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Analysis of output beam polarization in higher-order self diffraction via two-wave mixing in BSO crystal

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ABSTRACT

Generation of two higher-order diffraction beams in two-wave mixing in transmission geometry have been analyzed theoretically in photorefractive cubic crystal of 23 symmetry, BSO (Bismuth Silicon Oxide) and considering its optical activity as one of the important parameter. Results are shown graphically by solving coupled wave equations using fourth-order Runge–Kutta method. The effect of polarization state of pump beam, optical activity, off-Bragg parameter, coupling coefficients, absorption and thickness of crystal has been analyzed on the beam intensities and their respective polarizations. It has been observed that as the value of the off-Bragg parameter reduces the transfer of energy to the higher-order beams increases. It has been also observed that by selecting proper input beam polarization and crystal thickness, diffracted beam intensity and its polarization could be controlled considerably. It has also been seen that by controlling input pump beam polarization, particular higher-order beam can be selectively amplified.

1. Introduction

Photorefractive materials continue to stimulate a large research effort in the optical society because of strong nonlinearity at low laser power. Research on photorefractive materials, effects and devices [1–3] spans many scientific disciplines, including crystal growth, solid-state physics, material characterization, nonlinear optics and holography. The photorefractive effect has proved to be invaluable for demonstrating new techniques in interferometry, phase conjugation, locking of laser diodes, information processing [4], data storage, and image amplification. The photorefractive materials are also finding applications in fiber optics such as laser beam cleanup [5].

Lithium niobate, sillenite type crystals, semiconductor crystals, nanoparticle doped hybrid materials are active fields of research. New materials and techniques for their characterization including hybrid organic–inorganic photorefractive materials [6] continue to emerge. Driving forces of this work are in many cases interactions of the photorefractive effect with other phenomena, or the ability to learn about material physics by using the photorefractive effect as a method to study charge transport properties [7–9].

One of the areas of photorefractive materials which have not gained much attention is higher diffraction orders in photorefractive material. For small interaction angle and in a crystal with high two beam coupling, new waves in the form of higher diffraction orders are generated. Au and Solymar [10] presented the physics of the origin of these higher diffraction orders. In our work we have considered generation of higher-order through self diffraction [11–14]. Self diffraction refers to the process whereby the two writing laser beams, which interfere to form the photorefractive grating, diffract from the forming grating thereby modifying the interference fringe profile deeper within the crystal. Self diffraction was first studied in liquid crystal by Khoo and Liu [15,16]. Recently, H. Lorduy G. et al. [17] calculated the gain in a two-wave mixing process for BSO considering self-diffraction effects without taking any higher-order diffraction.

Some of the authors have studied applications of higher-order diffraction i.e., image rotation and amplification [18,19], optical beam splitter [20] based on the photorefractive higher-order grating. All these applications are not studied in an optically active medium. Optical activity has a major impact when we are concerned about the polarization of the beams.

In the present work, we have considered one of the sillenite crystals [21–23], which include Bismuth Silicon Oxide (BSO), Bismuth Germanium Oxide (BGO) and Bismuth Titanium Oxide (BTO). Sillenites are reversible holographic materials, efficient photoconductors [2]. Here we have only considered BSO crystal for our analysis. They exhibit a strong electro-optic effect, excellent

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Table 1
Absorption coefficient and optical rotatory power of BSO [22].

Parameters	BSO crystal
α (absorption coefficient) (cm^{-1})	0.65
a (optical rotatory power) (deg/cm)	386

piezoelectric properties [24], and a relatively high optical activity [25]. Owing to these features, sillenites find wide application in dynamic holography and real-time interferometry [26], optical information processing, optical sensors of electric and magnetic fields and piezoelectric devices. In our work we have neglected piezoelectric effect. The simple (cubic) structure of crystal facilitates experiments and theoretical analysis considerably. The coupling constant of BSO is not very high. However, by applying external electric field [22,23] and using moving grating technique [27], the higher values of coupling constant can be achieved.

In an earlier work we have studied the effect of pump beam polarization on the signal beam [28] in two-wave mixing, considering optical activity but without considering generation of any new higher-order. We have observed that by varying the polarization angle of pump beam we are able to control the polarization of the signal beam.

In this paper we have theoretically analyzed the energy transfer among beams with two newly generated higher diffraction orders in the optically active absorptive photorefractive medium. The analysis is done for diffusion regime i.e., the phase shift between interference pattern and refractive index grating is considered as $\pi/2$. We have considered two-wave mixing [29,30] (transmission geometry) in cubic crystal of 23 symmetry (sillenite crystal family) possessing a high value of optical activity (Table 1 [22]). The effect of various parameters on the intensities of the output beams have been studied such as thickness of crystal, coupling factors, absorption, optical activity, off-Bragg parameter. The parameters affecting the transfer of energy to the higher-order beams are analyzed. We have also analyzed the effect of input polarization state of pump beam A on output beam intensities and their polarizations. This analysis is valid for near collinear (very small angle between pump and signal) interacting beams in an absorbing crystal of 23 symmetry.

