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Two-wave mixing of laser narrow beams in $Fe:LiNbO_3$ crystals

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Abstract: Two-wave mixing (TWM) of laser narrow beams was investigated in photorefractive $Fe:LiNbO_3$ crystals. A simplified deduction of the relationship of the energy coupling efficiency ξ, the diffraction efficiency η and the phase shift ϕ_g were given. When the surface charge was preserved, the maximum values of the energy coupling efficiency ξ were about two times of that when the surface charge was removed. A refractive perturbation Δn_b induced by an argon ion laser would reduce the energy coupling efficiency ξ and diffraction efficiency η apparently, that reveals that the photorefractive effect has direct relationship with TWM about the phase shift ϕ_g, it initially decreased from π, after reaching a minimum, it regressed to π again when it went to steady state. The results clearly showed that the surface charge field has clear relationship with the space-charge field created by the two coherent beams, which induces space variation of refractive index via Pockel s effect.

Key words: two-wave mixing; photorefractive; laser narrow beams
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狭窄激光光束在掺铁铌酸锂晶体中的双波耦合

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摘 要: 研究了狭窄激光光束在掺铁铌酸锂光折射晶体中的双波耦合(TWM)现象。对双波耦合中的能量耦合效率 ξ,衍射系数 η 和相移 ϕ_g 之间的关系给出了一个简化的推导。保留表面电荷时候的能量耦合效率是不保留表面电荷时的两倍。氩离子激光诱发的折射率变化很明显地降低了能量耦合效率和折射率,这些都揭示了光折变效应和双波耦合有着直接的关系。相位差从最初的 π 降低到最小值后,重新恢复到 π,然后趋于稳定状态。这个结果表明了表面电荷和两相干光束导致的空间电荷场有着明显的联系,而空间电荷场通过普克尔效应导致了折射率的变化。

关键词: 双波耦合;光折变;狭窄激光光束
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When two coherent signal beams are interacting in medium or even in free space, the intensity distribution of the interference pattern is periodically varying in space. If two coherent signal beams are interacting inside photorefractive (PR) materials, energy exchange between the two light beams is possible, which is called photorefractive two-wave mixing (TWM). TWM exhibits fascinating nonlinear optical properties, which has been extensively studied since the discovery of PR effect in 1970 [1-6].

PR crystal illuminated by a light beam with periodical spatial intensity variation can be described by the charge transport model and the evolution of the photorefractive index grating, which is the fundamental mechanism of TWM in a PR crystal. A phase shift ϕ_g between intensity grating and photorefractive index grating plays a key role in TWM. A non-zero ϕ_g causes the energy transfer between two coupling beams [7], and, in many cases, the *c*-axis of PR crystals determines the direction of energy transfer.

The most important and useful application of PR effect comes from the photorefractive index grating or hologram inside PR crystals. It is well known that for a definite refractive index grating spacing, the grating has incident angle selectivity of light scattering.

1 Experiment Introduction

The effect of applied field has been studied by a number of groups since 1974 [8-11]. In our previous work, the signal noise ratio of TWM in Cu:KNSBN crystals was investigated[12]. In this work, an experiment was set to investigate the effect of the surface charge field to the TWM in Fe:$LiNbO_3$ crystals. The energy transfer between two narrow signal beams and the diffraction properties of the volume holographic gratings were investigated under various experimental configurations. "narrow beams" means the FWHM of light beam waist was focused to several tens of microns which resulted in small energy coupling efficiency as the result of the thin grating. The PR grating was almost in steady state because the reconstructing was weak. So the quasi-steady state theory can be introduced to describe and analyse the PR index grating. The relationship of the energy coupling efficiency ξ, the diffraction efficiency η and the phase shift ϕ_g were deduced in a simple method by the benefit of the corresponding specially designed experimental configurations. And ξ, η, and ϕ_g were calculated according to the experimental data. The results show that TWM with the effect of surface charge field (dc field) would be much obvious than that without surface charge field. And a refractive index perturbation Δn_b could make the TWM weaker. Both emphasize the role of the surface charge field in TWM.

2 A Simplified Analysis of Two-Wave Mixing of Narrow Beams

In the experiment, narrow signal beams (focused to 50 μm FWHM at beam waist) was used to conduct the TWM. Usually the energy coupling efficiency between two beams is small because the refractive index grating existed within a very small region and there were only a small number of layers, therefore the theoretical analysis can then be simplified. Since the energy transfer is small, the reconstruction of the refractive index grating can be ignored, and the grating can be considered as quasi-stable.

