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Simultaneous generation of three primary colours using aperiodically poled $LiTaO_3$

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Abstract

Simultaneous generation of efficient red, green and blue (RGB) light was achieved by doubling and tripling a diode-pumped, *Q*-switched 1342 and 1063 nm Nd:$GdVO_4$ laser using an aperiodically poled $LiTaO_3$ crystal. Quasi-white colour was obtained by mixing the RGB outputs at 115.8 °C. The average powers of the RGB light were 31.3, 18.4 and 3.7 mW, respectively.

With the development of modern optics technology, laser sources with wider ranges of wavelengths are needed more frequently. Optical frequency conversion with nonlinear optical materials is a key means by which such sources can be achieved. Thus this field has attracted much attention in the past few decades. For example, red, green and blue, the three primary colours, are essential for laser-based colour displays that take advantage of the high brightness, spectral purity and extremely large depth of focus of laser sources. There remains the problem of how to generate laser radiation with these colours in a single compact laser system in order to reduce cost, to reduce size and to obtain potential integration. Diode-pumped infrared solid-state lasers based on Nd^{3+} ions provide excellent possibilities for developing such devices, when combined with nonlinear frequency conversion to the visible.

In the past, many attempts at simultaneous generation of RGB light have been made [1–6]. Some progress was made in waveguides; for example, observations of quasi-phase-matching (QPM) of RGB lights using a proton exchanged $LiNbO_3$ waveguide [1] and using a dye-doped polymer waveguide [2] were reported. For bulk samples, results were obtained along two main routes. One is based on sum-frequency mixing or frequency doubling following an optical parametric process, in series. The other is based directly on self-frequency conversion in laser gain crystals with multiple pump wavelengths or oscillating wavelengths. However, the output power attained was comparatively low. Thus the simultaneous generation of the three primary colours is still a challenge.

Recently we have demonstrated the simultaneous generation of multiple-wavelength outputs by using optical superlattices (OSLs) with periodic [7], quasi-periodic [8] or aperiodic structures [6]. For periodic structure, the selections of period and matching temperature are rather restricted. For quasi-periodic structure, the locations of the reciprocals are not independent and are all related to an irrational number intrinsic to the structure (for Fibonacci structure, this number is the golden mean [9]). Therefore, quasi-periodic structures rely on coincidences. Thus it is difficult, if not impossible, to realize multiply QPM coupled parametric processes at an arbitrary wavelength in the transparent range of the material.

Aperiodic OSL structures can be designed by use of simulated annealing [10–12] to maximize the conversion efficiency for multiple-peak frequency doubling, tripling and parametric amplification. However, this approach does not take pump depletion into account and cannot be expected to yield accurate results when conversion efficiency is high. We proposed another method for designing aperiodic OSL structures and experimentally demonstrated simultaneous RGB light generation [6]. But its mathematical expression is somewhat complicated and not easy to follow.

In this paper, we report a different scheme for designing an aperiodic structure for RGB light generation. The output of RGB lights obtained is higher than ever. Here a Nd:$GdVO_4$ laser is used as a pump source, which operates at both 1342 and 1063 nm wavelengths. The RGB light output is realized by simultaneous frequency doubling and tripling of the fundamentals.

The Nd:$GdVO_4$ laser has been reported as an excellent laser crystal in the past [13, 14]. $GdVO_4$ belongs to the same group of oxide compounds as YVO_4, crystallizing in a zircon structure with a tetragonal space group. Compared with Nd:YVO_4, Nd:$GdVO_4$ crystals have almost entirely similar lasing properties, but a much higher absorption coefficient and larger absorption cross-section. Besides this, Nd:$GdVO_4$ crystal is characterized by its unexpectedly high thermal conductivity along the $\langle 110 \rangle$ directions, which was measured to be comparable to that of Nd:YAG [13].

