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A scheme to realize three-fundamental-colors laser based on quasi-phase matching

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Abstract

A simultaneous generation of red light at 631 nm and blue light at 460 nm was realized, in single-pass quasi-phase-matched scheme, from two periodical optical superlattices in the same $LiTaO_3$ crystal in series. Using a 532 nm laser as pump, the red light was generated at 631 nm as the signal of optical parametric process in the first superlattice, and the blue light at 460 nm was the sum-frequency mixing the idler and the pump in the second superlattice. Along with the remnant pump at 532 nm, red light, green light and blue light can be obtained from the superlattice system simultaneously. This may be an emulous scheme to realize a compact three-fundamental-colors laser in future. © 2001 Elsevier Science Ltd. All rights reserved.

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The use of periodically poled ferroelectric crystals like $LiNbO_3$ (PPLN), $LiTaO_3$ (PPLT) and KTP in laser devices is growing quickly. The high nonlinearity, long interaction length, and the ability to engineer their domain structures with photolithographic mask patterns make them attractive materials for many applications. Varieties of superlattice fabricated in $LiNbO_3$ [1,2,3,4,5], $LiTaO_3$ [6,7,8,10,11] and KTP crystals have been used to realize quasi-phase-matched (QPM) second harmonic generation (SHG), direct third harmonic generation and high-efficiency optical parametric oscillator (OPO). Rapid progresses have been made in realizing red [9], green [10], and blue [12] lasers. In some cases, it is of practical importance to generate the multi-wavelength output of laser, in particular, to generate red, green and blue radiation at the same time. Since any color to human eye can be generated through a weighted combination of only three fundamental colors, red, green, and blue, it is advantageous to generate laser radiation in these three colors in a single compact laser system. The compact red, green and blue (RGB) three-color laser will lead to many advanced applications in future opto-electronic technology such as full-color laser display and high-resolution laser printing.

Recently, Jaque et al., realized a significant breakthrough along this direction. An RGB laser was experimentally demonstrated by them [13]. Red (669 nm), green (505 nm), and blue (481 nm) were generated from the same $Nd{:}YAl_3(BO_3)_4$ crystal. The crystal was end-pumped by using two laser diodes whose output wavelengths were 807 and 755 nm, respectively. The laser radiation of Nd^{3+} at 1338 nm was a fundamental wave in this configuration. The red at 669 nm was obtained by self-frequency doubling of the fundamental wave, and the green at 505 nm and the blue at 481 nm were obtained through sum-frequency mixing of the fundamental at 1338 nm and two pump radiations, at 807 and 755 nm, respectively. However, this scheme needs two diodes as pump sources, which increases the complexity of the system.

In this paper, we report an alternate scheme to realize three-fundamental colors based on QPM theory at room temperature. The scheme here includes two processes achieved in two separate periodic superlattices in series.

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QPM parametric lights were generated in the first superlattice when it was pumped at 532 nm. The wavelengths of signal and idler were 631 and 3392 nm, respectively. The blue at 460 nm was obtained in the second superlattice through a QPM sum-frequency process of mixing the pump at 532 nm and the idler at 3392 nm generated in the first superlattice. Thus, we obtained three-fundamental colors, the red at 631 nm, the blue at 460 nm and the green at 532 nm, from the output end of the second superlattice by combination of these two QPM processes.

In order to avoid a complicated configuration, we designed and fabricated these two periodic superlattices in the same $LiTaO_3$ crystal wafer in series. The first is for optical parametric process and the second is for sum-frequency generation. For a collinear optical parametric interaction, the first order QPM condition in the first superlattice is

$$\mathbf{k}_p - \mathbf{k}_s - \mathbf{k}_i - \frac{2\pi}{\Lambda_1} = 0 \qquad (1)$$

where Λ_1 is the period of the superlattice, $\mathbf{k}_p$, $\mathbf{k}_s$ and $\mathbf{k}_i$ are the wave vectors of pump, signal and idler, respectively. In addition, in a three-wave nonlinear interaction, the frequencies are related by

$$\omega_p = \omega_s + \omega_i \qquad (2)$$

where ω_p, ω_s and ω_i are the frequencies of pump, signal and idler, respectively. According to Eqs. (1) and (2), we trace the tuning curve of signal and idler that corresponds to the pump wavelength at 532 nm and the operating temperature at 25°C, versus the period Λ_1 of the first superlattice, as shown in Fig. 1. The theoretical curve is calculated from dispersion [15]. Choosing the period of the first superlattice at the arrow point in Fig. 1, a red at 631 nm as a signal and an infrared at 3392 nm as an idler can be obtained. The corresponding period Λ_1 is 11.9 μm.

