

NONLINEAR OPTICAL PHENOMENA

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Controllable discrete diffraction in cascade-induced waveguides*

O.V. Borovkova, V.E. Lobanov, A.P. Sukhorukov, A.K. Sukhorukova

***Abstract*.** **A new method for generating periodic lattices in quadratically nonlinear media by the three-wave cascade interaction is proposed. This method allows one to obtain stable structures with changeable parameters. These structures make it possible to realise the all-optical control of the character of the laser beam propagation. The use of the discrete diffraction allows the signal multiplexing in optical processing and information transfer devices and the control of the number of channels at the crystal output. The effect of the discrete diffraction anisotropy in the system of induced waveguides makes it possible to redistribute in the specified way the energy in the channels at the output. It is shown that the optical switching efficiency is maximal in the regime of the transverse Bragg resonance. The signal switching rate in optical lattices induced in a quadratically nonlinear medium is limited by the time of light propagation though the crystal and can achieve several terahertz.**

Keywords: *waveguide induced structures, discrete diffraction, all-optical switching.*

1. Introduction

Progress in modern telecommunication systems imposes stringent requirements to the data transmission rate and, hence, to the switching rate in such systems. Modern data transmission channels use electronic and optoelectronic control devices. However, they cannot provide the switching rate achieving several terahertz. Such superfast switching can be obtained only with the help of all-optical switchers. Among other advantages of these switchers are their compact size and tunability.

Systems of weakly coupled optical waveguides have been used recently to control the laser beams. These systems employ fundamentally new propagation regimes, which are absent in homogeneous media. The most interesting among them are based on the phenomenon of anisotropic discrete diffraction, when the diffraction type depends on the beam propagation direction and the modulation depth of the lattice refractive index. The systems of coupled waveguides can be produced in crystals with the help of lithography, material modification, by embedding other substances, etc. [1 – 3]. But the parameters of such structures are fixed, which complicates their use. In practice, one can use periodic structures induced in nonlinear media by modulating the linear and nonlinear parts of the refractive index. The parameters of such induced lattices can be easily adjusted by changing the parameters of the reference signal. As a nonlinear medium, photorefractive and liquid crystals are often selected [4 – 8]. However, they have a rather long relaxation time and, hence, media with an electronic nonlinearity are required to realise superfast switching of optical waves. These media include noncentrally symmetric optical crystals with a quadratic nonlinearity, for example, lithium niobate crystal, etc. The use of quadratically nonlinear crystals as a media for generating optical matrices makes it possible to achieve stability of the latter. In quadratic media, cubic nonlinearity can be imitated by the cascade interaction of three waves with different frequencies: low-frequency pump, signal and sum wave. The cascade mechanism is described in paper [9] by the example of parametric reflection in the case of noncollinear three-frequency interaction.

In this paper, we describe the formation of a cascade lattice and consider the dynamics of discrete diffraction, in particular, for signal beams with the inclined wave front. We show that the cascade lattice is produced in two stages. First, a volume lattice is produced at the fundamental frequency by the interference of two inclined beams. Then, a narrow signal beam enters the medium, which, together with the pump, excites the wave at the sum frequency. This wave is confined in the region of the wave superposition at the fundamental and signal frequencies; as a result, the induced lattice becomes clearly apparent as the signal wave spreads: the wider the diffracting beam, the larger the transverse size of the lattice. This effect is well manifested in the discrete diffraction of the signal beam overlapping only one – two waveguides at the medium input. In the case of a large cascade modulation depth of the refractive index, the signal propagates in a waveguide manner, by preserving its shape. As in fixed lattices, in the cascade-induced periodic structure there exists the regime of diffractionless beam propagation with a certain wave-front inclination.

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O.V. Borovkova, V.E. Lobanov, A.P. Sukhorukov Department of Physics, M.V. Lomonosov Moscow State University, Vorob’evy gory, 119991 Moscow, Russia; e-mail: borovkovaolga@yahoo.co.uk, apsmsu@gmail.com
A.K. Sukhorukova Sergo Ordzhonikidze Russian State Geological Prospecting University, ul. Miklukho-Maklaya 23, 117997 Moscow, Russia

