# Observation of Nondegenerate Photorefractive Parametric Amplification

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We report on the first experimental observation of so-called nondegenerate photorefractive parametric amplification. We show that due to this effect it is possible for a weakly modulated photoinduced grating to be parametrically amplified via nonlinear interaction with a strongly modulated photoinduced grating. [S0031-9007(96)00328-6]

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Parametrically excited oscillation is a general nonlinear physical phenomenon that previously has been found in numerous systems such as mechanical [1], electronic [2], and optical [3] systems. In the optical case, for example, optical parametric oscillation and amplification refer to processes where a powerful optical wave, called the pump wave, incident on a nonlinear $\chi^{(2)}$ medium is capable of generating and amplifying two secondary optical waves called signal and idler waves with temporal and spatial frequencies that are different from the pump wave frequencies. In photorefractive media, parametric processes can appear also. The study of these effects was initiated by the observation of so-called spatial subharmonic generation in a crystal of $Bi_{12}SiO_{20}$ (BSO) [4]. This effect was observed in an ordinary two-wave mixing experiment, where two plane optical waves were incident on the crystal to form a holographic grating. An electric field applied to the crystal and a moderate frequency detuning of one of the optical beams were introduced to ensure a high photorefractive response, i.e., a high modulation depth of the induced grating. The authors observed that for certain choices of parameters the crystal responded in a highly nontraditional way: In addition to the conventional fundamental grating which has the same spatial period as the illuminating interference pattern, new secondary gratings arose with spatial periods being twice and sometimes even three or four times the fundamental period. Because the periods of the secondary gratings appeared to be integer multiples of the fundamental grating period, the phenomenon was referred to as spatial subharmonic generation. Later, it was shown that the effect is rooted in the material nonlinearities which manifest themselves as nonlinear terms in the band transport equations [5,6].

Recently, the more general process of nondegenerate photorefractive parametric oscillation was discovered in a crystal of BSO [7]. In this case, it was shown experimentally that, when inducing a strongly modulated running grating in the crystal, it is possible not only for one or two subharmonic gratings but for a whole continuum of secondary gratings to grow up spontaneously in the medium. This process was referred to as photorefractive parametric oscillation, and it was stated that subharmonic generation is simply a special case of this process. In Ref. [8] an example of photorefractive parametric amplification was given. Here it was demonstrated also in a crystal of BSO that a strongly modulated holographic grating is capable of amplifying a secondary weakly modulated grating. This process can be thought of as the degenerate case of parametric amplification where the signal and idler waves are identical. To summarize, four types of parametric processes can appear in a photorefractive medium: parametric *oscillation*, degenerate [4] and nondegenerate [7], parametric *amplification*, degenerate [8] and nondegenerate. To the best of our knowledge, all processes have been reported on in the literature except for the last one, nondegenerate amplification. This, however, will be presented in this Letter.

The experimental setup used is shown in Fig. 1. Two gratings are recorded in a $10 \times 10 \times 10$ mm$^3$ crystal of BSO: a signal grating and a pump grating. The signal grating is written by two linearly polarized (along the $\langle 110 \rangle$ direction of the crystal) and collimated argon ion

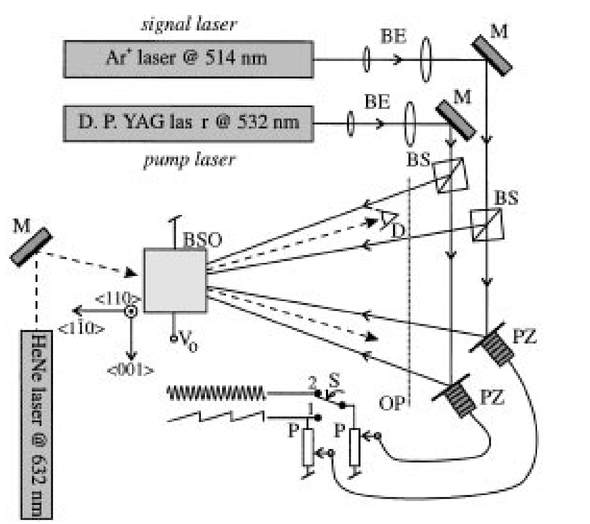


FIG. 1. Experimental setup for photorefractive parametric amplification. The shortenings are D.P. YAG, diode pumped YAG laser; BE, beam expander (1:10) and spatial filter; M, mirror; BS, beam splitter; D, photodetector; PZ, piezomirror; P, potentiometer; $V_0$, applied voltage; S, switch; and OP, observation plane.

