers for two reasons: First of all, we can use the well-developed blue laser diodes as pump lasers for our solid-state lasers. Due to the evolution of applications like optical storage and even the blue color for laser projection itself it is to be expected, that these laser diodes will improve quite rapidly. And secondly, the frequency conversion from the blue pump light into other visible wavelength ranges is a linear process where only one photon is converted into another one. This fundamentally simpler process allows for relaxed tolerances in the laser setup, e.g. a simplified thermal management as compared to frequency-doubled lasers.

Blue-emitting InGaN laser diodes are now commercially available with output powers exceeding the Watt-level [4]. The emission wavelength of these devices around 450nm is well suited as the projection light source for the blue primary wavelength and fits well to the absorption of the Pr$^{3+}$-ion, a very attractive rare-earth ion for visible solid-state lasers. As can be seen in Figure 2, for the excitation of Pr$^{3+}$ doped in the fluoride crystal YLF (LiYF$_4$) the wavelength of 444nm nicely matches an absorption line. Several transitions in the visible wavelength range can be used for laser operation; especially the green, orange and red transitions at 524, 607 and 639nm are well suited for projection applications.

In the experiments we used as a pump source an InGaN-laser diode from Nichia Corp. with an emission wavelength of 443nm and an output power of 1W. The beam from the diode was collimated by an aspheric lens and shaped with the help of an anamorphic prism pair, see Figure 3. With a second lens the beam was then focused into the laser crystal. These optical components used for collimation, shaping and focusing the pump laser beam are easily integrated into a single micro-optical element, allowing for relatively compact devices. The crystal used in the experiments presented here was a 0.2% Pr-doped, commercially available Pr:YLF crystal with a length of 12mm. The crystal was oriented in the laser setup with the crystallographic c-axis parallel to the electric field of the pump laser to match the maximum of the Pr$^{3+}$-absorption and it was placed in a plano-concave laser resonator, as sketched in Figure 3. By using resonator mirrors with different coatings for green, red or orange laser operation, the laser wavelength was changed without any further modifications of the setup. In every case the reflectivity of the outcoupling mirror was about 99% at the laser wavelength.

**Experimental results**

The characteristic curves for these three lasers at red, green and orange wavelengths are shown in Figure 4. The red laser at 640nm is the most efficient one with a power conversion efficiency PCE=5.6%, followed by green (PCE=4%) and then orange (PCE=3.3%). The power conversion efficiency is the ratio of optical laser power to electrical power supplied to the diode. The behaviour of the red and the green laser in terms of efficiency PCE, laser threshold $P_{th}$ and slope efficiency $\eta_s$ can be understood from the ratio of the respective emission cross-sections [5]. Based on the emission cross-sections, the orange laser should be similarly efficient as the red one. However, we have to assume that reabsorption processes towards the $^1D_2$-level reduce the efficiency of the orange laser.
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In these experiments we used a relatively long laser crystal with uncoated facets. For the green laser a much higher efficiency of 7% and above has been reached by using shorter laser crystals with appropriately coated facets [6], [7]. With these improvements, the maximum output power of the green laser could also be scaled to 380mW. Similar improvements are to be expected for the other laser wavelengths red and orange as well.

The orange laser wavelength of 607nm is nearly ideally suited to realize an efficient RGB light source with well-balanced white for projection purposes. Figure 5 shows the colour gamuts for two RGB-lightsources that use a blue laser diode at 443nm in combination with two blue diode pumped solid-state lasers. One of these solid-state lasers emits at 523nm in the green and the other one is either the red Pr:YLF-laser at 640nm or the orange one at 607nm. In both cases, a colour triangle is spanned that complies with the TV-standard set by the European Broadcasting Union (EBU).

By using the orange laser for the red primary colour of the RGB-lightsource, one can make good use of the higher eye-sensitivity at this wavelength: Even when the reduced power conversion efficiency of the orange laser is taken into account, a light source based on a blue laser diode and two blue diode pumped solid-state lasers is about 20% more efficient, when the orange transition at 607nm is used instead of the red transition at 640nm.

Table 1: The influence of the wavelength of the red primary on the efficacy of a 100lm RGB-lightsource is shown. The use of the orange laser instead of the red one leads to a 20% increase in the efficacy of the RGB-lightsource.

<table>
<thead>
<tr>
<th>R / nm</th>
<th>O / %</th>
<th>G / %</th>
<th>B / %</th>
<th>total lm RGB</th>
<th>total el. power / W</th>
<th>efficacy lm/W</th>
<th>efficacy O/R</th>
</tr>
</thead>
<tbody>
<tr>
<td>640</td>
<td>5.6</td>
<td>3.3</td>
<td>20</td>
<td>105</td>
<td>7,5</td>
<td>16,2</td>
<td>1,20</td>
</tr>
<tr>
<td>607</td>
<td>5.78</td>
<td>7</td>
<td>20</td>
<td>105</td>
<td>4,5</td>
<td>22,5</td>
<td>1,20</td>
</tr>
<tr>
<td>optimized PCE / %</td>
<td>9.8</td>
<td>88</td>
<td>120</td>
<td>105</td>
<td>3,8</td>
<td>26,9</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 shows this comparison of the RGB-lightsource efficacy for different wavelengths of the red primary. The laser powers at the different laser wavelengths were balanced to realize a white point with a correlated color temperature of 8000K and a light flux of 100lm. The throughput efficiency of the projection optics and display was not considered here. Based on the power conversion efficiencies of the lasers presented in this article, we
reach a luminous efficacy of 13.5lm/W when using the red laser at 640nm and of 16.2lm/W with the orange laser at 607nm. This means an increase of 20% in luminous efficacy. The efficacy could even reach values well above 20lm/W, when the improvements in power conversion efficiency that were already demonstrated for the green laser [7] are also realized for the red and orange emission wavelengths.

Conclusions
In conclusion we have realized blue diode pumped solid-state lasers emitting at red, green and orange wavelengths within the same laser setup and using the same laser material. While the setup was not optimized to achieve the maximum power conversion efficiency, a comparison of the efficiencies of the three laser transitions was made. Even though the orange laser is limited in its power conversion efficiency by reabsorption phenomena, it is quite useful to realize a highly efficient RGB-lightsource for display applications. It will therefore also be a good alternative to red emitting laser diodes for the red primary colour.

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References