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2. Mathematical model

Consider noncollinear three-frequency interaction of wave beams in a one-dimensional quadratically nonlinear crystal placed along the z axis. The pump wave has the frequency ω_1, the signal wave – the frequency ω_2, and the idle wave – the sum frequency $\omega_3 = \omega_1 + \omega_2$. We assume that scalar phase matching is fulfilled along the z axis: $\omega_3 n_3/c = \omega_1 n_1/c + \omega_2 n_2/c$, where $n_{1,2,3}$ are the refractive indices at the corresponding frequencies. The low-frequency pump is assumed highly intensive; and therefore, the inverse influence of weak signal and idler waves can be neglected. Then, the parametric interaction of the beams with allowance for the diffraction effects can be described by three equations for slowly varying amplitudes A_j:

$$\frac{\partial A_1}{\partial z} + \mathrm{i} D_1 \Delta_\perp A_1 = 0, \tag{1}$$

$$\frac{\partial A_2}{\partial z} + \mathrm{i} D_2 \Delta_\perp A_2 = -\mathrm{i}\gamma_2 A_3 A_1^*, \tag{2}$$

$$\frac{\partial A_3}{\partial z} + \mathrm{i} D_3 \Delta_\perp A_3 + \mathrm{i}\Delta k A_3 = -\mathrm{i}\gamma_3 A_2 A_1, \tag{3}$$

where $\Delta_\perp = \partial^2/\partial x^2 + \partial^2/\partial y^2$ is a transverse Laplacian; $D_j = L/2k_j a_1^2$ is the diffraction coefficient of the jth beam with the wave vector k_j; a_1 is the transversal scale; L is the longitudinal scale; $\gamma_j = \beta_j \sqrt{I_{01}} L$ is the nonlinearity coefficient; $\beta_j = 2\pi \boldsymbol{e}_1 \hat{\chi}^{(2)} \boldsymbol{e}_2 \boldsymbol{e}_3 \omega_j/(c n_j)$; $\boldsymbol{e}_1, \boldsymbol{e}_2, \boldsymbol{e}_3$ are the unit vectors of the coordinate axes; $\hat{\chi}^{(2)}$ is the tensor of the quadratically nonlinear susceptibility; n_j is the linear refraction coefficient; c is the speed of light; I_{01} is the pump wave intensity; $\Delta k = k_{1z} + k_{2z} - k_{3z}$ is the mismatch of the wave vector projections on the z axis.

3. Generation of a cascade-induced lattice

In the large mismatch approximation of the wave vectors $\Delta k \gg \gamma_3 A_1$, we can obtain from (3) an approximate coupling of the amplitudes $\Delta k A_3 = -\gamma_3 A_2 A_1$. By substituting this relation into (2), we will pass from system (1)–(3) to one equation for the signal beam with account for the cascade-induced inhomogeneity [9]:

$$\frac{\partial A_2}{\partial z} + \mathrm{i} D_2 \Delta_\perp A_2 = \mathrm{i} k_2 n_{\mathrm{nl}} A_2,$$

$$n_{\mathrm{nl}} = -[\gamma_2\gamma_3/(k_2 \Delta k)] |A_1(x,y,z)|^2, \tag{4}$$

where the inhomogeneity profile $n_{\mathrm{nl}}(x,y,z)$ repeats the pump intensity distribution in a nonlinear medium. In a defocusing medium, the mismatch is $\Delta k < 0$, and in the focusing medium, it is $\Delta k > 0$.

Consider the one-dimensional case when there is only one transverse coordinate x. The cascade process of the lattice formation starts with the interference of two pump waves crossed at the angle 2φ,

$$A_1(x,z) = 2A_1^{(0)} \cos(k_1 \varphi x) \exp(\mathrm{i} k_1 \varphi^2 z/2). \tag{5}$$

The modulated pump wave (5) together with the sum wave, according to (4), induce the refractive index lattice at the signal frequency

$$n_{\mathrm{nl}} = -4[\gamma_2\gamma_3/(k_2\Delta k)](A_1^{(0)})^2 \cos^2(k_1\varphi x). \tag{6}$$

In the numerical simulation, the lattice period $\Lambda = \pi/(k_1\varphi)$ is chosen so that a standing wave not subjected to diffrational distortions be produced in the cross section. The peculiarity of the cascade-induced lattice consists in the fact that it is manifested in a nonlinear medium only in the presence of a signal wave. This is explained by the fact that the first step in the cascade involves the generation of the sum wave with the amplitude $A_3 = -(\gamma_3/\Delta k) A_1 A_2$. Then, the sum wave together with the pump changes the refractive index at the signal frequency [see (4), (6)].

