

RGB Optical Parametric Oscillator Source for Compact Laser Projection Displays

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ABSTRACT

A compact and efficient laser source is required as an enabling technology for laser projection displays. We discuss a scalable green-pumped, non-critically phase-matched LBO optical parametric oscillator (OPO) which simultaneously generates red and blue wavelengths that are ideal for display applications. Pumping the OPO with 9.6 W of 523 nm green light from a frequency-doubled, diode-pumped Nd:YLF oscillator/amplifier laser system has resulted in a measured 3.6 W of 896 nm signal power and an estimated idler power of 2.6 W. The signal was extra-cavity frequency doubled to produce 0.65 W of blue light at 448 nm. Intra-cavity frequency doubling of the idler produced 1.66 W of red light at 628 nm.

1. INTRODUCTION

Laser projection displays offer a number 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, current 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 so 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 white light generation.

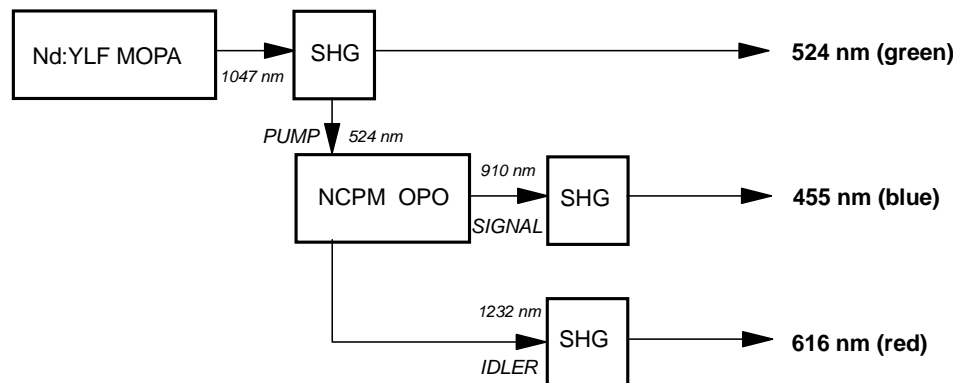


Figure 1. Block diagram of the RGB optical parametric oscillator scheme.

In our patented scheme [1], we generate all three primary colors from one laser source, shown schematically in Figure 1. This is achieved by first frequency-doubling a 1047 nm Neodymium-doped Yttrium Lithium Fluoride (Nd:YLF) laser to produce 523 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.

2. GREEN “PUMP” SOURCE

The green pump source for the optical parametric oscillator is shown schematically in Figure 2. It consists of a commercially available (Q-Peak MPS-1047) 10 W average power, repetitively Q-switched, Nd:YLF oscillator operating at 1047 nm. The oscillator is based on a multi-pass diode-pumped Nd:YLF slab gain module having a high small-signal gain of ≈ 6 which allows it to be also used as an efficient amplifier. For these experiments, the oscillator was run at a repetition rate of 10 kHz, where it produced a pulse energy of 1 mJ with a pulse width of 50 ns. A Faraday rotator prevents feedback into the oscillator and a relay telescope with a de-magnification of 1.4 is used to optimally match the oscillator beam into a second multi-pass, diode-pumped Nd:YLF gain module amplifier. This amplifier boosts the output to greater than 20 W average power, corresponding to a pulse energy of 2 mJ and a peak power of 40 kW. The output was then frequency-doubled to 523 nm by focussing it into an 18-mm long, non-critically phase-matched (NCPM) Lithium Triborate (LBO) crystal. A temperature controlled crystal oven was used to maintain the LBO at the NCPM temperature of 170°C. With 18.8 W of 1047 nm fundamental, 12.2 W of 523 nm second harmonic was generated with a pulse width of 35 ns.

