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Forward Phase Conjugation Wave due to Multi-wave Coupling and Grating Share in Lithium Niobate Crystal *

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The steady intensity of a forward phase conjugate wave (FPCW) is successfully observed along the c-axis in the highly magnesium-doped lithium niobate crystal. We put forward a detailed physical picture for our experiment phenomena. The FPCW is generated from the phase-mismatch in a three-wave coupling process, and tends to be stable accompanied with the building of photorefractive gratings and four-wave coupling processes. Our experimental result is also discussed and analysed by means of the wave coupling theory, and the theoretical expression is provided for the experiment.

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In recent years, the investigation of the properties of phase conjugate wave fronts have attracted much interest because of its potential in real-time corrections of wave fronts.[1−3] Especially, the use of a forward phase conjugate wave (FPCW) facilitates the design of photonic devices. The occurrence of the FPCW was demonstrated for the first time by Heer and Griffin[4] in studies of the simple image of a wire occurring in the high-order diffraction light beam after passing through a narrow cell with sodium vapour. A different kind of FPCW generation with perfect phase-matching of the wave vectors in the four-wave coupling process was demonstrated by Khyzniak *et al.*,[5] who make use of the thermal nonlinearity of absorbing liquid and the photorefractive effect in an iron-doped lithium niobate crystal. Nowadays, the four-wave coupling has become the most usual method to construct the phase conjugation wave. The FPCW was also obtained by Jones *et al.*,[6] who used three coplanar beams in $Bi_{12}SiO_{20}$. In this letter, we will illustrate the generation and stabilization of the FPCW as a result of grating sharing and wave coupling, and present the theoretical explanation.

In our experiment we used a lithium niobate crystal doped with 5 mol% magnesium as the sample. The linear dimensions $a \times b \times c$ of the crystal are $8 \times 7 \times 21$ mm with the c-axis along the long edge. An Ar^+ laser operated at 488.0 nm was chosen as the light source. The extraordinarily polarized Ar^+ laser beam entering into the sample was split into two parts, denoted as beam 1 and beam 2 in our further discussion. As shown in Fig. 1, beam 1 is incident to the surface normal, while beam 2 is slightly oblique with a small angle θ. The two beams intersect with each other in the crystal. When both beams pass through the sample simultaneously, diffraction light beams can be observed in the directions 3 and 6, which reach the saturated value and become stable after a while. We also found that the experimental configuration was very strict, when the angle θ was larger than 5°, or if beam 1 was not perpendicular but also slightly oblique to the surface even under a small angle, no additional generated light was observed. When the incident beam 2 was blocked, the diffraction light beams were also found in the directions 3 and 6 and disappeared after a few seconds. The time response of the diffraction efficiency of beam 3 is shown in Fig. 2. The curves are very similar to those observed during the photorefractive grating processes of reading and recording. As shown in Fig. 2, reading and recording processes vary with the same time constant. We obtain the time constant τ about 5.5 s from the fitting of our experimental data with the exponential expression $\eta = \eta_{\max} \exp(-t/\tau)$ for curve b and $\eta = \eta_{\max}[1 - \exp(-t/\tau)]$ for curve a in Fig. 2, where η is the diffraction efficiency and $\eta_{\max}$ is the maximum diffraction efficiency. From Fig. 2 we find that the saturation diffraction efficiency reaches 2.2% in our experiment. We use the common method developed by Heer and Griffin[4] to illustrate that the light beam 3 is the FPCW beam. Then we put a thin wire into the beam path 2 after beam 3 reached its saturation intensity, and the wire image could easily be detected in beam 3. This means that the forward direction beam 3, which carries the information of beam 2, is the FPCW of the incident beam 2.

As shown in Fig. 1, six light beams participate in coupling in the interaction area. The wave vectors involved are sketched in Fig. 3. We interpret the physical process of our experimental result as follows. At the very beginning, beams 1 and 2 are incident in the