Moreover the beam size is small, and the grating length induced by two-wave mixing is comparable short, the light intensity before and after passing through the grating will be essentially unchanged. Then, the absorption coefficient α can be treated as zero in the theoretical analysis. In the experiments, the intensity of two signal beams was adjusted to practically the same, i.e. the so called modulation index *m* was set to be unity. For the benefit of the foregoing simplification, the relationship between ξ, η, and ϕ_g can be deduced in a simple way.

Figure 1 shows the schematic diagram of

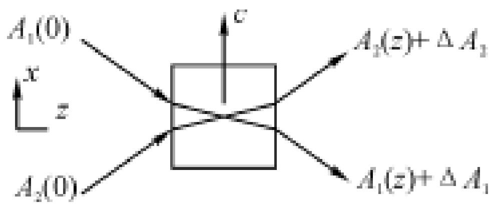


Fig.1 Schematic diagram of TWM using narrow laser beams

TWM using narrow beams, $A_1(0)$, $A_2(0)$ are the amplitudes of the light waves at the input face, $A_1(z)$, $A_2(z)$ are the amplitudes of the light waves at the output face before coupling builds up, and ΔA_1, ΔA_2 are the changes of amplitudes of the light waves when TWM happens. Figure 2 shows the detailed diagram of TWM. A_1, A_2 are the amplitudes of light waves at the input face, ΔA is the change of amplitude at the output face, and the arrow represents the direction of energy transfer. The energy coupling can be treated as the result of the interference between A_1 and ΔA at O'. The solid lines represent the intensity grating formed by the two signal beams, and the dashed lines represent refractive index grating, which has a shift ϕ_g with respect to the intensity grating. θ is the interacting angle inside the crystal and Λ is the grating spacing.

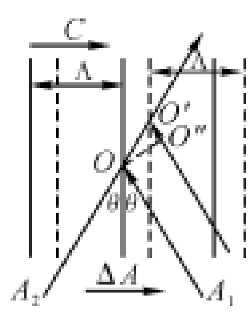


Fig 2 Detailed diagram of TWM using narrow beams

TWM is actually conducted in the refractive index grating. When A_1, A_2 arrive at O', the optical path difference is $|OO' - O'O''|$, the phase difference is

$$\Delta\phi = \frac{2\pi n}{\lambda}|OO' - O'O''|, \quad (1)$$

where $|OO'| = \phi_g \Lambda / 2\pi\sin\theta$, $|O'O''| = |OO'|\cos 2\theta = |OO'|(1 - 2\sin^2\theta)$, and $2n\Lambda\sin\theta = \lambda$, where n is the refractive index. Thus,

$$\Delta\phi = \frac{2\pi n}{\lambda}|OO' - O'O''| = \frac{2\pi n}{\lambda}\frac{\phi_g \Lambda\sin\theta}{\pi} = \phi_g. \quad (2)$$

Furthermore, when using a light beam to readout the transmission grating, provided that the Bragg condition is satisfied, it is well known that the phase of diffracted beam is delayed by $\pi/2$ compared with that of the readout beam. Then the phase difference between A_1 and ΔA is

$$\Delta\phi = \phi_g - \frac{\pi}{2}. \quad (3)$$

The intensity of the energy-gaining beam after coupling is

$$|A_1 + \Delta A|^2 = |A_1|^2 + |\Delta A|^2 + 2|A_1\Delta A|\cos\Delta\phi. \quad (4)$$

In the case of small energy transfer ($\xi \ll 1$), $|\Delta A|^2$ can be ignored, then the change of energy of each beam is

$$\Delta I \approx 2|A_1\Delta A|\sin\phi_g. \quad (5)$$

The energy coupling efficiency ξ is

$$\xi = \frac{I_1(z) - I_1(0)}{I_1(0)} = \frac{I_2(z) - I_2(0)}{I_2(0)}. \quad (6)$$

Then

$$\xi = \frac{2|A_1\Delta A|\sin\phi_g}{I_1} = \frac{2|A_1\Delta A|\sin\phi_g}{|A_1|^2}, \quad (7)$$

and the diffraction efficiency η can be written as

$$\eta = \left|\frac{\Delta A}{A_1}\right|^2 = \left|\frac{2A_1\Delta A}{2A_1^2}\right|^2 = \left|\frac{\Delta I}{2I_1\sin\phi_g}\right|^2 = \frac{\xi^2}{4\sin^2\phi_g}. \quad (8)$$

Suppose $\phi_g = \pi/2$, we have

$$\eta = \frac{\xi^2}{4}. \quad (9)$$

Thus, for small ξ ($\xi \ll 1$),

$$\xi = 2\sqrt{\eta} \quad (10)$$

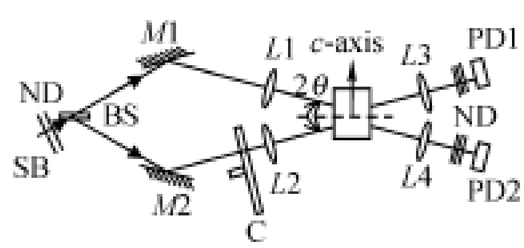
Then we get the relationship (Eq.(10)) using our simplification ($m = 1$, $\alpha = 0$, and $\phi_g = \pi/2$).

