

RGB source based on simultaneous quasi-phase-matched second and third harmonic generation in periodically poled lithium niobate

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Abstract: We present a pulsed RGB source based on cascaded nonlinear processes that occur inside a single crystal of PPLN with two poling periodicities placed in tandem. The first periodicity produces a $\sim 1.43 \mu\text{m}$ signal through optical parametric generation and the last section simultaneously produces the second (near - IR) and third harmonic (blue). The green is produced by second harmonic generation of the pump and the red is produced by non-phase-matched sum-frequency generation between the signal and pump beam.

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References and links

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Quasi-phase-matching using periodically poled ferroelectric crystals can be used to convert an incident pump beam to beams of practically any wavelength within the transparency region of the crystal. In addition, this technique can be used to obtain different nonlinear processes in the same crystal by using several regions with different periodicities placed side by side [1] or in tandem[2,3] to obtain cascaded nonlinear processes. Quasi-phase-matching has been used previously to create sources of the three primary colors (RGB sources). Lee and Moulton [4] and Brunner et al. [5] made high-average power RGB quasi-CW sources that used several nonlinear crystals to obtain different nonlinear processes in order to get the three primary colors. Jaque et al. [6] reported an RGB source based on simultaneous nonlinear processes occurring in Nd:YAl₃(BO₃)₄; Capmany [7] made an RGB source based on a single Nd⁺³-doped aperiodically poled lithium niobate pumped with a 744 nm cw-Ti:sapphire laser. The Nd ion emitted laser radiation at 1084 and 1372 nm, and the aperiodic domain structure generated their second harmonics (green and red); the blue light resulted from the sum of the 744 nm pump and the 1084 laser line. Liu et al. [8] used a stoichiometric lithium tantalate crystal with two periodicities pumped with a green 532 nm source to produce red and blue light. The first section produced a red 631 nm signal through optical parametric generation (OPG), and the second section produced blue (460 nm) by sum-frequency mixing between the pump and the idler produced in the first section. Liao et al. [9] made an RGB source using a single aperiodically poled LiTaO₃ crystal to obtain the second and third harmonic (red and blue) of a 1.342 μ m pump while the green was obtained by frequency doubling of a 1.064 μ m pump; both pumps were derived from a Q-switched Nd:YVO₄ laser. Gao et al. [10] also created a single-crystal RGB source based on cascaded nonlinear interactions in stoichiometric lithium tantalate crystal with two periodicities. In this case the pump was the second harmonic (532 nm) of a Nd:YVO₄ laser.

Here we present a pulsed RGB source made by pumping a single crystal of PPLN with two periodicities with the common 1.064 μ m line of an Nd:YAG laser. The first section produces OPG at \sim 1.43 μ m, and the last section produces the second harmonic (\sim 715 nm) and third harmonic (\sim 477 nm) of this signal. The green is produced by non-phase-matched frequency doubling of the pump and the red is produced by non-phase-matched sum-frequency generation between the pump and signal.

Assume that three collinear plane waves - a fundamental pump wave of frequency ω , its second and third harmonics, with propagation constants k_1 , k_2 and k_3 , respectively - interact in a periodically poled crystal. Quasi-phase-matching of the second harmonic waves requires a modulation of the nonlinearity of the medium with a periodicity Λ_{shg} that satisfies

$$k_2 - 2k_1 = \pm \frac{2\pi}{\Lambda_{shg}}, \quad (1)$$

while third harmonic generation due to the sum of the fundamental wave and its second harmonic requires a periodicity Λ_{thg} such that

$$k_3 - k_2 - k_1 = \pm \frac{2\pi}{\Lambda_{thg}}. \quad (2)$$

In periodically poled crystals, both processes can occur at the same time provided that $\Lambda_{shg} = m\Lambda_{thg}$, where m is an integer that indicates the order of quasi-phase-matching [11]. Taking $m = 3$, we find from Eqs. (1) and (2) that second and third harmonic generation will occur simultaneously provided that the poling periodicity Λ satisfies both of the following two equations:

$$\Lambda = \frac{\lambda}{2(n_{2\omega} - n_\omega)}, \quad (3)$$

$$\Lambda = \frac{3\lambda}{3n_{3\omega} - 2n_{2\omega} - n_\omega}. \quad (4)$$

where λ is the wavelength of the fundamental beam and n_ω , $n_{2\omega}$, $n_{3\omega}$ are the refractive indices of the 3 waves. For a given material at a given temperature, Eqs. (3) and (4) can only be satisfied for one pump wavelength and one periodicity. Using the Sellmeier equation given in [12], we can calculate the pairs of wavelengths and periodicities at which this occurs in LiNbO₃. The results are shown in Fig. 1.

