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2003 J. Phys.: Condens. Matter 15 4651

(http://iopscience.iop.org/0953-8984/15/26/315)

J. Phys.: Condens. Matter **15** (2003) 4651–4655 PII: S0953-8984(03)61775-3

Generation of three primary colours with a 1064 nm pump wave in a single optical superlattice

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Received 4 April 2003
Published 20 June 2003
Online at stacks.iop.org/JPhysCM/15/4651

Abstract
We propose a scheme for generating three primary colours with a 1064 nm pump wave. Three quasi-phase-matched parametric processes, i.e., second-harmonic generation, optical parametric generation, and sum-frequency generation, are coupled in a single optical superlattice. On the basis of the plane-wave approximation, the coupling process is investigated theoretically. And a special design for a quasiperiodic structure is presented.

Recently, artificial microstructure material, for example, periodically poled $LiNbO_3$ (PPLN), has attracted much research attention because of its outstanding physical properties [1–3]. In PPLN, the ferroelectric domains are modulated periodically through the crystal growth technique [4–6] or electric field poling method [7]. Meanwhile, three odd-rank tensors, i.e., the electro-optic coefficients, the piezoelectric coefficients, and the nonlinear optical coefficients are modulated correspondingly. Associated with these physical parameters, some interesting phenomena have been recognized. The variation of electro-optic coefficients brings about coupling between the ordinary wave and extraordinary wave [8]. If the piezoelectric coefficients are modulated, ultrasonic excitation [9, 10] and coupling between the electromagnetic wave and superlattice vibrations will be established [11, 12]. And if nonlinear coefficient modulation is considered, the result is a quasi-phase-matched (QPM) frequency conversion [13] and the microstructure is termed an optical superlattice (OSL). In such an OSL, the nonlinear coefficients change sign from positive to negative domains, and the reciprocal vectors of the periodic structure can be used to compensate the phase mismatching of the interacting waves [14]. This method, having many advantages in phase-match engineering, is verified to be more efficient than the conventional birefringence phase matching [15]. In fact, the structure modulation is not restricted to periodic structure; for example, quasiperiodic or aperiodic structures have been investigated both theoretically and experimentally [16–18]. In general, a periodic OSL can provide one reciprocal vector in the QPM process, while a quasiperiodic one can provide more, so coupled multiple-parametric processes may occur

0953-8984/03/264651+05$30.00

efficiently in a single OSL [16, 19]. Thus, it is possible to tailor or design microstructures for some special purposes.

In this paper, we aim at generation of three primary colours (TPC) with 1064 nm as the pump wave. The scheme involves three QPM processes. The first process is second-harmonic generation (SHG) for the pump wave, which gives the green light. In the second process, through optical parametric generation (OPG) of the green, the red and an infrared light are produced. And in the last one, i.e., the sum-frequency generation (SFG), the green couples with the infrared to generate the blue light. Although generation of TPC has been demonstrated before [20–22], our scheme provides a new method. On one hand, three QPM parametric processes are coupled in a single OSL, which can lower the complexity of the device. On the other hand, previous works were focused on the coupling of two parametric processes—for instance, the coupling of SHG and SFG results in third-harmonic generation [16, 23]. However, less attention was paid to the coupling of more parametric processes. As an example of this case, three coupled processes will be treated here. On the basis of the plane-wave approximation, the coupling process is described with five equations. These coupled equations have been solved and discussed. And a special design for a quasiperiodic structure is presented.

