Observation of spontaneously frequency-shifted beam fanning in photorefractive $Bi_{12}SiO_{20}$

Henrik C. Pedersen, Peter E. Andersen, and Per Michael Johansen

Optics and Fluid Dynamics Department, Risø National Laboratory, DK-4000 Roskilde, Denmark

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We present several new characteristics of beam fanning in a bulk sample of $Bi_{12}SiO_{20}$ with a dc electric field applied to it. Significant dependence of the beam fanning on the polarization state of the incident laser beam is observed. Moreover, the fanning light experiences a spontaneous frequency shift with respect to the incident light that ensures maximum beam coupling, because of which the fanning itself can exist. © 1995 Optical Society of America

When a photorefractive medium is illuminated with a single light beam optical noise is generated as a result of different crystal imperfections. Part of the noise interferes with the original illuminating beam to form parasitic gratings that diffract even more light out of the illuminating beam. Because of this self-diffraction process the noise is amplified to form what is referred to as beam fanning.[1]

Traditionally, beam fanning was believed to be an effect exhibited only by so-called high-gain materials such as $BaTiO_3$, $LiNbO_3$, and $KNbO_3$. In low-gain media such as the sillenites ($Bi_{12}SiO_{20}$, $Bi_{12}TiO_{20}$, and $Bi_{12}GeO_{20}$) the electro-optic coefficient is normally too small for fanning effects to be observed. However, by application of an ac electric field to the crystal it is possible to form a refractive-index grating that is phase shifted 90 deg with respect to the illuminating interference pattern. This situation gives rise to maximum beam coupling.[2] Under such circumstances beam fanning has been observed both in bulk samples[3,4] and in fibers[5] of sillenite crystals.

In this Letter we present what are to our knowledge new properties of beam fanning in a photorefractive crystal of $Bi_{12}SiO_{20}$ (BSO). The results are based on experimental investigations of the fanning beam.

The experimental setup used is shown in Fig. 1. A 10 mm $\times$ 10 mm $\times$ 10 mm crystal of BSO is illuminated by a single laser beam from a frequency-doubled diode-pumped YAG laser at 532 nm. The beam is expanded to a diameter of 2 cm to ensure that the entire crystal aperture is illuminated homogeneously. The intensity of the beam is 12.5 mW/cm^2. A dc electric field of 9 kV/cm is applied along the $\langle 001 \rangle$ crystallographic direction. The state of polarization of the incident beam is controlled by rotation of the $\lambda/2$ plate as shown in Fig. 1.

At an angle of incidence θ of 3.2 deg, the plane of incidence being perpendicular to the y axis, the fanning pattern shown in Fig. 2(a) appears on the screen. In this case the input beam is polarized along the x axis. The fanning spot appears at a fanning angle of approximately 30 deg. This observation agrees quite well with similar observations presented in Ref. 4. The actual fanning spot appears to consist of a dynamic speckle pattern with all the speckles moving around apparently without any well-defined direction. This observation was our first indication that some frequency-shifted light is involved in the fanning process. Judging from the direction of the fanning beam, the grating spacings of the fanning gratings assume values between 5 and 10 μm. Moreover, the shape of the fanning spot is highly dependent on the angle of incidence, θ. By increasing θ the fanning spot is extended along the 30-deg direction.

When the polarization state of the incident beam is switched from x to y polarized a highly spectacular change of the fanning pattern is observed. The fanning angle switches from $+30$ deg to -30 deg, as is shown in Fig. 2(b). Such dependence on the state of polarization has, to our knowledge, never been observed before. The extinction ratio at the center of the fanning beam was measured to be approximately 1:15 when we switched from an x- to a y-polarized input beam. Rotating the crystal 180 deg around the surface normal, $\hat{n}$, leads to an inversion of the fanning pattern, meaning that the fanning angle increases by 180 deg. At present we do not have any physical explanation for the polarization dependence of the beam fanning. In Ref. 6 it was stated that for $BaTiO_3$ inclusion of piezoelectric effects is needed for a complete theoretical description of beam fanning to be obtained. One might suspect that piezoelectric effects are also involved in the present case.