Therefore, a signal beam of width $a_2 = \Lambda/2$ is delivered to the medium input:

$$A_2(x) = A_2^{(0)} \exp(-x^2/a_2^2). \tag{7}$$

In the case of average modulation depth of the cascade-induced lattice, we observe discrete diffraction of the signal beam. The field distribution of the signal wave at large distances resembles the distribution in a fixed lattice, which is described by the Bessel function: $A_{2n}(z) = E_2 \mathrm{i}^n J_n(2\alpha z)$, where n is the waveguide number and α is the waveguide coupling coefficient [1]. This distribution is close to the pattern observed in induced lattices [5]. The modulation depth of the lattice increases with increasing the pump intensity and the signal beam is captured into the waveguide whose walls are the channels with the minima of the pump amplitude (Fig. 1). Therefore, by varying the power of the reference beams, we can change the coupling strength between the adjacent channels and obtain the required number of excited channels at the crystal output.

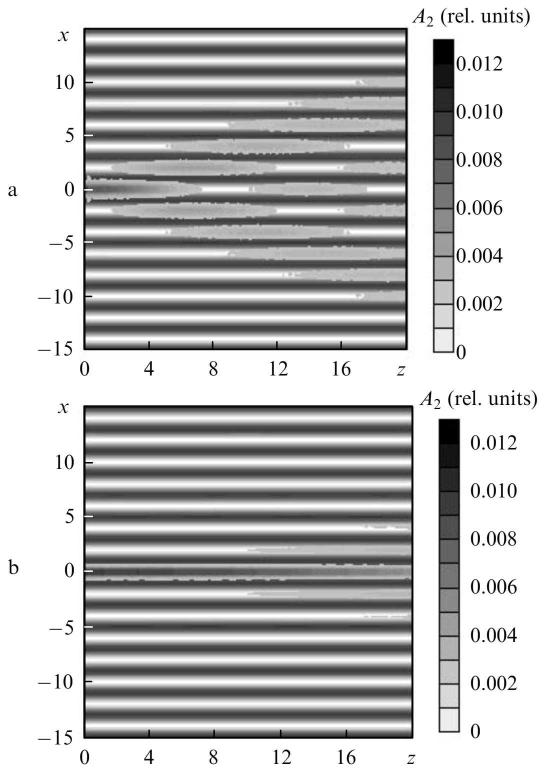

Figure 1. Degeneracy of discrete diffraction of the signal beam on a cascade-induced lattice to a waveguide trap (a); same in the case of fourfold magnification of the power of reference signals (b).

4. Inclined propagation of a signal beam

So far, we considered only symmetric redistribution of the signal beam energy over the channels with respect to those waveguides, which were excited at the crystal input. In this case, the wave vector of the signal beam will be directed along the axis of the waveguide structure. If this wave vector is directed at the angle θ to the lattice symmetry axis, the discrete diffraction anisotropy appears and the energy distribution over the channels at the output becomes asymmetric. The signal beam amplitude, in this case, is given by the expression:

$$A_2(x) = A_2^{(0)} \exp\left[-\left(\frac{x}{a_2}\right)^2 + \mathrm{i}k_2\theta x\right]. \quad (8)$$

Similarly, a dispersion relation $k_{2z} \sim \cos(k_{2x}\Lambda)$ can be written for induced lattices in a system of coupled waveguides [5]. For an inclined signal beam, $k_{2x} = k_2\theta$. Thus, the diffraction coefficient depends on the propagation direction of the signal wave:

$$D = \partial^2 k_{2z}/\partial k_{2x}^2 = D_0 \cos(k_2\theta\Lambda). \quad (9)$$

By analysing expression (9), we obtain that if the angle of inclination is

$$\theta = \pm\pi/(2k_2\Lambda), \quad (10)$$

the discrete diffraction coefficient (9) vanishes, $D = 0$. This implies the diffractionless propagation of the inclined signal beam at the frequency ω_2, when its width does not change with distance (Fig. 2). This is the regime of the transverse Bragg resonance, when the efficiency of the signal switching is maximal. Figure 3 demonstrates the dependence of the signal beam broadening in the case of diffraction on the angle of the waveguide front inclination at the medium input. One can see that the minimum of the beam spreading in the case of the discrete diffraction is achieved when condition (10) is fulfilled.