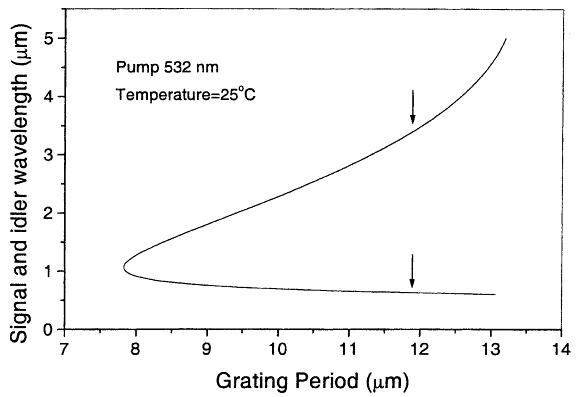

Fig. 1. First-order QPM period for collinear optical parametric process with 532 nm pump. All the waves are polarized parallel to the z axis of crystal. We chose the period of superlattice (11.9 μm) at the arrow points.

The second superlattice should be used to realize a QPM sum-frequency process in which two added parametric waves were the idler at 3392 nm and the pump at 532 nm, respectively. According to energy conservation, the generated wave is a blue at 460 nm. The QPM condition corresponding to the sum-frequency process is

$$\mathbf{k}_a - \mathbf{k}_i - \mathbf{k}_p - \frac{2\pi m}{\Lambda_2} = 0 \qquad (3)$$

where $\mathbf{k}_i$, $\mathbf{k}_p$ and $\mathbf{k}_a$ are the wave vectors of idle, pump and sum-frequency whose wavelengths are 3392, 532 and 460 nm, respectively, and m the order of QPM. The period of the second superlattice, Λ_2, can be established from Eq. (3). Along with the red at 631 nm generating in the first superlattice and the remnant pump at 532 nm, the three fundamental colors, red, green and blue, can be transmitted from the output-end of superlattice system simultaneously.

Due to some uncertainties in the Sellmeier equation and the operation temperature, the second superlattice was designed into a multigrating structure: four parallel gratings, each 1 mm wide, with periods ranging from 8.74 to 8.80 μm in the step of 0.02 μm. These periods correspond to a first-order QPM sum-frequency process. The perfect phase matching of sum frequency was accomplished by translating the gratings through the pump beam.

The sample was fabricated by poling at room temperature [14]. Two superlattices were in the same $LiTaO_3$ crystal wafer and arrayed in series. They were respectively poled in order to make their duty cycle uniform on account of their different domain periods. The thickness of sample was 0.5 mm and the lengths of the first and the second superlattices were 2 and 1 cm, respectively. After poling, two end faces of the crystal wafer were polished for optical measurement, but not coated.

The schematic setup for the measurement of three-fundamental colors is shown in Fig. 2. The 532 nm pump radiation came from the second harmonic output of a ps-Nd:YAG laser (PY61-10, Continuum, Santa Clara, CA) with a pulse width of 43 ps and a repetition rate of 10 Hz. The pump beam was z-polarized and propagated along the x-axis of the sample as shown in Fig. 2. The beam was weakly focused and coupled into the polished end face of the sample. The foci of the focus lens is 400 mm, and the radius of the beam waist inside the sample was around 0.1 mm. A prism was used to separate the lights with different wavelengths at the end of sample.

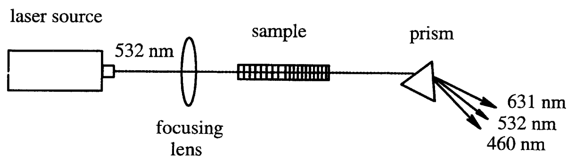

Fig. 2. Experimental setup for measuring three-fundamental-colors generation in the superlattice sample.