  

($Ar^+$) laser beams at 514.5 nm. By means of reflection from a piezomirror driven by a sawtooth voltage form, one of the beams is shifted in frequency to form a uniformly running grating in the crystal. The fringe spacing of this grating is 43 $\mu$m and the temporal angular frequency is 172 $s^{-1}$. In a similar way the pump grating with spatial period 16 $\mu$m is written by two linearly polarized (again along the $\langle 110 \rangle$ direction of the crystal) and collimated beams from a diode pumped YAG laser at 532 nm. When the switch (S) is in position 1, a second sawtooth driven piezomirror causes this grating to run with a temporal angular frequency of 273 $s^{-1}$. The total intensity of the four incident recording beams is 21 $mW/cm^2$, and the modulation coefficients of the signal and pump interference patterns are 0.012 and 0.97, respectively. A dc electric field of 8 kV/cm is applied to the crystal in the $\langle 001 \rangle$ crystallographic direction. By means of the switch (S) it is possible to change the movement of the pump piezomirror from the sawtooth movement (switch in position 1) to a high frequency sinusoidal movement (switch in position 2) and vice versa. In this way it is possible to switch on and off the fringe contrast (modulation coefficient) of the pump interference pattern without changing the total intensity in the crystal [9,10] and, hence, the modulation coefficient of the signal interference pattern is unaffected by the switching. A readout beam from a 7 mW linearly polarized HeNe laser is incident backwards through the crystal at an angle so as to Bragg match the signal grating.

In the first experiment the diffraction efficiency of the signal grating is measured by a photodetector positioned as shown in Fig. 1. Initially, the pump grating is switched off (switch S in position 2 in Fig. 1). Then, by putting the switch in position 1, the pump grating is suddenly turned on and the temporal evolution of the signal grating diffraction efficiency is monitored on a digital oscilloscope. Now, according to the conventionally used linear theory modeling the photorefractive response to an optical intensity pattern (i.e., the linearized band transport model) [11], nothing should happen to the signal grating when activating the switch. This is due to the fact that neither the total intensity nor, hence, the modulation coefficient of the signal interference pattern is affected by the switching. What actually happens in the present case is shown in Fig. 2. The switching has occurred at $t = 0.2$ s. It is seen that in less than 0.2 s the signal grating's diffraction efficiency experiences a very significant increase by a factor of about 8. Thus certainly the signal grating is strongly affected by the presence of the pump grating. However, because the two pairs of beams writing the gratings originate from two different laser sources, no beam coupling can appear between them. Therefore, it is clear that only the nonlinear terms in the band transport equations can be responsible for this effect.

The same experimental situation is described in Fig. 3, where the diffraction pattern in the observation plane (OP) has been recorded by a charge coupled device camera. Figure 3(a) shows the read-out diffraction pattern in the case where the pump grating is switched off. The large intense spot at position O stems from the directly transmitted read-out beam. At position S a very weak spot is observed due to diffraction from the signal grating. When switching on the pump grating the diffraction pattern changes to that shown in Fig. 3(b). In this case, it is seen that in agreement with Fig. 2 the signal diffraction spot is strongly increased in intensity. The spot on the right at position P corresponds to the diffraction in the pump grating. An interesting observation is seen at position I. A new spot appears here due to diffraction from an additional grating which we refer to as the idler grating. The term idler is inspired by the analogous process of optical parametric amplification, where an idler wave appears in addition to the pump and signal waves [3]. The presence of the idler grating is of fundamental importance in the parametric process because this grating enables the signal grating to be coupled to the pump

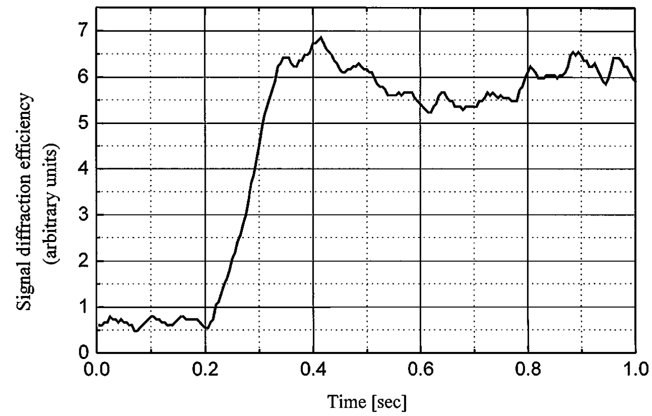


FIG. 2. Diffraction efficiency of the signal grating versus time. The pump grating is turned on at $t = 0.2$ s.