There are three main emission peaks in its fluorescence spectrum: centred at 912.6 nm ($^4F_{3/2} \longrightarrow {}^4I_{9/2}$), 1063.1 nm ($^4F_{3/2} \longrightarrow {}^4I_{11/2}$) and 1341.9 nm ($^4F_{3/2} \longrightarrow {}^4I_{13/2}$). The one near 1063.1 nm is the strongest. Because the laser output of Nd^{3+} for $^4F_{3/2} \longrightarrow {}^4I_{9/2}$ is a quasi-three-level system, the maximum Stark splitting ΔE of $^4I_{9/2}$ limits the laser emission of the host materials. However, the laser emissions for the $^4F_{3/2} \longrightarrow {}^4I_{11/2}$ and the $^4F_{3/2} \longrightarrow {}^4I_{13/2}$ manifolds are four-level systems; one may get laser output for wavelengths of 1063 and 1340 nm more easily [14].

For QPM frequency conversion, the reciprocals play an important role. Usually the reciprocals can be obtained by Fourier transformation of a given microstructure. Alternatively, we can reverse the process, i.e., construct a microstructure from the given reciprocal vectors. Here in this work, RGB light generation involves one SFG and two SHG process. That is, three reciprocals are needed:

$$k_{s1} - 2k_{f1} - G_R = 0 \tag{1}$$

$$k_{s2} - 2k_{f2} - G_G = 0 \tag{2}$$

$$k_{t1} - k_{s1} - k_{f1} - G_B = 0 \tag{3}$$

where k is a wavevector and G is a reciprocal vector, the subscripts f, s and t indicate the fundamental, second harmonic and third harmonic, respectively. The subscripts 1 and 2 differentiate the processes based on the pump waves of 1342 and 1063 nm.

Based on the three reciprocals required (G_i, i = R, G, B), a straightforward way to design is to use the following function, which was suggested in [15]:

$$f(x) = \sin(G_R x) + a \sin(G_G x) + b \sin(G_B x) \tag{4}$$

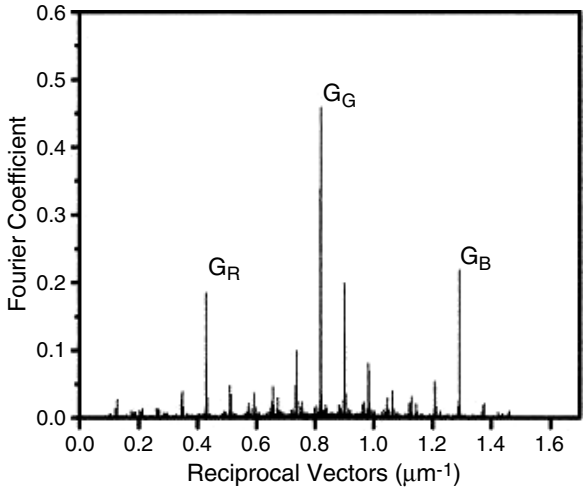

Figure 1. The Fourier spectrum of the designed aperiodic OSL.

and

$$g(x) = \mathrm{sgn}[f(x)] \tag{5}$$

where sgn represents the signum function, corresponding to positive or negative domains. This is just the reverse Fourier transformation. The positions of the domain walls of the superlattice are determined by the roots of $f(x)$. This function provides three reciprocals automatically. The coefficients a and b can be tuned to optimize the structure of the superlattice. When the ratio between any two of the three Gs is a rational number, then the structure becomes a periodic one.

In the designing, considering the limitation of the poling technique, the narrowest domains are controlled to be no less than 3 μm. In other words, the domains whose lengths are less than 3 μm will flip their sign and merge into the adjacent domains, until all the domains are not shorter than 3 μm. In this way and setting the matching temperature to be at 110 °C, we get the OSL structure. The Fourier spectrum of the designed structure is somewhat different from equation (4). Figure 1 shows the result. Apart from the three required components, there are many others. Since they do not satisfy QPM conditions, they do not participate in the nonlinear optical interactions. The Fourier coefficients of the three required reciprocals are 0.1851, 0.4587 and 0.2187, respectively, which are shown in figure 1. These values are fairly large and can be adjusted independently. These are the obvious two advantages of this design scheme.

