HIGH-POWER RGB LASER SOURCE FOR DISPLAYS

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Abstract

High-power, laser-based red, green and blue (RGB) sources are required for high-performance display systems. We have developed a high-power RGB source based on a diode-pumped solid state laser combined with an optical parametric oscillator. The source is efficient, compact and reliable, and to date has generated a total power of 15 W, in the form of pulsed energy at a 22-kHz rate. The source has been transitioned from a breadboard device to a complete, rack-mounted system. In addition, working with Photera, Inc., we have coupled the laser source to a modified, high-resolution, commercial LCD projector to make an entire, laser-based display system.

Introduction

Laser projection displays offer a number of advantages over their lamp-based counterparts. The greater spatial coherence results in greater depth of focus (permitting projection on curved surfaces), higher resolution and greater pixel contrast. The monochromatic nature of laser light results in brilliant, saturated colors and greater optical efficiency. However, laser projection displays based on lamp-pumped solid-state or gas lasers are bulky, inefficient and require frequent maintenance (every few hundred hours). Recently, diode-pumped solid-state lasers and improved non-linear optical frequency conversion techniques have resulted in efficient and reliable low to moderate power (<1 W in red and blue, <5 W in green) visible laser sources with diode laser lifetimes in excess of 10,000 hours. These sources are based on second harmonic generation (SHG) of various lines of the Neodymium (Nd) ion and hence are very efficient for the green light generation based on SHG of the strongest Nd laser transitions around 1000 nm. However they are much less efficient for red generation based on SHG of the 1300-nm transitions and blue generation from the 900-nm transitions. Furthermore, the luminous efficiency of the red light (657-671 nm) is low, requiring 4-5 times the amount of green power for balanced white-light generation.

In our patented scheme [1], we generate all three primary colors from one laser source. This is achieved by first frequency-doubling a 1047-nm Nd-doped Yttrium Lithium Fluoride (Nd:YLF) laser to produce 524-nm green light. The green source then becomes a pump for an optical parametric oscillator (OPO) with a signal wavelength around 900 nm and an idler wavelength around 1260 nm. The signal and idler are then frequency-doubled to produce blue light around 450 nm and red light around 630 nm. The unused green pump light is then used for the display.

In the following we describe how we have implemented the RGB source and generated significant power levels. In addition, we describe a demonstration projection system based upon the use of a commercial LCD projector.

Laser Development

The RGB source consists of a green-wavelength pump laser to drive the OPO and the OPO itself.

Pump Laser

The pump laser is based on a diode-pumped, Nd:YLF “Gain Module” active element, which consists of a 28-mm-long Nd:YLF slab side-pumped by a pair of opposed and offset, 40-W, collimated, 805-nm laser diode bars. External, closely coupled high reflectors are used to make

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multiple passes (five) of the 1047-nm laser beam through the slab, which increase the gain and improve the fundamental-mode extraction efficiency.

Fig. 1 shows the pump-laser configuration, consisting of two gain modules, one in a cw-pumped, repetitively Q-switched oscillator, and the other in an amplifier stage, along with a SHG crystal to produce 524-nm green power. The oscillator produces >25 W of cw output in a TEM_{00} mode, with an $M^2 < 1.2$, and a diode drive power of 32 W/diode. With the amplifier added, the output rises to 54 W CW, and the system generates 50 W of average power at a Q-switched pulse rate of 22.5 kHz, with 35-ns-duration pulses. The 524-nm output of the SHG stage, non-critically phase-matched (NCPM) LBO, is 30 W average, at a total of 128 W of optical pump power from the four diode lasers.

OPO

Figure 2 is the singly resonant OPO configuration. We use Type I, NCPM LBO as the OPO nonlinear medium due to its high damage threshold and ability to be non-critically phase-matched to generate the wavelengths of interest at temperatures around 150°C. Furthermore, the phase-matching temperature may be changed to tune the output wavelengths. We employ a ring OPO cavity to reduce feedback, eliminating the need for an optical isolator between the pump source and the OPO. For white-light generation, more red than blue power is required; however the OPO naturally generates more signal than idler power. In order to favor red generation, we chose to intra-cavity frequency-double the idler using an 18-mm long, non-critically phase-matched Type II LBO, mounted in a temperature controlled oven at 40°C. Consequently, the OPO cavity is resonant at the idler wavelength (1256 nm) rather than at the signal wavelength. The majority of the signal power is rejected along with the unused pump through the second cavity mirror. The signal is then frequency doubled to the blue by a walkoff-compensated, critically phase-matched LBO crystal configuration.

Our OPO has, to date, generated 13 W of 898-nm signal power and an estimated 9.3 W of intracavity idler power at 1256 nm. With ~76% pump depletion, the power of the residual green light for projection is about 5.8 W. We have produced ~3.5 W of 449-nm blue light and ~6 W of 628-nm red light.