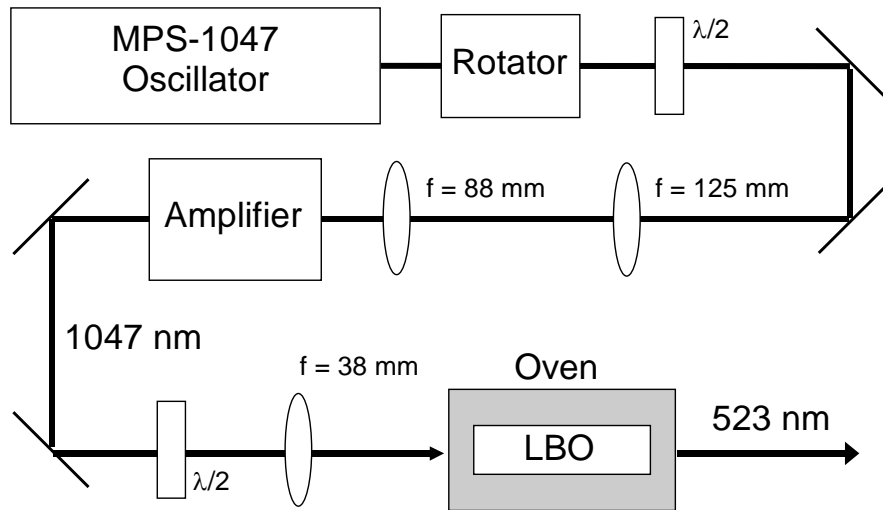


Figure 2. Optical schematic of the 523 nm green OPO pump source.

3. RGB OPTICAL PARAMETRIC OSCILLATOR DESIGN

The RGB optical parametric oscillator design is shown schematically in Figure 3. Type I Lithium Triborate (LBO) was chosen as the OPO material 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 wavelength. Phase match calculations indicate a signal wavelength of 896 nm and an idler wavelength of 1256 nm using a 523 nm pump at a temperature of 152°C. The disadvantage of using LBO is its relatively low non-linear coefficient which necessitates the use of long crystals to minimize OPO threshold. Since long lengths of LBO were not readily available, we chose to use three 18-mm long crystals in series. These crystals were mounted in a temperature controlled oven at 150°C which resulted in non-critical phase-matching for a signal wavelength of 896 nm and an idler wavelength of 1256 nm corresponding to a blue wavelength of 448 nm and a red wavelength of 628 nm. A ring cavity was chosen to reduce feedback in order to eliminate 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 mirrors in the OPO cavity are “dichroic”, having high reflectivity at the idler wavelength and high transmission at the pump and signal wavelengths. Hence, the majority of the signal is rejected along with the unused pump through the second cavity mirror. The signal is then separated from the pump by a pair of dichroic mirrors and focussed by a 75-mm focal length lens into the critically-phase-matched LBO harmonic generator. Due to the small angular acceptance and

walk-off present in critical phase matching, we chose to implement a walk-off compensated harmonic generator using a pair of critically-phase-matched 5-mm long LBO crystals with opposed crystal axes. Thus, the walk-off generated by the first crystal is “undone” by the second crystal. Hence the walk-off and acceptance angle are given by the length of each crystal segment and are effectively half the values for an equivalent crystal that is twice the length [2].

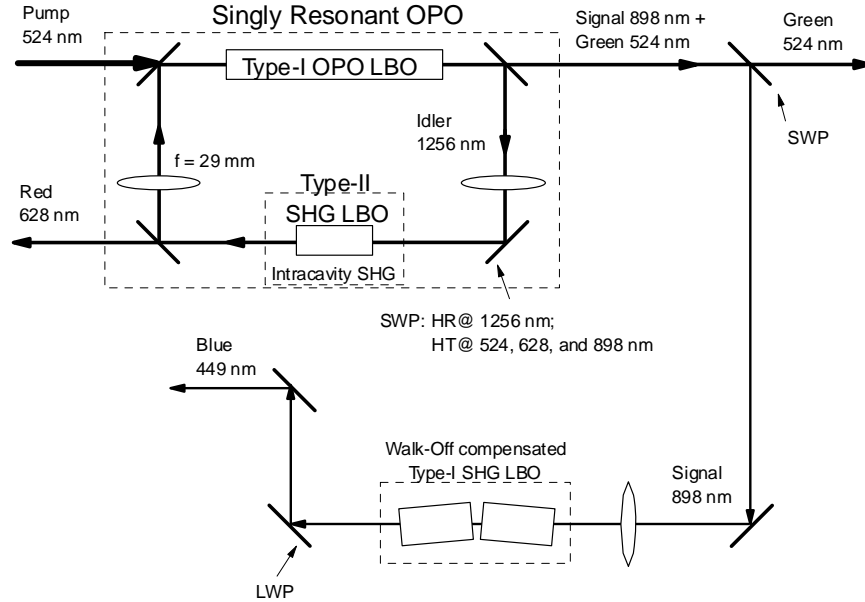


Figure 3. Schematic diagram of the RGB OPO optical layout.