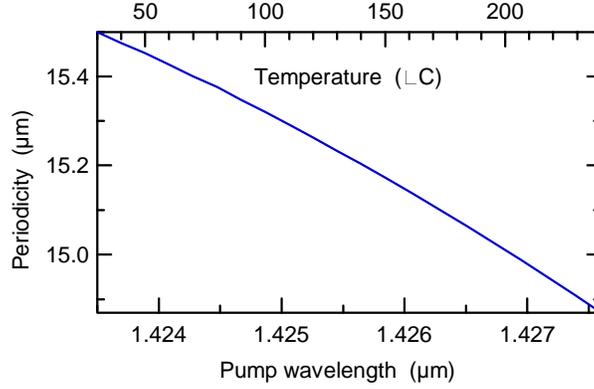


Fig 1. Temperature dependence of the pairs of Λ and λ at which both second and third harmonic generation occur through quasi-phase-matching.

The conversion efficiency of the fundamental to the third harmonic depends critically on the deviation of both the pump wavelength and the poling periodicity from the quasi-phase-matched values. Let $\Delta k_{shg}^{qpm} = k_{2\omega} - 2k_\omega \pm 2\pi/\Lambda$ and $\Delta k_{thg}^{qpm} = k_{3\omega} - k_{2\omega} - k_\omega \pm 6\pi/\Lambda$ be these deviations. Assuming that the three beams are extraordinarily polarized, that the duty cycle of the poling is 50%, and that $I_\omega \gg I_{2\omega} \gg I_{3\omega}$, where I_ω , $I_{2\omega}$ and $I_{3\omega}$ are the intensities of the different beams, a coupled-wave analysis shows that the output intensity $I_{3\omega}$ is given by

$$I_{3\omega} = GI_\omega^3 L^4 (d_{shg}^{qpm} d_{thg}^{qpm})^2 \Phi. \quad (5)$$

Here G is a constant given by $G = 144\pi^4 Z_0^2 / \lambda^4 (n_{3\omega} n_{2\omega}^2 n_\omega^3)$, $Z_0 \approx 377\Omega$ is the impedance of vacuum and L is the interaction length; the effective quasi-phase-matching nonlinearities for second and third harmonic generation are given by $d_{shg}^{qpm} = \frac{2}{\pi} d_{33}$, $d_{thg}^{qpm} = \frac{2}{3\pi} d_{33}$, respectively, and d_{33} is the element of the nonlinear tensor for interactions among extraordinarily polarized waves. The departure from perfect quasi-phase-matching is described by the factor Φ , given by

$$\Phi = \left| \frac{\left[\exp\left[i \frac{\Delta k_{shg}^{qpm} L}{2}\right] \text{sinc}\left[\left(\Delta k_{shg}^{qpm} + \Delta k_{thg}^{qpm}\right)L/2\right] - \text{sinc}\left(\Delta k_{shg}^{qpm} L/2\right) \right]}{\Delta k_{shg}^{qpm} L/2} \right|^2. \quad (6)$$

For perfect quasi-phase-matching of both nonlinear processes, that is when $\Delta k_{2\omega}^{qpm} \rightarrow 0$ and $\Delta k_{3\omega}^{qpm} \rightarrow 0$, the factor $\Phi \rightarrow 1$; in this case Eq. (5) reduces to the simple formula

$$I_{3\omega} = GI_{\omega}^3 L^4 \left(d_{shg}^{qpm} d_{thg}^{qpm} \right)^2. \quad (7)$$

Figure 2 shows the expected output intensity as a function of the input intensity for a 1.5 cm long sample, where perfect quasi-phase-matching has been assumed. The top and right axes show the equivalent input and output powers, assuming beams of uniform intensity and radii equal to 100 μm . As can be seen, with intensities of the order of 500 kW/cm^2 the conversion efficiency can be higher than 20%. These intensities can be attained inside the cavity of a continuous wave laser. We did not plot the power obtained at higher pump intensities since Eq. (7) would no longer be valid due to the two undepleted-pump approximations used in our analysis.

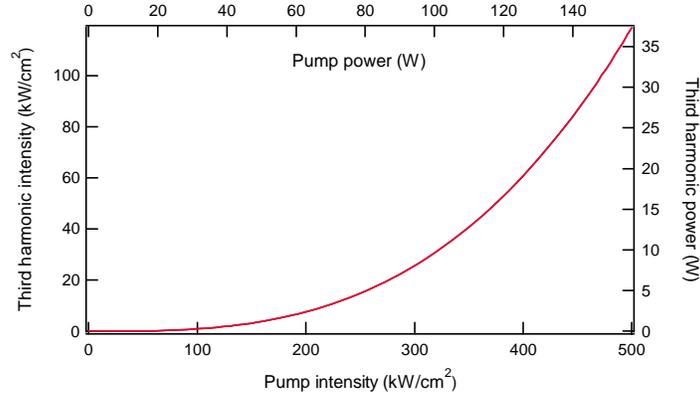


Fig. 2. Third harmonic intensity and power vs. pump intensity and power. $L = 1.5$ cm; beam radius = 100 μm .