At our RGB output wavelengths of 628 nm, 524 nm, and 449 nm, the power level requirements to achieve D65-balanced white per 1000 lumens are 1.42 W, 1.33 W and 0.85 W, respectively. Based upon these values and the powers generated in our laser, the red would support a 4084 lumen D65 white, the green, a 4511 lumen white, and the blue, a 4000 lumen white. Therefore, the RGB-OPO light source is capable of generating 4000 lumens of D65-balanced white, with the amount of blue light as the limiting factor. The estimated total power consumption for the laser head, including diode bars, Q-switch and crystal heaters is 365 W, yielding an electrical to luminous efficiency of ~11 lumens/watt.

Packaging

We initially developed the entire RGB source on an optical table and, after testing the breadboard layout, transferred the components to a 23” rack-mounted package, which contains the RGB laser head, control electronics, power supply and chiller for the laser head.

Included in the laser head are coupling optics to direct the red, green and blue power into three separate optical fibers. We used 365-µm-core fibers with a numerical aperture of 0.22 in the system. The fibers had a silica core/silica clad structure to provide higher power-handling capability than plastic-clad fibers. For this fiber the maximum power rating is 3.4 MW for pulsed light and 700 W for CW, much greater then the powers from the system. The fibers allow delivery of the laser light to a LCD projector.

Projector

One of the applications of the RGB system is for simulation, and in choosing a projector to demonstrate the RGB source we had that application in mind. When surveying the projectors, the primary requirements were a resolution of at least 1024 x 768 (XGA) and three spatial light modulator (SLM) panels in the projector. Additionally, the projector had to have a VGA input to interface with a standard PC.

The two options for SLM’s are digital micromirror devices™ (DMD™) and liquid crystal displays (LCD). DMD's use an array of mirrors as pixels and either reflect the illumination light into the projection optics for a pixel that is on, or into a beam block for an off pixel. They are binary devices that create a gray scale through pulsewidth modulation. Although this scheme functions well for static displays, due to a psychovisual function it produces a double or possibly multiple images when presenting rapidly moving objects.

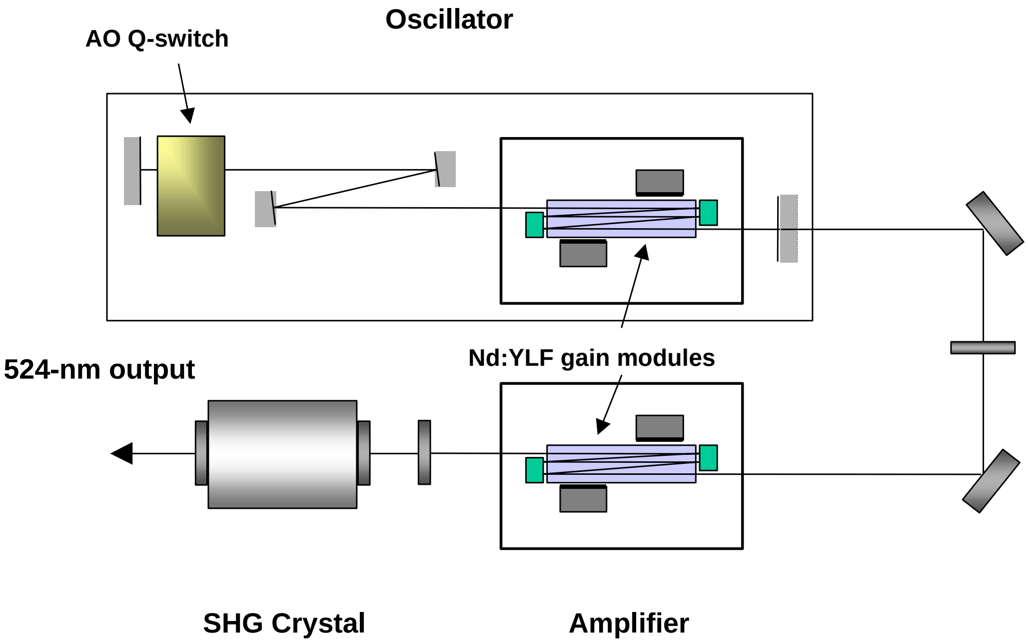

Fig. 1. High-power, 30-W green pump-laser configuration.