4. RGB OPTICAL PARAMETRIC OSCILLATOR RESULTS

The best results were obtained with a 150-mm focal length lens focussing the pump to a radius of $42 \mu\text{m}$ in the OPO. These results, showing signal and estimated idler output power as a function of pump power, are plotted in Figure 4. Operating at 10 kHz, an average signal power of 3.6 W was obtained at a incident 523 nm pump power of 9.6 W. Using the energy difference between photons, the corresponding estimate of the idler power was 2.6 W resulting in a total near-infrared OPO power conversion of 64.6%. The pump power at threshold was 1.1 W corresponding to a pulse energy of 0.11 mJ and a peak power of 3.1 kW. The observed threshold is in good agreement with threshold calculations made using the model of Brosnan and Byer [3] where a threshold of 0.07 mJ was calculated assuming a $50 \mu\text{m}$ radius pump beam and perfect overlap between the pump and signal beams.

Figure 5 shows the visible output power as a function of pump power. A maximum red output of 1.66 W was obtained for 9.6 W of pump. Using an idler power estimate of 2.6 W, the intra-cavity SHG efficiency is 63.8%. The maximum blue power was 0.65 W and was obtained using a 15 mm long LBO cut for Type I SHG at room temperature. Similar results were obtained with the walk-off compensated LBO crystal pair but these crystals experienced damage on the inside surfaces where the beam was focussed. The signal SHG efficiency is 18.1% and is much lower than expected and a result of the unfavorable conditions of critical phase-matching and the low peak power ($\approx 10 \text{ kW}$). Modelling these results with harmonic generation model incorporating Gaussian spatial and temporal profiles verifies that the maximum conversion efficiency that may be obtained under these conditions, is on the order of 20%. As a result, in its present configuration, the RGB OPO is blue limited for generation of white light. It is expected that the use of a longer walk-off compensated crystal or a non-critically phase matched material would increase the SHG efficiency to $>30\%$ which would then result in full power color-balanced RGB operation. In color balanced operation producing D_{65} white, the infrared (1047 nm) to visible power conversion efficiency is greater than 32% with a total IR to visible conversion of 44%. The color-balanced white output of the RGB OPO source is greater than 1500 ANSI lumens and the electrical input to the pump diode lasers is 200 W resulting in a luminous efficacy of 7.5 lm/W.

