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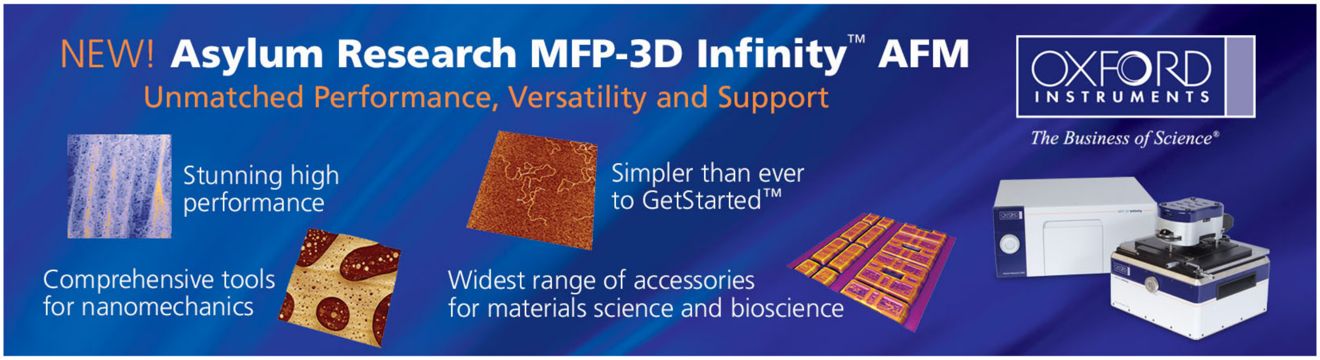
Citation: Applied Physics Letters **89**, 181101 (2006); doi: 10.1063/1.2372737
View online: http://dx.doi.org/10.1063/1.2372737
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/89/18?ver=pdfcov
Published by the AIP Publishing



APPLIED PHYSICS LETTERS **89**, 181101 (2006)

Monolithic red-green-blue laser light source based on cascaded wavelength conversion in periodically poled stoichiometric lithium tantalate

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(Received 20 June 2006; accepted 22 August 2006; published online 30 October 2006)

A compact, pulsed, red, green, and blue laser source based on cascaded quasi-phase-matched wavelength conversion in two periodic superlattices set in tandem in a single stoichiometric $LiTaO_3$ crystal and pumped by a laser source at 532 nm is reported. The white light equivalent flux obtained was 80 lm per 1 W input with a green to white light power conversion efficiency of $>30\%$. Unity power conversion is feasible in this monolithic approach. *© 2006 American Institute of Physics.* [DOI: 10.1063/1.2372737]

The three colors red (R), green (G), and blue (B) constitute the primary colors in vision. Most visual colors including white light can be produced by combining these three primary colors in the proper proportion. Hence in large area display systems, such as a rear projection television, three intense RGB light beams can be used to produce video images with high brightness, sensation, and saturation. It has been estimated that in order to illuminate a 2 m wide 16:9 to display approximately, 1000 lm or 10 W total of RGB laser power is required.[1] Current solutions to produce high power RGB are either by using harmonic generation of multiple lasers[2–5] or by using several discrete stages of parametric conversion of a powerful pump laser.[6] Both lines of approach involve a complex arrangement of linear and nonlinear optical components to achieve the final goal. They are thus relatively inefficient and are quite expensive to implement in commercial projection systems. It is thus desirable to continue to look for alternative solutions.

In this letter we report on a RGB laser source based on quasi-phase-matched (QPM) wavelength conversion in a single crystal. Two superlattices of ferroelectric domain sections periodically poled in tandem in the crystal were used as the frequency conversion medium. Red light was generated as the signal wave by parametric down-conversion of an incident green beam in an optical parametric oscillator (OPO) setting. Subsequent frequency mixing of the residual green light with the mid-ir idler radiation of the OPO produced the third color, blue. We chose stoichiometric lithium tantalate (SLT) as the nonlinear medium. In SLT the nonstoichiometric defect is significantly reduced. This leads to a reduction of the coercive field by one order of magnitude and an increase of the optical damage threshold by two to three orders.[7] In addition, especially when doped with 1 at. % MgO, photorefractive damage and green-induced ir absorption can be elimnated.[8] Hence, periodically poled SLT (PPSLT) and doped PPSLT samples have been successfully fabricated and have been used for efficient second harmonic generation, OPO, and frequency mixing throughout the visible and near infrared regions.[9–15] By cascading two of these processes the desired RGB radiation can be obtained. These two processes can be executed in the same SLT crystal wafer by arranging the two QPM sections in tandem.