The anisotropic character of the discrete diffraction provides additional possibilities for controlling the excitation of the channels and energy distribution in them. All this can be used to design all-optical optical switchers for telecommunication systems.

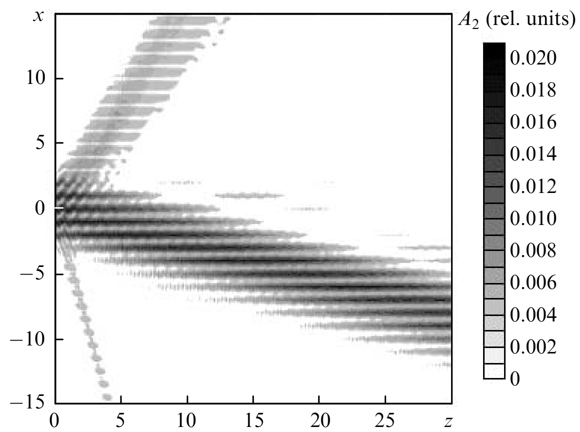

Figure 2. Diffractionless propagation of the signal beam (transverse Bragg resonance) in a one-dimensional system of induced waveguides.

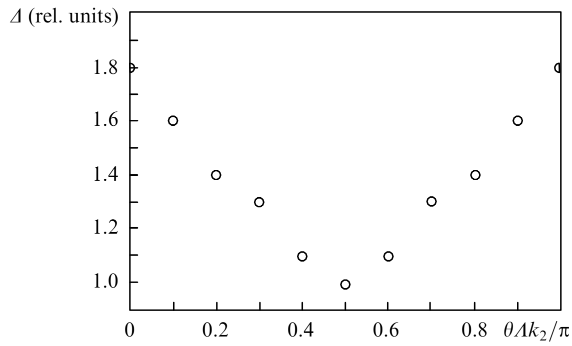

Figure 3. Relative broadening of the signal beam Δ in the case of diffraction on a one-dimensional induced grating as a function of the inclination angle of the wave front at the input to the medium.

5. Two-dimensional cascade-induced lattices

In quadratically nonlinear media, not only one-dimensional lattices of coupled waveguide but also two-dimensional optical matrices with different symmetries can be generated with the help of three-frequency cascade interaction. In such systems, the effects of signal wave switching between the waveguides are also observed. The character of the discrete diffraction significantly depends on the structure or the symmetry of the optical matrix.

Consider square lattices which are generated with four reference beams:

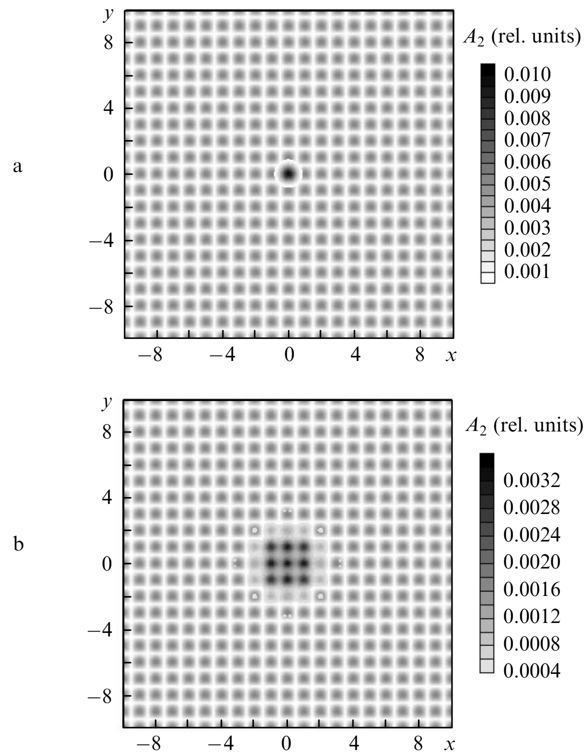

Figure 4. Discrete diffraction on a two-dimensional quadratic optical matrix: the signal beam at the input to the medium (a) and at the crystal output (b).

$$A_1(x, y) = 4A_1^{(0)} \cos(k_1 \varphi x) \cos(k_1 \varphi y) \exp(ik_1 \varphi^2 z/2). \quad (11)$$

In analogy with the planar case, in the case of cascade interaction, periodic modulation of the pump leads to the appearance of the periodic modulation of the refractive index at the signal frequency (6):

$$n_{nl} = -16 \frac{\gamma_2 \gamma_3}{k_2 \Delta k} (A_1^{(0)})^2 \cos^2(k_1 \varphi x) \cos^2(k_1 \varphi y). \quad (12)$$

When the central waveguide is excited, the discrete diffraction phenomenon is observed (Fig. 4). By increasing the pump intensity, we can decrease the number of excited waveguides at the output from the medium.