The superlattice made of a $LiTaO_3$ crystal wafer was fabricated by a standard electric field poling technique at room temperature, with the pattern designed according to the above method. The sample was observed after poling and etching and the size of the shortest domains was 2.8 μm. The domain walls show some irregularity, which would influence the conversion efficiency [16]. The thickness of the wafer was about 0.5 mm and the length was 1.2 cm. The two end-faces of the wafer were polished for optical measurement, but not coated. Figure 2 shows the optical micrograph on the $+c$ side of an etched sample.

The schematic diagram of our experimental measurement is shown as figure 3. The fundamentals of 1342 and 1063 nm were generated from a Q-switched Nd:$GdVO_4$ laser pumped by a fibre-coupled continuous diode laser (FAP-System, Coherent Inc.) at 808 nm. The pumping output power was 15 W and the optical fibre diameter was 100 μm. The

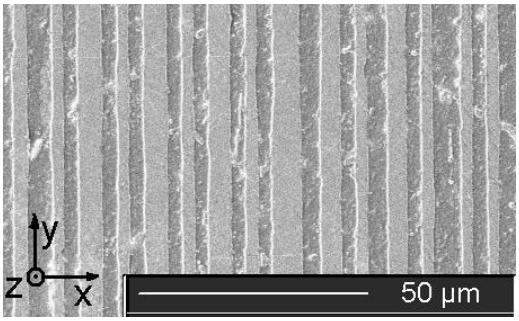

Figure 2. The micrograph of a sample revealed by etching (the side of +*c*). The direction of the beam inside the sample was parallel to the *x* axis and the polarization of the beam was parallel to the *z* axis.

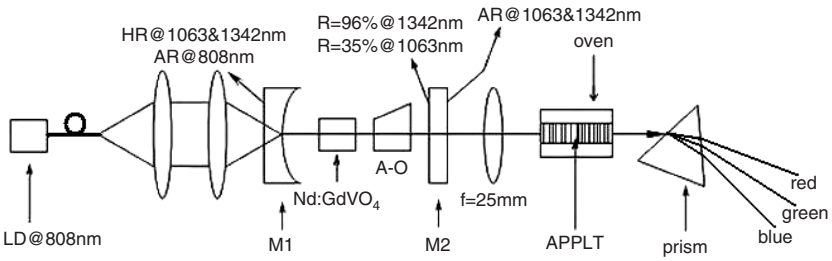

Figure 3. A schematic diagram of the experimental set-up for the simultaneous generation of RGB lights.

4 mm × 4 mm × 7.6 mm laser host was a Nd:$GdVO_4$ crystal, whose dopant concentration, of Nd^{3+}, is 0.5%. M1 and M2 made up a two-mirror resonator with the length of 12.5 cm. The input mirror M1 had antireflective (AR) coating at 808 nm on its entrance face and the high reflectivity (HR) coating at both 1342 and 1063 nm and high transmission (HT) coating at 808 nm on the other face. The beam sizes inside the laser host were estimated to be ∼377 μm at 1342 nm and ∼322 μm at 1063 nm. The output coupler M2 was a flat mirror with partial reflection (PR) coating at both 1342 nm ($R \sim 96\%$) and 1063 nm ($R \sim 35\%$) on one face and AR coating at both 1342 and 1063 nm on its other face. An acousto-optic Q-switch with a repetition rate of 10 kHz is mounted inside the resonator cavity. For 1063 nm output, the pulse width was 23 ns and the average power was 580 mW. The corresponding parameters for 1342 nm were 48 ns and 1.21 W. The beam was focused by a lens ($f = 25$ mm) and coupled into the polished entrance face of the sample. The radius of the beam waist inside the superlattice was about 45 μm. The beam quality factors (M^2) were about 3.2 and 2.5 at 1063 and 1342 nm, respectively. The sample, namely the aperiodically poled $LiTaO_3$ (APPLT), was heated in an oven (model OTC-PPLN-20, Super Optronics Ltd) in order to adjust the phase-matching temperature with accuracy of 0.1 °C. At the appropriate temperature, the RGB lights can be detected simultaneously.