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crystal. At that time only beams 4, 4′, 5 and 5′ exist in the interaction area, where 4 and 5 represent the incident beams in the crystal, respectively, and 4′ and 5′ represent the light beams reflected from beams 4 and 5 by the back surface of the crystal. The beam paths of 4 and 4′ should overlap with each other in the crystal, since FPCW is observed only under the configuration of beam 1 perpendicular to and beam 2 slightly oblique to the surface. At the beginning of the coupling, we consider that the three-wave coupling is the dominant coupling process in the crystal. In Fig. 3, k_g is the photorefractive grating vector recorded by beams 4 and 5. We also notice that, in our experiment, the angle θ is very small. An additional diffraction light is expected to occur in direction 3 due to the small phase-mismatch Δk (the angle θ is very small, thus the phase-mismatch is very small) which comes from the ordinary multi-order diffraction process.[7−8] Similarly, beam 6 is obtained due to the phase-mismatch Δk and its coupling with beams 4′ and 5′. This is the so-called three-wave coupling. We know that usually this kind of phase-mismatch in three-wave coupling does not often lead to a stable but a fluctuating gain beam. There are other processes contributing to the stability of the FPCW. The obtained beam 3 also records photorefractive grating $k_{34} = k_3 - k_4$ with the incident beam 4. If the grating vector k_{34} coincides with the grating vector k'_g recorded by beams 4′ and 5′, we treat this case as the grating sharing. From Fig. 3, it is easy to see that the phase-mismatch Δk should be

$$\Delta k = 2k_4 - k_5 - k_3. \tag{1}$$

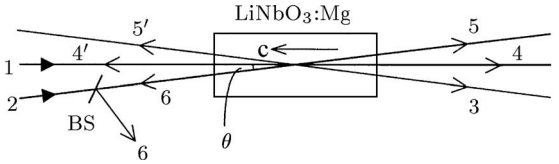


Fig. 1. Extraordinarily polarized beams 1 and 2. Beam 1 is normal to the illuminated surface and a small intersection angle θ exists between 1 and 2. BS is the beam splitter used to observe the beam 6. Beam 3 is the FPCW of beam 2.

A similar process occurs to beam 6 as expressed above. Grating sharing processes are self-consistent and will lead to relatively stable gain beam. In addition, four-wave coupling processes may occur in our experiment, for example, between the beams 3 and 4 and beams 4′ and 5′. The four-wave coupling process also contributes to the gain of stable beam intensity because of its perfect phase-mismatch under the Bragg condition. However, we should point out that the four-wave coupling does not show any dependence on the angle θ, while our result shows that a small angle θ is necessary to obtain the FPCW. Therefore, we consider that the three-wave coupling is the dominant process in generating the FPCW, and then the FPCW becomes stable due to the grating sharing and the four-wave coupling processes.

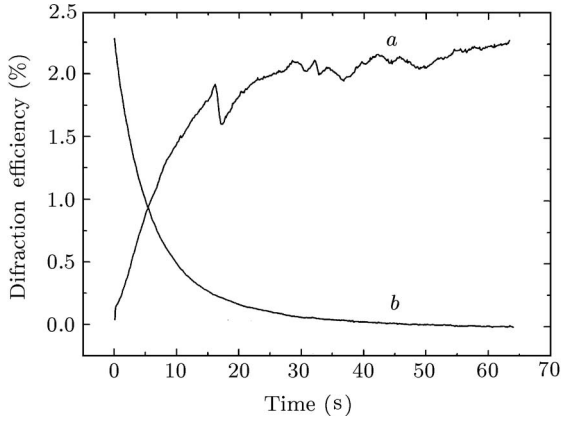


Fig. 2. Time response of the FPCW beam 3 with (*a*) the build-up process when beams 1 and 2 are coupled and (*b*) the erasing process with beam 1 turned on and beam 2 blocked.

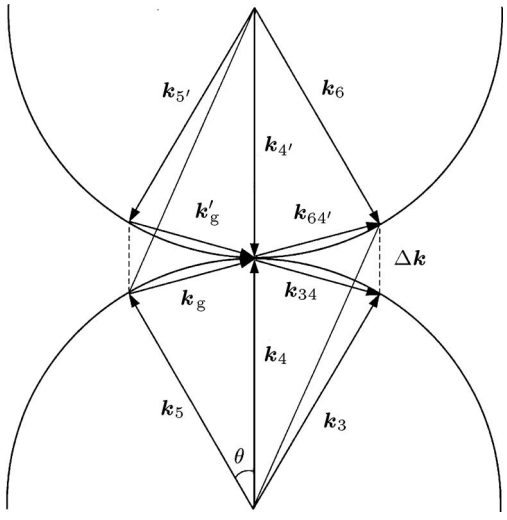


Fig. 3. Schematic diagram of multi-wave coupling: k_i is the corresponding wave vector in Fig. 1; Δk is the phase-mismatch; k_g, k'_g, k_{34} and $k_{64'}$ are the photorefractive grating vectors recorded during the multi-wave coupling.