Using the published Sellmeier equation of SLT,[16] we calculated that for the signal and idler wavelengths to be 633 and 3342 nm at 160 °C, then the period of the first section should be 11.7 μm. To combine 532 and 3342 nm to generate blue at 459 nm at the same temperature, the period of the second section should be 8.5 μm. Poling was done with metal electrodes at room temperature.[17] The two sections were poled in separate runs in order to ensure uniformity of their duty cycles on account of their different domain periods. The thickness of the sample was 1 mm and the lengths of the first and the second section were 22 and 13 mm, respectively. After poling, the end faces of the sample were cut parallel to <10 min and optically polished. The input face of the sample was dielectric coated for high reflection ($R > 99\%$) at 633 nm and antireflection ($R < 1\%$) at 532 nm. The output face of the crystal was coated for 65% for reflection at 633 nm and antireflection ($R < 1\%$) at 532 and 460 nm to form a compact monolithic cascaded OPO/sum frequency generation (SFG) device. The red beam from the OPO, the blue beam from frequency summing, and the residual green beam constitute the desired RGB output.

A frequency-doubled Lightwave Electronics model M210S diode-laser-pumped Q-switched neodymium doped yttrium aluminum garnet laser was used as the input laser source. The TEM_{00} 1064 nm output from the laser was converted to 532 nm through a type-II phase-matched hydrothermal-grown potassium titanyl phosphate crystal, yielding 1 W of 532 nm radiation at a repetition rate of 4 kHz and a pulse duration of 25 ns. The 532 nm output was focused at the center of the sample with a beam waist of 165 μm. The pump beam had its linear polarization in parallel with the z axis and propagated along the x axis of the PPSLT crystal. When the average pump power was 1 W, the maximum intensity reached 23 MW/cm^2. The crystal was embedded in an oven whose temperature was controlled to

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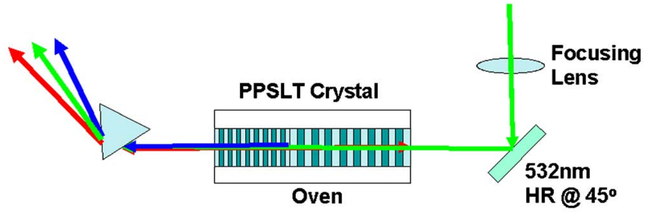

FIG. 1. (Color online) Schematic showing generation of three basic colors in a single crystal. 532 nm light is incident from the right. The three colors are dispersed by a prism exiting to the left. The columns in the PPSLT crystal depict two superlattices with a different domain periodicity.

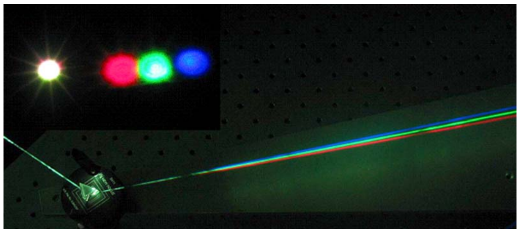

FIG. 3. (Color online) Generated white light from the left is incident onto a prism which disperses the light into three colored beams. On top are pictures of the beams terminated on a piece of paper, from left: white, red, green, and blue.

±0.1 °C to get a steady output (Fig. 1). The output beams generated in the crystal were dispersed through a Pellin-Broca prism. A thermopile was used to measure the power of each beam.

We began by setting the crystal temperature at 165 °C. Oscillation threshold was reached for an incident input power of 350 mW. The red average power increased to 203 mW at a 1 W input, giving a slope efficiency of ~30%. This is low compared to our earlier SLT OPO study[14] and could be due to insufficiencies in the parallelism of the end faces of the oscillator and the quality of the poling. The power of the output RGB light when pumped by 1 W of input green power versus the crystal temperature is shown in Fig. 2. The power of the red output remained nearly constant when the temperature of the crystal was changed but the wavelength of the red light changed by about 0.5–1 nm to satisfy the QPM condition.[14] Intense blue output appeared when the QPM condition for the SFG stage was satisfied at the temperature of 158.3 °C. As expected this second stage summing process had a much more critical temperature dependence than the first stage. The temperature full width at half maximum (FWHM) of 3.8 °C as shown in Fig. 2 is in close agreement with the calculated width of 3 °C. The maximum output at 459 nm was 69.4 mW. This blue output was stable throughout the course of the measurements, indicating that the PPSLT crystal was able to withstand at least this much power in the blue for an extended period of time.[15] While the red power remained quite constant, the green power dipped by ~8.7% when the blue output was maximized. This is consistent with the measured conversion of the internal green power to the blue at the QPM temperature. A dip of <1% in the red power when the blue power reached its peak is attributed to a blue-induced red absorption process. Judging from the temperature half-width of the blue generation, this absorption is deemed to have only a minor effect on the RGB generation in this experiment. Figure 3 is a camera-recorded screen image of the output RGB beams and the three separate colors obtained after dispersing the beams with a prism.