Without loss of generality, we take $LiTaO_3$ (LT) as the working material. In order to use the largest nonlinear optical coefficient d_{33}, the pump beam propagation is in the x-direction with its polarization along the optical axis of the crystal LT. In the plane-wave approximation, the equations for three coupled QPM processes ($\omega_1+\omega_1 \rightarrow \omega_2$, $\omega_2 \rightarrow \omega_3+\omega_4$, $\omega_2+\omega_3 \rightarrow \omega_5$) are as follows:

$$
\begin{aligned}
\mathrm{d}A_1/\mathrm{d}x &= -\mathrm{i}\gamma A_1^* A_2 \mathrm{e}^{-\mathrm{i}\,\Delta k_c\, x} \\
\mathrm{d}A_2/\mathrm{d}x &= -\mathrm{i}(\gamma/2) A_1^2 \mathrm{e}^{\mathrm{i}\,\Delta k_c\, x} - \mathrm{i}\alpha A_3 A_4 \mathrm{e}^{\mathrm{i}\,\Delta k_a\, x} - \mathrm{i}\beta A_3^* A_5 \mathrm{e}^{-\mathrm{i}\,\Delta k_b\, x} \\
\mathrm{d}A_3/\mathrm{d}x &= -\mathrm{i}\alpha A_2 A_4^* \mathrm{e}^{-\mathrm{i}\,\Delta k_a\, x} - \mathrm{i}\beta A_2^* A_5 \mathrm{e}^{-\mathrm{i}\,\Delta k_b\, x} \\
\mathrm{d}A_4/\mathrm{d}x &= -\mathrm{i}\alpha A_2 A_3^* \mathrm{e}^{-\mathrm{i}\,\Delta k_a\, x} \\
\mathrm{d}A_5/\mathrm{d}x &= -\mathrm{i}\beta A_2 A_3 \mathrm{e}^{\mathrm{i}\,\Delta k_b\, x}
\end{aligned}
\qquad (1)
$$

with

$$A_i = \sqrt{n_i/\omega_i}\,E_i, \qquad i = 1, 2, 3, 4, 5$$

$$\gamma = \frac{f_c d_{33}}{c}\sqrt{\frac{\omega_1^2\omega_2}{n_1^2 n_2}}, \qquad \alpha = \frac{f_a d_{33}}{c}\sqrt{\frac{\omega_2\omega_3\omega_4}{n_2 n_3 n_4}}, \qquad \beta = \frac{f_b d_{33}}{c}\sqrt{\frac{\omega_2\omega_3\omega_5}{n_2 n_3 n_5}}$$

$$\Delta k_c = 2k_2 - k_1 - G_c, \qquad \Delta k_a = k_2 - k_3 - k_4 - G_a, \qquad \Delta k_b = k_5 - k_2 - k_3 - G_b.$$

The subscripts $i = 1, 2, 3, 4, 5$ refer to the pump wave (1064 nm), the second harmonic (green), the signal (infrared), the idler (red), and the sum-frequency wave (blue), respectively. E_i, ω_i, n_i, and k_i are the electric fields, the angular frequencies, the refractive indices, and the wavevectors, respectively. α, β, and γ are the coupling coefficients, f_a, f_b, and f_c are the Fourier coefficients, and G_a, G_b, and G_c are the reciprocal vectors. c is the speed of light in vacuum, d_{33} is the nonlinear optical coefficient, and an asterisk denotes complex conjugation. Here, we assume that the coupled processes are all QPM; then $\Delta k_a = \Delta k_b = \Delta k_c = 0$. In other words, three reciprocal vectors provided by a single OSL simultaneously compensate three wavevector mismatches. Under this condition, the coupling between the three processes is greatly enhanced.

An exact analytical solution of equations (1) is difficult to obtain. In fact, among the three coupled QPM processes, the SHG process is much more efficient than OPG, and at the same time the latter limits the conversion efficiency of SFG greatly. Thus, we have reasons for neglecting the energy transferred from the second harmonic to other waves. In this small-signal approximation, the last two terms in the second equality of equations (1) can be omitted and the variation of the second harmonic is just the same as that of a single SHG process, where the depletion of the pump wave should be considered. Now, for convenience, the A_j are rewritten in the form $A_j = y_j \exp(i\varphi_j)$ (then the y_j are all real; $j = 1, 2, 3, 4, 5$) and substituted into equations (1). And the boundary conditions are assumed to be $y_1(0) = y_{10}$, $y_3(0) = y_{30}$, and $y_2(0) = y_4(0) = y_5(0) = 0$ (in fact y_{30} is usually produced from the noise and y_{30} is much smaller than y_{10}). Then, the amplitude of second harmonic is expressed as

$$y_2(x) = \frac{y_{10}}{\sqrt{2}} \tanh\left(\frac{\gamma y_{10} x}{\sqrt{2}}\right). \tag{2}$$