Next, we try to explain our experimental results using the multi-wave coupling theory. Since the intensity of the FPCW is much weaker than that of the pump light, we are only allowed to consider the dominant photorefractive gratings k_g(or $k_{64'}$) and k'_g(or k_{34}), and the gratings between 5 and 3 can be neglected. According to the multi-wave coupling equations, we obtain the equations of motion for the FPCW beam 3 under the assumption $\boldsymbol{E}_1$, $\boldsymbol{E}_2 \gg \boldsymbol{E}_3$,[9,10] for example, the undepleted pump beam approximation

$$\frac{\partial^2 \boldsymbol{E}_3^*}{\partial z^2} + (\gamma_1^* + \gamma_2 + \mathrm{i}\Delta\boldsymbol{k})\frac{\partial \boldsymbol{E}_3^*}{\partial z} + \mathrm{i}\Delta\boldsymbol{k}\gamma_2\boldsymbol{E}_3^* = 0, \tag{2}$$

$$\gamma_1 = \frac{\omega^2 n_\mathrm{o} n_1}{2kc^2\cos\theta}\exp(-\mathrm{i}\phi_1), \tag{3}$$

$$\gamma_2 = \frac{\omega^2 n_\mathrm{o} n_2}{2\boldsymbol{k}c^2\cos\theta}\exp(-\mathrm{i}\phi_2). \tag{4}$$

Here E_3 is the complex amplitude of the FPCW, n_o is the refractive index of the sample, ω is the angular frequency of the pump light, $\boldsymbol{k} = 2\pi n_\mathrm{o}/\lambda$ is the wave vector in the crystal, $\Delta\boldsymbol{k}$ is the phase-mismatch given by Eq. (1), θ is the intersection included angle, ϕ_1 and ϕ_2 represent the phase shifts between the intensity patterns and the resulting photorefractive gratings, and n_1 and n_2 represent the amplitude of the respective refractive-index gratings. According to the theory of the photorefractive effect, n_j can be expressed by [11]

$$n_j = -\frac{1}{2}n_\mathrm{o}^3 r_\mathrm{eff}\boldsymbol{E}_{\mathrm{sc(j)}} \quad (j = 1, 2), \tag{5}$$

where r_eff is the effective electro-optic coefficient of the crystal and $\boldsymbol{E}_\mathrm{sc}$ represents the space charge electric field due to the photorefractive effect. We solve Eq. (3) and obtain

$$\boldsymbol{E}_3^* = \frac{2\gamma_1^*}{\beta I_4}\boldsymbol{E}_4^*\boldsymbol{E}_4^*\boldsymbol{E}_5\sinh\left(-\frac{\beta}{2}z\right) \cdot \exp\left[-(\gamma_1^* + \gamma_2 + \mathrm{i}\Delta\boldsymbol{k})\frac{z}{2}\right] \tag{6}$$

for the complex amplitude of the FPCW. Here

$$\beta = \sqrt{(\gamma_1^* + \gamma_2)^2 - \Delta\boldsymbol{k}^2 + 2\mathrm{i}\Delta\boldsymbol{k}(\gamma_1^* - \gamma_2)}. \tag{7}$$

$\boldsymbol{E}_4$ and $\boldsymbol{E}_5$ are the complex amplitudes of the electric field in the area of interaction of the incident light beams 4 and 5, respectively. $\boldsymbol{E}_1$ and $\boldsymbol{E}_2$ are related to $\boldsymbol{E}_4$ and $\boldsymbol{E}_5$ via ordinary absorption in the crystal, namely by

$$\boldsymbol{E}_4 = \boldsymbol{E}_1\exp\left(-\frac{\alpha}{2}d_1\right), \tag{8}$$

$$\boldsymbol{E}_5 = \boldsymbol{E}_2\exp\left(-\frac{\alpha}{2}d_2\right), \tag{9}$$

where α is the absorption coefficient of the crystal, d_1 and d_2 represent the effective absorption path distances of the beams 1 and 2 from the surface to the interaction area in the crystal. With Eqs.(6), (8) and (9) we find

$$\boldsymbol{E}_3 \propto \boldsymbol{E}_1^2 E_2^*. \tag{10}$$

Apparently the complex amplitude of the light beam 3 is the phase conjugation of beam 2. It carries all the information of the beam 2, including the amplitude and phase information. Thus, if a wire is placed in the path of beam 2, its image will be observed in beam 3, the FPCW of beam 2.

In conclusion, the FPCW is generated from three-wave coupling and becomes relatively stable due to the photorefractive grating sharing and four-wave coupling in the magnesium doped lithium niobate crystal. We illustrated that the new light wave is FPCW in experiment and in theory. If the diffraction efficiency is improved effectively, for example, maybe in a UV band,[12] the prospective method can be used to gain the forward phase conjugation wave.

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