The specified waveguides at the output from the medium are excited by the anisotropic discrete diffraction, similarly to the planar case described above. The signal displacement in the case of inclined propagation of the beam is shown in Fig. 5.

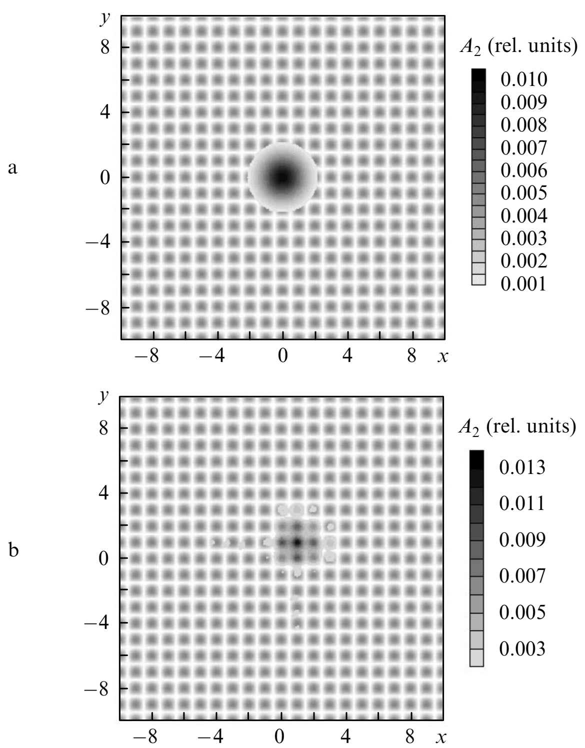

Figure 5. Displacement of the inclined signal beam on a two-dimensional quadratic optical matrix due to the discrete diffraction anisotropy at the input to the medium (a) and at the crystal output (b).

6. Conclusions

We have studied the cascade generation of the periodic lattice in the medium with a quadratic nonlinearity. The lattice was produced by crossed waves at the fundamental frequency and then was transferred by the sum wave to the signal frequency. By using the numerical simulation, we have observed different regimes of discrete diffraction upon initial excitation of one or several waveguides of a cascade-induced lattice. We have considered the anisotropic properties of discrete diffraction of a narrow signal beam at different modulation depths of the parametric lattice, in particular, we have determined the propagation directions along which the discrete diffraction is not manifested in one-dimensional lattices. The advantages of the cascade-induced lattice consist in its stability, simple adjustment of its parameters by varying the amplitude and the inclination angle of the reference waves. By using discrete diffraction it is possible to multiplex a signal in optical processing and information transfer systems. This method allows one to achieve the switching rate of the order of several terahertz.

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References

1. Lan S., Del Re E., Chen Z., Shih M., Segev M. *Opt. Lett.*, **24**, 475 (1999).
2. Sukhorukov A.P., Chuprakov D.A. *Laser Phys.*, **52**, 582 (2005).
3. Guo A., Henry M., Salamo G.J., Segev M., Wood G.L. *Opt. Lett.*, **26**, 1274 (2001).
4. Petter J., Schroder J., Trager D., Denz C. *Opt. Lett.*, **28**, 438 (2003).
5. Martin H., Eugenieva E.D., Chen Z., Christodoulides D.N. *Phys. Rev. Lett.*, **92**, 123902 (2004).
6. Eisenberg H.E., Silberberg Y., Morandotti R., et al. *Phys. Rev. Lett.*, **81**, 3383 (1998).
7. Fleische J.W., Segev M., Efremidis N.K., Christodoulides D.N. *Nature*, **422**, 147 (2003).
8. Pertsch T., Zentgraf T., Peschel U., Brauer A., Lederer F. *Phys. Rev. Lett.*, **88**, 093901 (2002).
9. Lobanov V.E., Sukhorukov A.P. *Izv. Ros. Akad. Nauk., Ser. Fiz.*, **69**, 1775 (2005).