With equation (2), we can derive from equations (1) that

$$\begin{aligned} y_3(x) &\approx \frac{y_{30}}{2} \exp\left\{k\left(x + \frac{1}{b} \ln \frac{1 + e^{-2bx}}{2}\right)\right\} \\ y_4(x) &\approx \frac{t}{\sqrt{t^2 - 1}} y_3(x) \\ y_5(x) &\approx \frac{1}{\sqrt{t^2 - 1}} y_3(x) \end{aligned} \tag{3}$$

with

$$k = \sqrt{(\alpha^2 - \beta^2)/2}\, y_{10}, \qquad b = \gamma y_{10}/\sqrt{2}, \qquad t = \alpha/\beta.$$

One can see from equations (3) that the coupling process is governed by the ratio of two coupling coefficients $t \equiv \alpha/\beta$, which is similar to the case in the coupling of OPG and SFG [24]. If $t \leqslant 1$, then $y_3(x)$ keeps constant ($t = 1$) or oscillates periodically ($t < 1$) with its original amplitude. That is to say, the efficient generation of TPC cannot be realized and the coupling process is just equivalent to a single SHG process. If $t > 1$, $y_3(x)$ will increase with the crystal length. These results are still valid even if the depletion of the second harmonic is considered. This is not difficult to understand. Inspecting equations (1) reveals that the right-hand side of the third equality is composed of two terms; one represents the parametric gain, the other the loss from the SFG. If t equals unity, the gain is just balanced by the loss [25]. If t is less than unity, the loss exceeds the gain and the last two coupled processes will be inefficient. Moreover, equations (3) or (1) suggest that $y_4(x) = t y_5(x)$. With $I(x) = \varepsilon_0 c \omega y^2(x)/2$, we find that the intensity ratio of the red and blue light is determined by the coupling coefficient ratio. When t equals a critical value $\sqrt{\lambda_4/\lambda_5}$, the intensities of the two types of light are equal throughout the crystal. However, equations (3) show that the generations of the red and blue are less efficient compared to that of the green light, for the reason that the signal field is just amplified from the noise. To obtain efficient outputs of red and blue light, larger values of k and b will be preferable. And the interacting length of the five waves is responsible for the conversion efficiency of the TPC. Thus, the crystal must be long enough.

To demonstrate such a coupled multiple-parametric process, generally, a three-component quasiperiodic OSL should be used, which can provide three reciprocal vectors for phase matching [26]. Fortunately, the calculations show that if the wavelengths of the TPC and the temperature are chosen properly, the wavevector mismatch of the SHG and that of the SFG are equal. Thus, a generalized two-component quasiperiodic OSL will be workable [27, 28]. Here, to simplify the design process, the wavelengths of the pump, green, red, blue, and infrared are chosen as 1064, 532, 647.1, 451.7, and 2990.9 nm, respectively. The crystal temperature is set at 95.0 °C. Then the differences of wavevectors are calculated to be $\Delta k_{SHG} = \Delta k_{SFG} = 0.8143$ and $\Delta k_{OPG} = 0.5636$. In the calculations, the Sellmeier equation for LT is used [29].