On the other hand, if the phase shift ϕ_g is not $\pi/2$, according to Eq.(8), the time dependence of ϕ_g can be calculated by measuring the time dependences of ξ and η:

$$\sin\phi_g = \frac{\xi}{2\sqrt{\eta}}. \quad (11)$$

3 Experimental Setup

The experimental setup for TWM using narrow beams is shown in Figure 3. An ordinary polarized 632.8 nm He-Ne laser beam was used as the signal beam that is split into two coherent signal beams by a beam splitter. Both of the two beams have the same intensity of (100 ± 1) μW, and the intersecting angle 2θ in air was 30°. Two lenses of the same focal length (10 cm) were used to focus the signal beams (FWHM was focused to 50 μm at the beam waist). The two beams were made to interact at their beam waists and in the middle of the photorefractive Fe:$LiNbO_3$ crystal. A chopper was used to block one signal beam periodically (about once per second, each blocking lasted 100 ms) to get the diffracted signal (usually the sampling rate was 50/s, such that 5 data points were taken when the beam was blocked by the chopper). Because beam 1 was blocked for a very short time (100 ms) and the slow photorefractive response, thus ξ′ can be considered as the energy coupling efficiency before blocking. Two lenses were used to collect the signal beams in front of the photodiodes, each of which was connected to a linearizing amplifier and then to an interface card (National Instrument BNC-2110) installed in a PC. The data were acquired by the National Instrument Lab View software.



*L*1, *L*2, *L*3, *L*4: focusing lenses; *M*1, *M*2: mirrors; ND: neutral density filters; BS: beam splitter; SB: signal beam; PD1, PD2: photodiodes; *C*: chopper

Fig.3 Experimental setup for TWM using narrow beams

First, TWM experiments were conducted using a fresh crystal under open-circuit and short-circuit condition, in which any refractive index perturbation was erased by the uniform illumination of a white lamp. Short-circuit condition means the surface charge induced by the incident light was removed by using a wet lens paper to make contact with the surfaces of the crystal, and it is called open-circuit condition when the surface charge was preserved. Second, TWM experiments were conducted using a crystal with Δn_b under open-circuit and short-circuit condition, Δn_b is the residual refractive index grating induced by an unfocused 514.5 nm argon-ion laser of which the FWHM is about 2.5 mm and the power is about 100 mW.

4 Results and Discussion

Figure 4 shows the evolution of the intensity of the two light beams $I_{1,2}(t)$ after getting across the crystal with Δn_b under short-circuit condition. Upper curve is the beam with energy gain, lower curve is the beam with energy lost, and middle curve is the sum of the two curves divided by two. It took about 10 minutes for ξ to reach the maximum value. One can see that the coupling reaches a maximum ((9.0 ± 1.0)%) at $t = 10$ min, and then decays gradually to a very low steady state level. $I_{1,2}(t)$ are similar in trend under different experimental conditions (described previously), the differences are in the maximum ξ (see Table 1), which can be calculated according to Eq.(6).