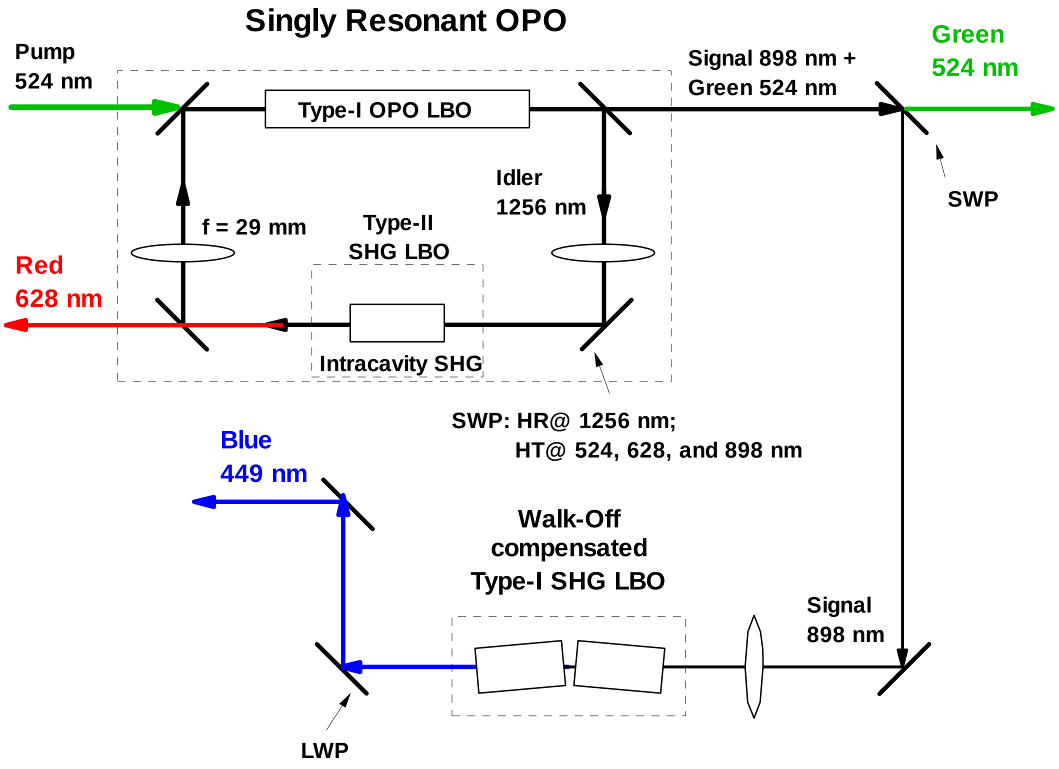

Fig. 2. Optical parametric oscillator (OPO) configuration.

LCD's use an array of polarization-rotating material that is combined with polarized input illumination and with an analyzer that modulates the light. LCD's are analog devices that can partially rotate the polarization of light, so that part of the light gets blocked and does not pass through the projection optics. They typically are on for the majority of the frame time, at the appropriate gray level. In the past, liquid crystal materials have been slow to respond, producing smearing in moving images. However, recent improvements in liquid crystal materials have significantly reduced this problem.

Because simulators must display rapidly moving objects, LCD technology is better suited to simulators, and therefore an LCD projector was selected for this display. After surveying available products, we chose to use a JVC DLA-G11U system. The device uses 3 reflective LCD (D-ILA) 0.9" chips and has a native resolution of 1365 x 1024 in 4:3 aspect, for a total of 1.4 M pixels.

The product uses a 420-W xenon lamp (1000-hour life) to produce 1000 ANSI lumens. We modified the unit by removing the lamp, adding fiber-coupling, beam-formatting optics and re-wiring the electronics to allow operation without the lamp in place. The beam-formatting optics included a re-polarizing scheme to recover the linear polarization for the three colors that was partially compromised by the fiber-delivery system. Also included in the optics were de-speckling components and optics to transform the round beam from the fiber to a rectangular beam for illuminating the LCD. Fig.3 is a photograph of the rear of the JVC projector, showing the fiber-coupling optics added to the bottom of the unit.

Fig. 3. Rear view of modified JVC projector

In our initial tests of the entire system we observed that there was no speckle apparent for the blue and red components of the image, as expected from the spectral properties of the OPO. The green component did exhibit some speckle, and future efforts will address this issue.

Conclusions

Our compact RGB-OPO light source is highly efficient as it derives all three wavelengths from one drive laser. The OPO design is also power scalable for different application requirements. To date we have generated >15 W of total RGB power. We expect the RGB output power to scale linearly with the OPO pump input power. To obtain higher RGB output power, one can increase the available 1047-nm power by increasing the Nd:YLF pump-diode power, either by operating the 40-W bars at full power, by employing 60-W diode bars, or by using additional amplifier modules. Another unique feature of our RGB-OPO design is frequency tunability. Since the OPO output wavelengths are temperature tunable, we can select the red and blue wavelengths in accordance with our requirements for maximum luminosity or for expanded color space operations. Finally, although the technology to date has been based on a Q-switched drive laser, suitable for LCD and DMD modulators, it can also be arranged to operate with high-power mode-locked lasers, providing essentially cw-like performance for other types of image-projecting techniques.

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References

1. P. F. Moulton, U.S. Patent #5740190 "Three-color coherent light system"