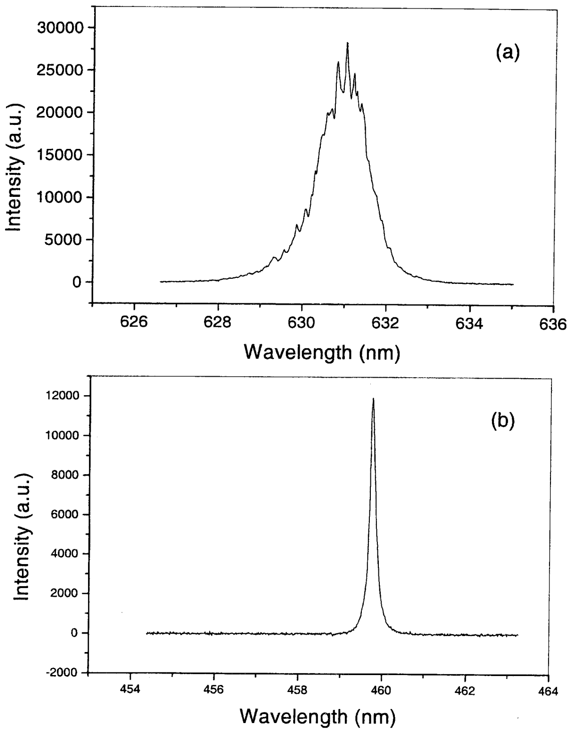

Fig. 3. Red and blue light spectra measured in the superlattice sample pumped by a 532 nm laser. The peaks for red and blue were at (a) 631 nm and (b) 460 nm, respectively.

RGB were detected from the output end of the sample simultaneously. Fig. 3 shows the red and blue spectra at the pump wavelength of 532 nm. The spectra were recorded by a CCD spectrograph (SpectraPro ®-750, Acton, MA). The peak of red light was located at 631.0 nm with the full width at half maximum (FWHM) of 1.2 nm (Fig. 3(a)). The wide linewidth verified that the red was a parametric fluorescence. The peak of blue shown in Fig. 3(b) was located at 459.8 nm with the FWHM of 0.2 nm. The narrow linewidth at blue implied that only a small portion of idler participated in the QPM sum-frequency process due to wide linewidth of the idler and narrow acceptable bandwidth of the second superlattice. Though the peak power of the pump light is very high, the photorefractive effect is little because of the low repetition rate.

In the limit of low gain and phase matching, the single pass parametric gain is given by Ref. [16]

$$G(L) = \{E_s(L)/E_s(0)\}^2 - 1 \sim \frac{2\omega_s \omega_p d_Q I_p L^2}{n_p n_i n_s \varepsilon_0 c^3} \qquad (4)$$

where I_p is the pump intensity and L is the interaction length in the first superlattice and n_p, n_i, and n_s are the refraction indices of the pump, idler and signal. $\varepsilon_0$and c are the dielectric constant and the speed of light in vacuum, respectively. ω_s, ω_p are the frequency of the signal and pump, $d_Q = 2d_{33}/\pi$ is the first-order effective nonlinear coefficient for a QPM superlattice material. Harris noted that the parametric gain and the conversion efficiency of SHG are equal in the low gain limit [17]. The gain available for parametric interaction in a superlattice crystal like $LiNbO_3$ or $LiTaO_3$ using the maximum d_{33} coefficient opens the possibility of simultaneously generating RGB three-fundamental-colors laser with low threshold operation. Under our experimental condition, the red parametric fluorescence was generated when the average pump power is over 0.08 mW.

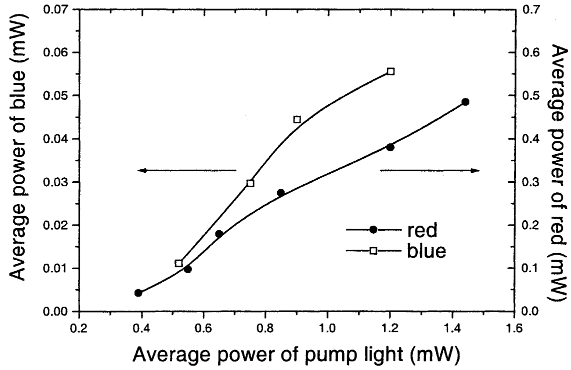

Fig. 4. The average power of red and blue lights versus the average power of pump.

Fig. 4 shows the measured power of red and blue versus the pump power at 532 nm. In our case, we measured the total power from the end face of the superlattice as the pump power. We can see that red and blue both increase gradually with increasing pump powers. The curve of red is in accordance with Eq. (4) at the lower pump power (average pump power < 0.8 mW). When the pump power gets higher (average pump power > 0.8 mW), the curve begins to deviate from Eq. (4), showing that the small signal approximation can not be satisfied. The fluorescence efficiency is defined as $\eta = P_s/P_p$, where P_s is the signal power and P_p is the pump power, respectively. When the pump power is up to 1.2 mW, the red and blue light can reach 0.38 mW and 55.6 μW, with conversion efficiency 31.7 and 4.6%, respectively.