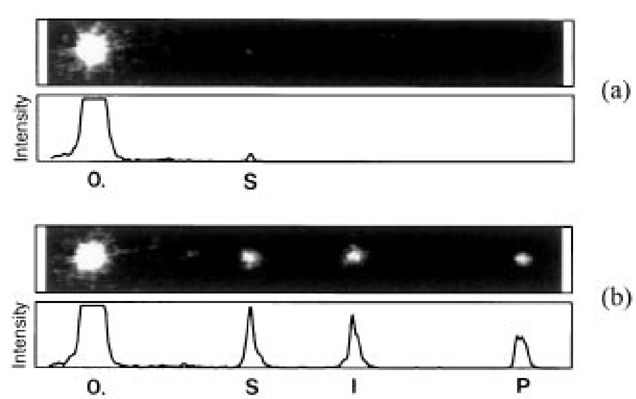


FIG. 3. Diffraction patterns observed in the observation plane OP. Two cases are displayed: (a) The pump grating is switched off and (b) the pump grating is switched on.

grating and, hence, makes possible the transfer of energy from the pump to the signal grating.

One might wonder here how it is possible to read out all three gratings simultaneously using only one read-out beam. This is due to the fact that (i) the gratings have very large fringe spacings (more than 16 $\mu$m) and (ii) anisotropic diffraction takes place. These two circumstances imply that the angular selectivity for the three gratings is very weak [12] and, hence, due to off Bragg diffraction it is possible to read out all three gratings. Since the read-out angle is adjusted to Bragg match the signal grating, the angular read-out detuning is most pronounced for the pump grating. Therefore, the intensity of this diffraction spot [at position P in Fig. 3(b)] is significantly reduced as compared to the case where the read-out beam is exactly Bragg matched to the pump grating. In conclusion, the intensity distribution in Fig. 3(b) does not give a true picture of the grating strength distribution between the signal, idler, and pump gratings.

The photograph in Fig. 3(b) is a convincing experimental proof of the existence of parametric processes in photorefractive crystals. This is due to the fact that in the theoretical work by Sturman *et al.* [5] one of the main statements was that a three-wave interaction was responsible for the parametric process. This statement is elegantly verified by the three diffraction spots in Fig. 3(b). According to the predicted theory [5], the general so-called spatial synchronism condition must apply for the gratings involved:

$$\vec{k}_S + \vec{k}_I = \vec{k}_P , \qquad (1)$$

where $\vec{k}_S$, $\vec{k}_I$, and $\vec{k}_P$ are the signal, idler, and pump grating vectors, respectively. This condition implies that the distances $|OS| + |OI|$ should equal the distance $|OP|$ in Fig. 3(b). As is seen, this is excellently obeyed.

Figure 3(b) shows, however, only the special case where all wave vectors are collinear, i.e., all the running gratings propagate in the same direction. In Fig. 4 a result of the more general case called noncollinear interaction is shown. In this case, the three grating vectors are noncollinear. To obtain this picture we have tilted one of the optical beams that records the signal grating downwards in the vertical direction. This tilts the signal grating vector, and, as a consequence of this, the idler grating is tilted correspondingly upwards to still fulfill the spatial synchronism condition (1). The vectorial synchronism condition is shown schematically in Fig. 4(b). Also in the case in Fig. 4 a considerable amplification of the signal grating is obtained when the pump grating is turned on.

With the present experiment we believe we have found a much better tool to perform detailed investigations of parametric processes in photorefractives. This is due to the fact that in ordinary subharmonic experiments or experiments on parametric oscillation it appears that several continuously distributed gratings are involved [7]. This strongly complicates the matter. With the present experiment only two secondary gratings are involved. This makes it possible to focus on one parametric interaction at the time involving only three gratings: the pump grating, the signal grating, and the idler grating.

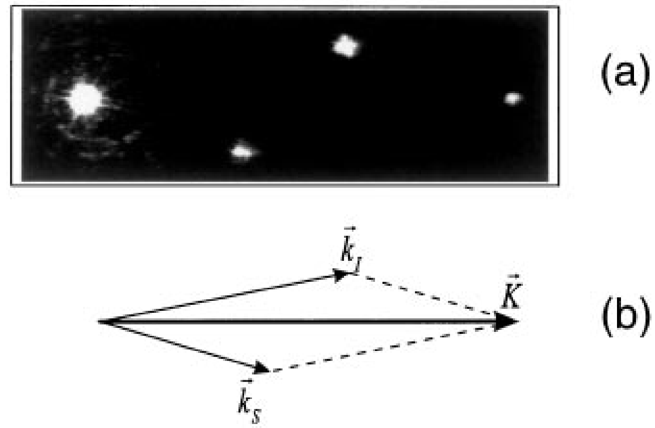


FIG. 4. (a) Diffraction pattern in the noncollinear case. (b) The spatial vectorial synchronism condition.

In conclusion, we have demonstrated the first, to our knowledge, experimental evidence of nondegenerate photorefractive parametric amplification. We show that the diffraction efficiency of a weakly modulated signal grating can be enhanced by more than 800% via nonlinear parametric interaction with a strongly modulated pump grating. Moreover, in addition to the externally recorded pump and signal gratings, we observe a so-called idler grating. The wave vector of this new grating is determined by the spatial synchronism condition. Both the collinear and noncollinear cases of parametric amplification are presented.

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