Figure 3 shows the dependence of Φ on deviations from perfect quasi-phase-matching. This function depends on Δk_{shg}^{qpm} and Δk_{thg}^{qpm} , which in turn depend on 3 controllable experimental parameters: the pump wavelength, the poling periodicity and the temperature. Figure 3(a) shows how Φ changes when the periodicity is varied around its ideal value, calculated at 100 $^{\circ}\text{C}$, while the pump wavelength is kept constant at its optimum for this temperature. Figures 3(b) and 3(c) show how Φ changes when the pump wavelength and the temperature, respectively, are changed while keeping the other parameters constant.

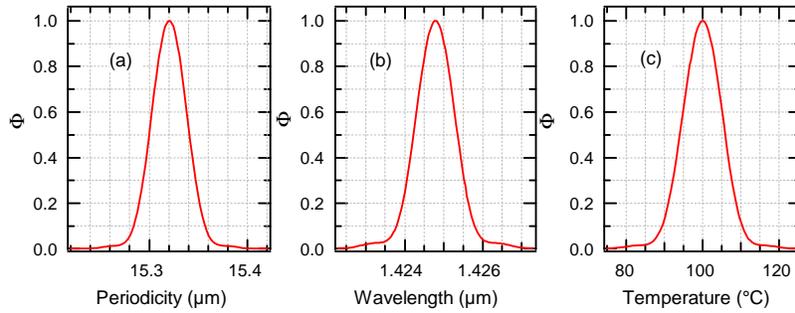


Fig. 3. Theoretical calculation of Φ . (a) Φ vs. Λ at $T = 100$ $^{\circ}\text{C}$ and $\lambda = 1.4248$ μm ; (b) Φ vs. λ at $T = 100$ $^{\circ}\text{C}$ and $\Lambda = 15.32$ μm ; (c) Φ vs. T at $\Lambda = 15.32$ μm and $\lambda = 1.4248$ μm . $L = 1.5$ cm

A source emitting near 1.43 μm is required to observe this effect in LiNbO_3 . Using standard electrical poling techniques, we made a PPLN crystal with two periodicities, one to convert through optical parametric generation a Q-switched, ~ 7 ns $\lambda = 1.064$ μm pulse into a

1.43 μm signal, and another to generate its second and third harmonics. Using the Sellmeier equation given in [12], we calculated that the first section of the PPLN sample required a periodicity close to 27.6 μm . From Fig. 3 we see that in order to obtain a high conversion efficiency it is essential to use the correct periodicity and pump wavelength; for example, a 50 nm deviation of the periodicity from its optimum reduces the conversion efficiency to about 2% of the maximum. Since we cannot expect the Sellmeier equation used in our calculations to have sufficient accuracy to predict the exact wavelengths and periodicities required and since our technique of fabricating the masks used in the electrical poling limited their resolution to 100 nm [13], we made a PPLN sample with several pairs of periodicities that varied slightly around the theoretically predicted values and looked for the best pair. To avoid photorefractive damage, we designed the crystal to work around 100° C. The sample had 6 pairs of domain gratings with the following periodicities: 27.5 : 15.4 μm ; 27.5 : 15.3 μm ; 27.6 : 15.3 μm ; 27.6 : 15.2 μm ; 27.7 : 15.2 μm ; and 27.7 : 15.1 μm . In all the above cases the first grating was 2.0 cm long and the second was 1.5 cm long.

The strongest third harmonic signal we observed was obtained using the 27.6 and 15.2 μm grating pair at temperatures around 160°C. By varying the temperature around this value we could change the signal wavelength generated by the first grating and therefore the wavelength of the third harmonic. We did not measure the signal wavelength directly, since we did not have a calibrated spectrometer sensitive at 1.4 μm ; instead, we inferred the wavelength from the second and third harmonics of this beam, measured with a CCD-based spectrometer (Ocean Optics USB2000). The full-width at half maximum of the second harmonic signal was ~ 2 nm, while the width for the third harmonic was 0.7 nm or lower, close to the resolution of the spectrometer. Figure 4(a) shows the third harmonic wavelength vs temperature; Fig. 4(b) shows the third harmonic energy vs temperature, obtained by pumping the crystal with ~ 1 mJ. The FWHM of the plot shown in Fig. 4(b) is more than 3 times the width shown in Fig. 3(c). We believe this is due to effects not considered in the theory, such as the finite bandwidth of the fundamental wave produced by the first grating (at least 4 nm) and the change of the wavelength of this wave with temperature.