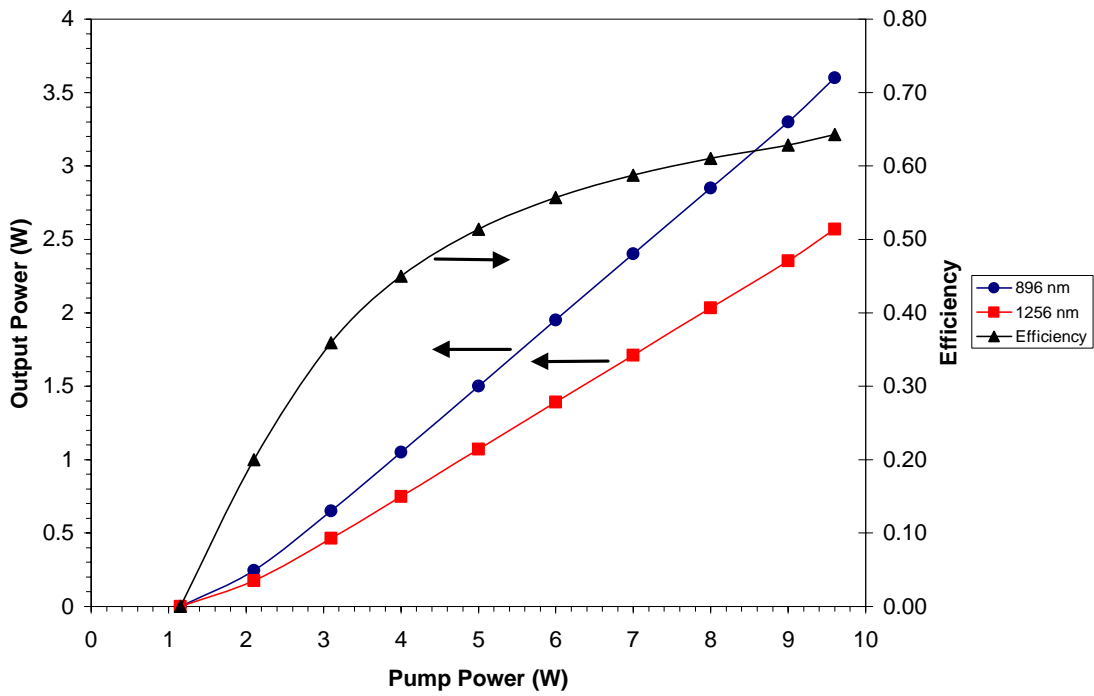


Figure 4. RGB optical parametric oscillator near-infrared output as a function of pump power. Idler power is estimated from signal power.

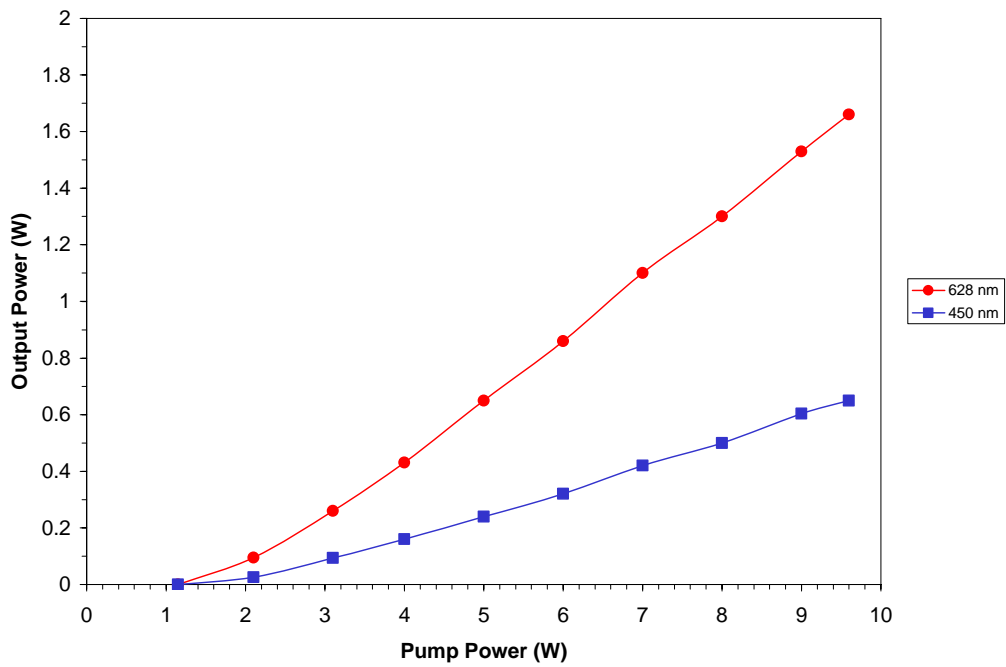


Figure 5. Red (628 nm) and blue (448 nm) output power as a function of OPO pump power.

5. CONCLUSIONS

We have demonstrated an efficient RGB coherent light source based on harmonic generation of a green-pumped near-infrared optical parametric oscillator (OPO). Driven by 9.6 W of 523 nm green light from a frequency-doubled, diode-pumped, Q-switched Nd:YLF laser, the OPO produced 3.6 W of signal at 896 nm and an estimated 2.6 W of idler at 1256 nm. Using extra-cavity frequency doubling in critically phase-matched LBO, 0.65 W of blue light at 448 nm was generated. Intra-cavity frequency doubling of the idler resulted in the production of 1.66 W of red light at 628 nm. Since all the visible light is produced from a single laser head, the RGB OPO source is compact and efficient. It is capable of a 1047 nm pump to color-balanced RGB white light efficiency of 32% and a brightness of greater than 1500 ANSI lumens.

6. REFERENCES

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2. A. V. Smith, D. J. Armstrong, W. J. Alford, *J. Opt. Soc. Am. B.*, **15**, 122 (1998)
3. S. J. Brosnan, R. L. Byer, *IEEE J. Quantum Electron.*, **QE-15**, 415 (1979)