A generalized quasiperiodic OSL is constructed from two building blocks A and B, each composed of a pair of oppositely polarized domains. The lengths of the building blocks are $l_A = l_A^+ + l_A^-$, $l_B = l_B^+ + l_B^-$, and $l_A^+ = l_B^+ = l$; and the arrangement of the blocks

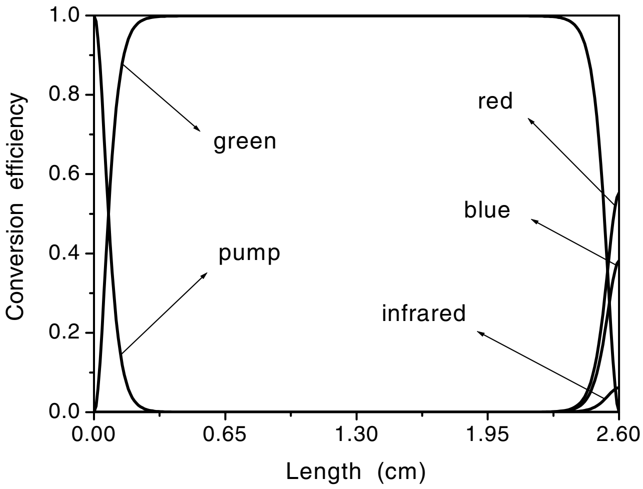

Figure 1. The dependence of the conversion efficiency on the length of the quasiperiodic structure, with $\tau = 0.801\,44$, $l_A = 13.579$ μm, $l_B = 9.200$ μm, and $l = 5.00$ μm. The starting conditions are assumed to be $y_{10} = 4.05$ and $y_{30} = 10^{-12}$.

can be determined by the projection method [26, 30]. In our case, the QPM conditions are $\Delta k_{OPG} = G_{1,1}$, $\Delta k_{SHG} = \Delta k_{SFG} = G_{1,2}$ with $G_{m,n} = 2\pi(m + n\tau)/D$, where $D = \tau l_A + l_B$ is an average structure parameter. Then we got the structural parameters $\tau = 0.801\,44$, $l_A = 13.579\,\mu$m, $l_B = 9.200\,\mu$m, and $l = 5.00\,\mu$m. Correspondingly, the Fourier coefficients are written as $f_{1,1} = 0.481$, $f_{1,2} = 0.283$ with $f_{m,n} = 2(1+\tau)lD^{-1}\sin c(G_{m,n}l/2)\sin c(X_{m,n})$, where $X_{m,n} = \pi D^{-1}(1 + \tau)(ml_A - nl_B)$. Additionally, the crystal length can be estimated with equations (3); it is determined by α, β, γ and y_{10}, y_{30}. With the above parameters, we have $\gamma = 431$, $\alpha = 563$, and $\beta = 391$ ($t = 1.44$). We assume that the 1064 nm pump wave comes from a Q-switched Nd:YAG laser (*LOTIS TII LS-2136-LP-IM*) with a pulse width of 33 ns and pulse energy of 40 mJ. The radius of the beam waist inside the OSL is 0.1 mm. Then $y_{10} = 4.05$. And y_{30} is related to the zero-point energy of the signal field by $\frac{1}{2}\hbar\omega_3 = \frac{1}{2}\varepsilon_0\varepsilon_3 E_{30}^2 = \frac{1}{2}\varepsilon_0 n_3\omega_3 y_{30}^2$, giving $y_{30} \sim 10^{-12}$. According to equations (3), the crystal length is estimated to be 2.5 cm, which is close to the numerical result that is calculated from equations (1) (see figure 1).

In summary, a scheme for generating TPC with a 1064 nm pump wave has been proposed. Three QPM parametric processes are coupled in a single OSL, which can lower the complexity of the system. On the basis of the plane-wave approximation, the coupling process has been investigated theoretically. And as an example, a design for a quasiperiodic structure is presented. The results identify the possibility of realizing the outputs of TPC with coupled multiple-parametric processes and special designs of microstructures.

Acknowledgments

This work was supported by a grant for the State Key Programme for Basic Research of China and by the National Natural Science Foundation of China (No 10021001)

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