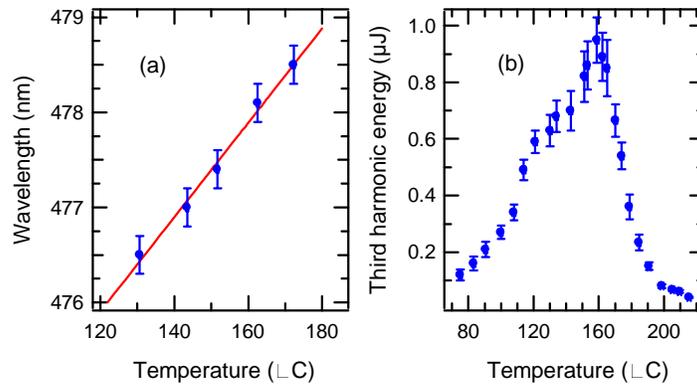


Fig. 4. Third harmonic vs. temperature. (a) wavelength vs. temperature; (b) energy vs. temperature

Aside from the quasi-phase-matched processes, other non-phase matched frequency conversion processes occur within the crystal. Green (532 nm) is generated by frequency doubling of the pump beam, and red (~ 610 nm) is generated by sum-frequency mixing of the pump and the 1.43 μm signal, as shown in Fig. 5. For a perfect periodically poled crystal the intensities of these beams should be negligible. However, slight fluctuations of the domain widths, which are always present in PPLN crystals, increase the intensity of these beams dramatically. Random fluctuations of less than 0.5 μm can increase the output intensity by over 4 orders of magnitude.

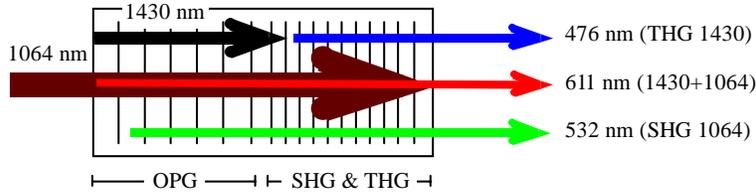


Fig. 5. Nonlinear processes involved in the RGB source.

The output energy of the infrared (second harmonic of the signal), red, green and blue beams vs. input pump (1.064 μm) energy is shown in Fig. 6(a). The data were taken using a single-pass of the pump through the crystal. Pump energies above 2.2 mJ damaged the input surface, which is why data taken with energies above this value are not shown. As can be seen, the energies of the three primary colors are roughly the same. To the eye, the output beam looks white. Figure 6(b) shows an image of the three colors after being separated by a prism.

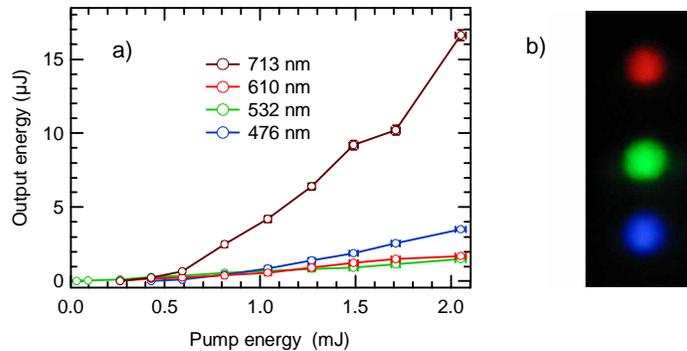


Fig. 6. Output of the RGB source. (a) Infrared, red, green and blue output energy vs. pump energy. Pump wavelength: 1.064 μm ; Pump duration (FWHM) ~ 7 ns; pump radius: ~ 120 μm ; $T = 165^\circ\text{C}$; (b) image of the red, green and blue beams after being separated by a prism.

To conclude, we have demonstrated that an RGB source can be made with a single PPLN crystal pumped with the common 1.064 μm line of an Nd:YAG laser. A theoretical analysis of how the intensity of the blue light depends on the pump power, interaction length and phase-mismatching was presented. Although the reported conversion efficiencies are low, there is room for much improvement. For simplicity our system was based on optical parametric generation; however, in order to obtain a high conversion efficiency into the blue, an antireflection coated PPLN sample could be placed in a cavity highly resonant at the 1.43 μm signal. In addition, according to our theoretical analysis the power increases with the fourth power of the interaction length, so any increase of the length of the second section of the crystal should dramatically increase the power of the blue light. To increase the power in the red and green beams, the masks used to create the domains could be deliberately altered to obtain larger domain width fluctuations, or a third section with the appropriate domain structure to enhance the conversion into these colors may be included.

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