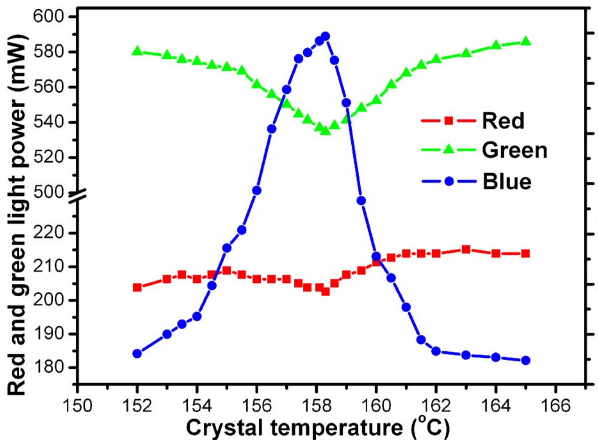

FIG. 2. (Color online) Average power of the red, green, and blue lights as a function of the oven temperature.

Efforts to increase the pump power above 1 W were limited by photorefractive damage evidenced by bright flashes and beam distortion in the output beam. Since PPSLT has been demonstrated to withstand photorefractive damage up to 60 MW/cm^2,[14] we believe the low threshold observed in the present case must have resulted from imperfections in the poled domains of the present crystal. Once this is overcome it should be possible to apply a higher intensity of up to a factor of 2 with an associated improvement in the overall optical conversion.

From the measured red and blue powers we can estimate the amount of white light that was generated. Based on the CIE chromaticity diagram and the generated 69.4 mW blue light (least of the three colors) we calculated a color-balanced power of 304 mW of white light (R=140 mW, G=94.3 mW, and B=69.4 mW) defined for a color temperature of 5800 K and realized by blocking the excess red and green powers. The luminous flux that corresponds to this RGB power is 80 lm. Thus the white light generation efficiency was then 80 lm per 1 W input, and the optical to optical power conversion efficiency was 30%. If we utilize the full power of the red and the blue light, then cool white light (R=203 mW, G=146 mW, and B=69.4 mW) at 408 mW was obtained. The luminous flux that corresponds to this cool white light is 114 lm and the corresponding color temperature is 4850 K.

The temporal profile of the input and output pulses are displayed in Fig. 4. The pulses were sent to the same Si photodetector (EOT model 2000, rise time of 0.5 ns) and were detected individually by inserting the appropriate filter to select a particular color for detection. The profile shown is the average of 16 pulses recorded by a digital oscilloscope (Tektronix 235) and triggered by a common source. The input green pulse had a Gaussian profile with a FWHM of 25 ns. The red pulse appeared after a delay of 12 ns from the start of the input pulse when the OPO reached threshold. The blue pulse followed immediately as it was the sum of the green pulse and the idler from the OPO. The fourth profile is that of the depleted green pulse.

In conclusion, we have demonstrated a monolithic RGB light laser source based on a tandem PPSLT superlattice design. White light and cool white light were obtained at 304 and 408 mW, respectively, with 1 W pump light input. The

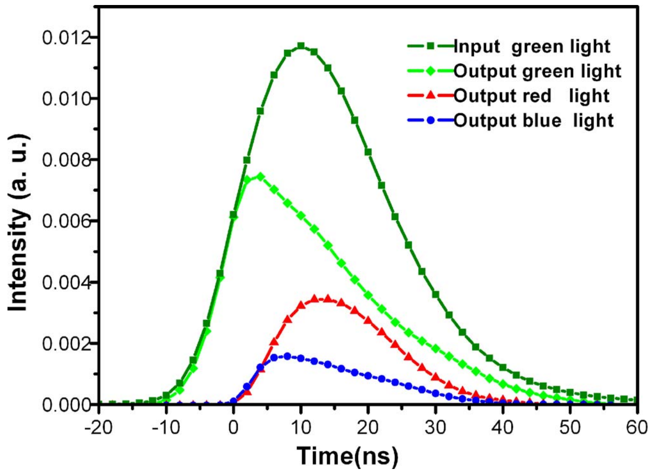

FIG. 4. (Color online) Temporal profile of the input green pulse and the output RGB pulses. Each trace is the average of 16 pulses.

luminous fluxes of the white light and the cool white light were 80 and 114 lm, respectively. The 30% optical conversion efficiency could be increased to nearly 100% with improvements on crystal fabrication and optimization on the crystal design. Since the powers are readily scalable, more than 1000 lm of white light can be obtained by using a 2 mm thick crystal and 12 W, 532 nm input focused to a 550 μm waist size in this monolithic design even if we are restricted to the present input intensity of 23 MW/cm^2. This would be sufficient to illuminate a 2 m full-size display called for in Ref. 1. The monolithic design could also be suitable for cw or quasi-cw operation with modifications to the optical cavity arrangement to result in a low cost, robust, high power, and compact RGB laser source for various applications. Finally, owing to a small amount of absorption by PPSLT and PPMgSLT, proper thermal management becomes necessary to avoid thermal degradation of the beam when scaling to higher average power and thicker samples.[9,15]

This work was supported by the State Key Program for Basic Research under Grant No. 2004CB619003, the National Natural Science Foundation under Grant Nos. 10534020 and 60578034, the Academia Sinica, and the National Science and Technology Program for Nanoscience and Nanotechnology under grant No. NSC-93-2120-M-001-012.

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