2. Formulation of coupled wave equations

We have considered two-waves A (pump) and B (signal) incident on a photorefractive crystal (Fig. 1), which create a phase grating inside the medium. Due to high coupling between the beams or basic nonlinearity of the material equations, the writing beam is

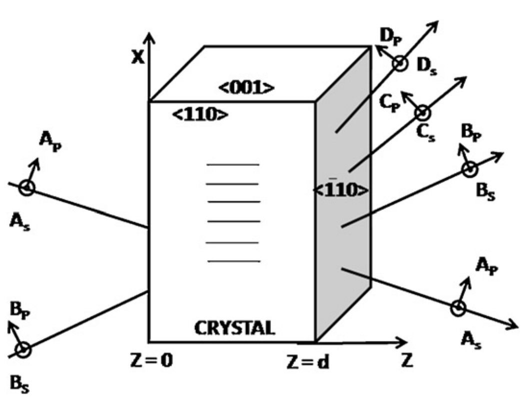

Fig. 1. Input beams and higher diffraction orders in two-wave mixing in transmission geometry (here A is the Pump Beam, B is the Signal Beam, C and D are the first and second higher-order diffracted beams).

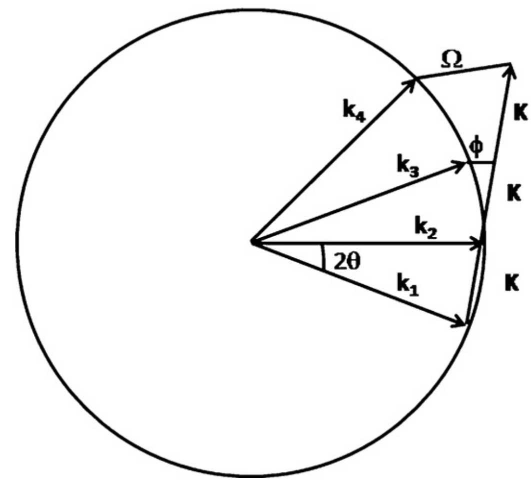

Fig. 2. Ewald sphere construction relating the interacting wave vectors and the grating vectors ($\mathbf{k_1}$, $\mathbf{k_2}$, $\mathbf{k_3}$ and $\mathbf{k_4}$ are the propagation vectors of the beams A, B, C and D respectively).

diffracted by the recorded phase grating. The transfer of power, or coupling of beams, is possible when there is a phase shifting between the interference pattern and the index grating impressed in the crystal. In other words, when the imaginary part of the coupling constant has a value different than zero. When the inter-beam angle in the two-wave mixing is small enough and grating spacing is large, other new waves are generated within the crystal and these new waves are known as higher diffraction orders. The input wave vectors and diffracted wave vectors are shown in Fig. 2.

The generated diffracted beams interfere with the writing beams and create new phase gratings which not only help in transferring energy to the diffracted beam but also modify the modulation of the original phase grating. A and B are the input writing beams, and C and D are the two possible higher-order diffracted beams. Here the higher-order diffracted beams C and D interfere with the input beams A and B and create new gratings inside the medium.

Each beam considered to be consists of two orthogonally polarized components, designated as "**s**" and "**p**" components. The electric fields of the four interacting beams, A, B, C and D can be represented as

$$\mathbf{E_1} = (\mathbf{s}A_S + \mathbf{p_1}A_P)\exp(-i\mathbf{k_1}\cdot\mathbf{r}) \tag{1}$$

$$\mathbf{E_2} = (\mathbf{s}B_S + \mathbf{p_2}B_P)\exp(-i\mathbf{k_2}\cdot\mathbf{r}) \tag{2}$$

$$\mathbf{E_3} = (\mathbf{s}C_S + \mathbf{p_3}C_P)\exp(-i\mathbf{k_3}\cdot\mathbf{r}) \tag{3}$$

$$\mathbf{E_4} = (\mathbf{s}D_S + \mathbf{p_4}D_P)\exp(-i\mathbf{k_4}\cdot\mathbf{r}) \tag{4}$$

where $\mathbf{k_1}$, $\mathbf{k_2}$, $\mathbf{k_3}$ and $\mathbf{k_4}$ are the propagation vectors of the two input beams, and the two higher-order diffracted beams. Also $\mathbf{s}$ is the unit vector perpendicular to the plane of incidence, $\mathbf{p_1}$, $\mathbf{p_2}$, $\mathbf{p_3}$ and $\mathbf{p_4}$ are the unit vectors parallel to the plane of incidence and perpendicular to the beam wave vector. The interference pattern [11,12] inside the medium can be written as

$$\begin{aligned}\mathbf{E}^*\mathbf{E} = {} & \{(A_SB_S^* + A_PB_P^*) + (B_SC_S^* + B_PC_P^*)\exp(-i\phi z) + (C_SD_S^* + C_PD_P^*) \\ & \times \exp[i(\phi-\Omega)z]\}\exp(i\mathbf{K}\cdot\mathbf{r}) + [(A_SC_S^* + A_PC_P^*)\exp(-i\phi z) \\ & + (B_SD_S^* + B_PD_P^*)\exp(-i\Omega z)]\exp(i2\mathbf{K}\cdot\mathbf{r}) + (A_SD_S^* + A_PD_P^*) \\ & \times \exp(-i\Omega z)\exp(i3\mathbf{K}\cdot\mathbf{r}) + c.c.\end{aligned} \tag{5}$$

where

$$\mathbf{k_2} = \mathbf{k_1} + \mathbf{K}, \tag{6}$$