Even now, the conversion efficiencies of single-pass red and blue generation are still limited by the interaction length and the diffraction spreading of the focussed laser beam. However, it is expected that the efficiencies can be drastically increased by either confining the field to a waveguide or using antireflection coating on the crystal end faces and laying the crystal inside a cavity. In a cavity, the parametric oscillation can be built up by repeated reflections and refocusing, which will improve the quality of beam, depress the linewidth of spectra and raise the gain efficiencies greatly. Therefore, the blue light power can achieve a considerable level similar to red light power. Moreover, the ratio of the intensities of red, green and blue can be adjusted by selecting suitable configuration and parameters of the cavity.

In summary, this work reports a scheme to realize three-fundamental colors based on QPM theory at room temperature. Two superlattices with different periods were designed and fabricated in the same $LiTaO_3$ crystal wafer in series. QPM red light (signal) at 631 nm and IR light (idler) at 3392 nm were generated from the first superlattice pumped by a 532 nm laser. Blue at 460 nm was generated in the second superlattice through a QPM sum-frequency process of mixing the pump 532 nm light and the idler 3392 nm light, thus, three-fundamental colors were simultaneously obtained in the scheme. On the other hand, fixing the pump laser, red and blue light in different wavelengths can be obtained by changing the structural parameter of the two superlattices. The potential high efficiency and the multiplex output wavelength make this scheme emulous to realize a compact RGB laser.

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References

[1] L.E. Myers, G.D. Miller, R.C. Eckardt, M.M. Fejer, R.L. Byer, W.R. Bosenberg, Opt. Lett. 20 (1995) 52.
[2] V. Pruneri, J. Webjorn, P.St.J. Russell, D.C. Hanna, Appl. Phys. Lett. 67 (1995) 2126.
[3] L.E. Myers, R.C. Eckardt, M.M. Fejer, R.L. Byer, W.R. Bosenberg, Opt. Lett. 21 (1996) 591.
[4] P.E. Powers, T.J. Kulp, S.E. Bisson, Opt. Lett. 23 (1998) 159.
[5] P. Schlup, L.T. McKinnie, S.D. Butterworth, Appl. Opt. 38 (1999) 7398.
[6] P. Baldi, S. Nouh, K. El Hadi, M. de Micheli, D.B. Ostrowsky, D. Delacourt, M. Papuchon, Opt. Lett. 20 (1995) 1471.
[7] M.E. Klein, D.-H. Lee, J.-P. Meyn, B. Beier, K.-J. Boller, R. Wallenstein, Opt. Lett. 23 (1998) 831.
[8] U. Strossner, A. Peters, J. Mlynek, S. Schiller, J.-P. Meyn, R. Wallenstein, Opt.Lett. 24 (1999) 1602.
[9] Y. Inove, S. Konno, T. Kojima, S. Fujikawa, IEEE J. Quant. Electron. 35 (1999) 1737.
[10] S.N. Zhu, Y.Y. Zhu, N.B. Ming, Science 278 (1997) 843.
[11] S.N. Zhu, Y.Y. Zhu, Y.Q. Qin, H.G. Wang, C.Z. Ge, N.B. Ming, Phys. Rev. Lett. 78 (1997) 2752.
[12] C.Q. Wang, Y.T. Chow, W.A. Gambling, et al., Appl. Phys. Lett. 75 (1999) 1821.
[13] D. Jaque, J. Capmany, J.G. Sole, Appl. Phys. Lett. 75 (1999) 325.
[14] S.N. Zhu, Y.Y. Zhu, Z.Y. Zhang, H. Shu, H.F. Wang, J.F. Hong, C.Z. Ge, N.B. Ming, J. Appl. Phys. 77 (1995) 5481.
[15] J.P. Meyn, M.M. Fejer, Opt. Lett. 22 (1997) 1214.
[16] L.E. Myers, R.C. Eckardt, M.M. Fejer, R.L. Byer, W.R. Bosenberg, J.W. Pierce, J. Opt. Soc. Am. 12 (1995) 2102.
[17] S.E. Harris, Proc. IEEE 57 (1969) 2096.