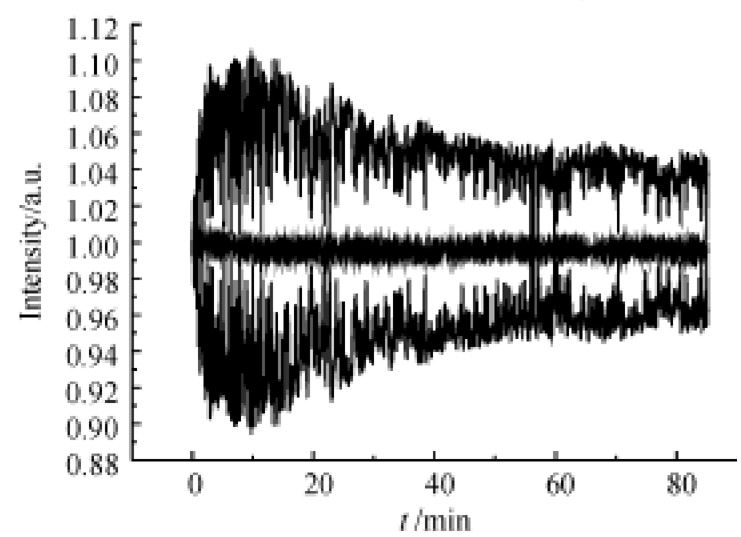


Fig.4 $I_{1,2}(t)$ in crystal with Δn_b under short-circuit condition

Table 1 The maximum ξ under different conditions

Experimental condition	Open-circuit fresh crystal	Open-circuit crystal with Δn_b	Short-circuit fresh crystal	Short-circuit crystal with Δn_b
ξ/%	32.5 ± 2.5	18.8 ± 1.8	17.9 ± 1.8	9.0 ± 1.0

The maximum of the energy coupling efficiency ξ is shown in table 1. As can be seen, ξ under open-circuit condition are higher that that under short-circuit condition, and ξ in fresh crystal are higher than that in crystal with the refractive index perturbation Δn_b. But ξ under open-circuit condition with Δn_b is almost the same with that under short-circuit condition in fresh crystal.

Table 2 shows η at maximum and at steady state, as well as the rise time to reach the maximum diffraction efficiency η, which can be calculated according to Eq. (8). For the relationship between η and ξ, the variation of the maximum η with the experimental configurations shows similar properties to that of ξ. At steady state, ξ under open-circuit condition are about two times of that under short-circuit condition, and it seems to affect η not so much whether the crystal is fresh or with Δn_b, especially under short-circuit condition. At a fresh crystal or with Δn_b, the rise time to reach maximum η under open-circuit are higher than that under short-circuit. And under open-circuit or short-circuit condition, the rise time to reach maximum η in a fresh crystal are higher than that in a crystal with Δn_b. Both Δn_b and the surface charge affect the the rise time apparently.

Table 2 The η at maximum and at the stead state, and the rise time to reach the maximum η under different experimental conditions

Experimental condition	Open-circuit fresh crystal	Open-circuit crystal with Δn_b	Short-circuit fresh crystal	Short-circuit crystal with Δn_b
Maximum η/ %	4.94 ± 0.1	1.81 ± 0.05	1.66 ± 0.05	0.72 ± 0.02
η at steady state/ %	0.62 ± 0.02	0.53 ± 0.02	0.28 ± 0.01	0.28 ± 0.01
Rise time to reach maximum η/ min	28.2 ± 4.0	18.9 ± 0.5	24.0 ± 2.0	11.9 ± 0.2

In summary, the results clearly show that the open-circuit or short-circuit and the perturbation of refractive index Δn_b could affect the properties of the volume refractive index grating significantly, which can be explained as follows. For a crystal with Δn_b, the intersection of two waves coupling was placed at the center of the 514.5 nm argon ion laser beam, where Δn_b has been made saturated. The saturated value of Δn_b induced by the 514.5 nm laser is larger than that induced by the 632.8 nm signal beams. Thus, the TWM could form an index grating with smaller magnitude. As a result, η was reduced, so did ξ, provided that the phase shift φ_g was in phase with the evolution of the index grating.

The difference between open-circuit and short-circuit conditions is that in short-circuit the surface charge is removed, that is, making the surface charge field zero, which was responsible for the build-up of the space-charge field inside the crystal. Thus, the magnitude of the refractive index grating was reduced by the reduction of space-charge field.

The evolution of the phase shift φ_g was also investigated which was deduced from Eq. (11) and averaged by 1 over 25 data points to show the trend more clearly. In the experiment, the crystal was under open-circuit condition and Δn_b was induced. Since the charge transport in Fe:$LiNbO_3$ crystal is mainly determined by photovoltaic (PV) effect, so the initial phase shift was set as π. Results are shown in Figure 5. It can be seen that the clear trend