Figure 4 shows the experimental results for RGB light output powers as a function of temperature. The measured phase-matching temperatures for red, green and blue lights were 122.5, 106.5 and 113.4 °C, with the bandwidths (full width at half-maximum) of 3.5, 11.2, 1.5 °C respectively. The maximum average powers were 251.5, 193.3 and 13.1 mW, with conversion efficiencies of 20.8%, 33.3% and 1.1%. (Here the conversion efficiency is defined

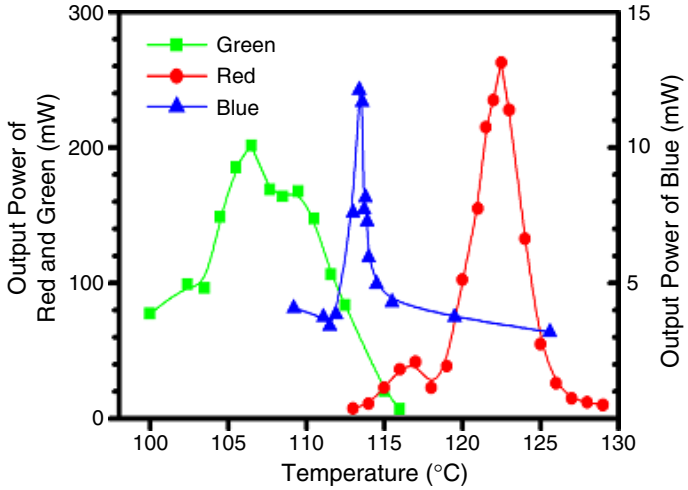

Figure 4. The measured temperature tuning curves of the RGB light outputs. (This figure is in colour only in the electronic version)

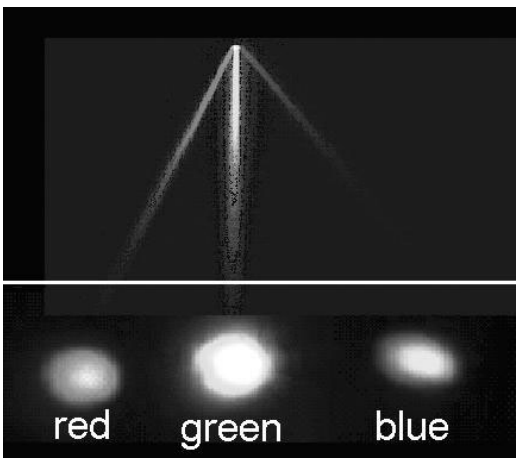

Figure 5. A photograph of RGB beam paths and beam spots.

to be the ratio of the output power of one colour to the input power at 1342 or 1063 nm.) In the temperature tuning curves, the peaks of the three lights deviated from the expected point due to some unsolved problems [6]. The power levels and the conversion efficiencies were fairly high.

The motive for simultaneous generation of RGB lights is to obtain white. In order to get equal-energy white with these three wavelengths, the RGB light power distribution must be around 14:1.5:1. We attempted to mix the three lights by changing the temperature. At 115.8 °C, we got average powers of RGB lights of 31.3, 18.4 and 3.7 mW, which was the state nearest to equal-energy white that we got on this occasion. Figure 5 shows the simultaneous output of RGB lights separated by a prism. The position of the mixture in the X–Y coordinate system [17] was (0.278, 0.350) where the mixture can be called 'quasi-white'. Comparing to the theoretical values for equal-energy white, we can see that red was still somewhat wanting and green was a little beyond requirements. Thus much remains to be done.

In summary, we demonstrated simultaneous, efficient RGB light generation, by multi-frequency conversion from a diode-pumped Nd:$GdVO_4$ dual-wavelength laser with a single-pass aperiodically poled $LiTaO_3$. Experimentally we got quasi-white colour when the RGB lights were mixed at 115.8 °C. The average powers of the RGB lights are 31.3, 18.4 and 3.7 mW, respectively.

Acknowledgments

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