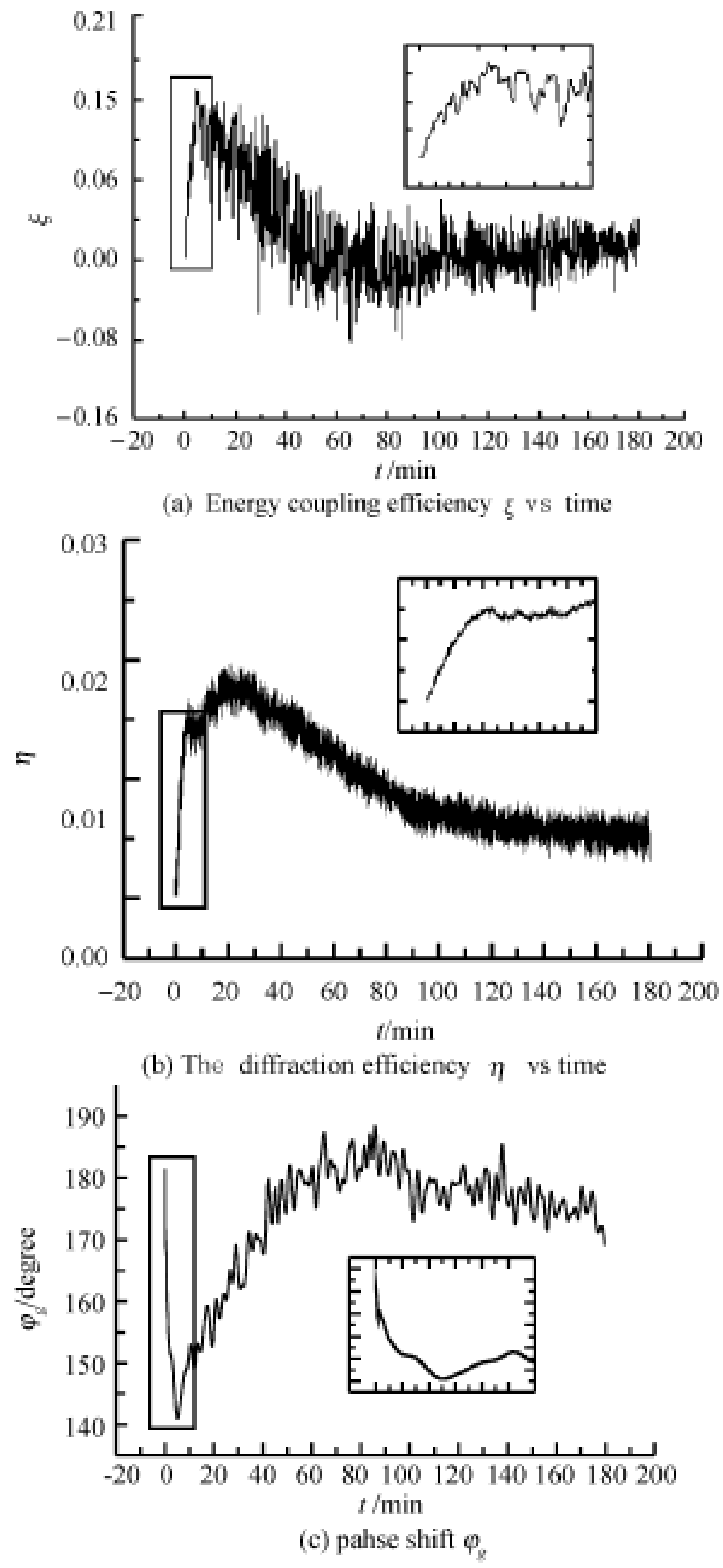


Fig.5 The insets are the magnified regions indicated by the rectangles

of the evolution of ϕ_g in time. When the signal beams were incident, the TWM was not so obvious instantly. The energy coupling coefficient spent (6.0 ± 1.0) min to climb to the maximum ξ, and diffraction coefficient η reaches the maximum value at t = (18.0 ± 1.0) min. According to the experimental data, it seems that the time evolutions of ξ and η are not in-phase. Maybe some physical vibrations of the light beam and the crystal were introduced, remember that the experiments were conducted with narrow light beams. At steady state, the value of ϕ_g was around π, so that there was no energy coupling between the two beams. Also, η decreases to a lower value at steady state that also leads to lower value of ξ.

5 Conclusion

The TWM phenomenon was investigated in a photorefractive Fe:$LiNbO_3$ crystal. The time evolution of the energy coupling efficiency ξ, diffraction efficiency η and phase shift ϕ_g were obtained by monitoring the output signal beams and corresponding calculation. The experiments were conducted under four different experimental configurations. When the surface charge was preserved, the maximum values of the energy coupling efficiency ξ were about two times of that when the surface charge was removed. A refractive perturbation Δn_b induced by an argon ion laser would reduce the energy coupling efficiency ξ and diffraction efficiency η apparently, that reveals that the photorefractive effect has direct relationship with TWM about the phase shift ϕ_g, it initially decreased from π, after reaching a minimum (in about (6.0 ± 1.0) min), it regressed to π again (about one hour later) when it went to steady state. The results clearly show that the surface charge field has clear relationship with the space-charge field created by the two coherent beams, which induces space variation of refractive index via Pockel s effect (electro-optic effect).

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