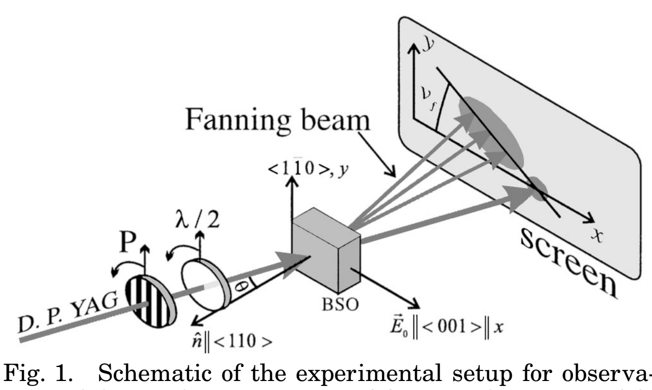

Fig. 1. Schematic of the experimental setup for observation of beam fanning in a BSO crystal. D. P. YAG, frequency-doubled diode-pumped YAG laser beam at 532 nm; P, linear polarizer; $\lambda/2$, half-wave plate; $\hat{n}$, unit vector perpendicular to the input surface; θ, angle of incidence; ν_f, fanning angle.

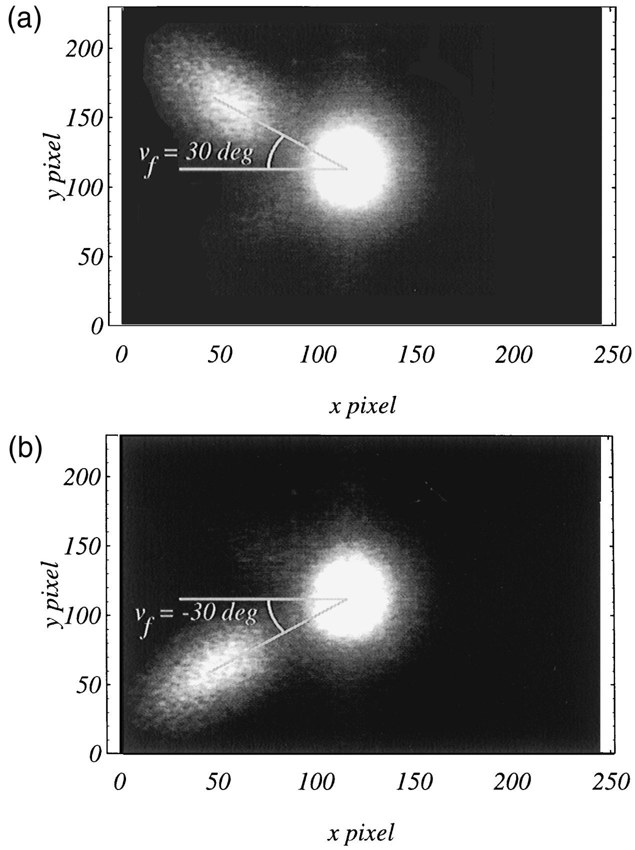

Fig. 2. Fanning patterns observed on the screen corresponding to illumination by (a) x-polarized light, (b) y-polarized light.

Motivated by the dynamic speckle patterns mentioned above, we investigated whether the fanning light is frequency shifted with respect to the incident beam. The experimental setup used for this experiment is shown in Fig. 3. We performed essentially the same experiment as shown in Fig. 1; however, we inserted a lens, L_1, behind the crystal to expand both the fanning beam and the directly transmitted beam. At some distance behind L_1 the expanded beams overlap to form an interference pattern. By placing a second lens, L_2, in the region of overlap we are able to magnify the interference pattern so that is can be observed on a screen (see Fig. 3). Even though the fanning beam is far from being a simple plane wave it is still possible to observe a fringe pattern on the screen, the length of each fringe being a couple of centimeters. The frequency shift is measured by insertion of an aperture into the interference pattern so that only a single fringe is let through at a time. The transmitted light signal is then recorded on a photodetector, where the photocurrent is spectrally analyzed on a fast Fourier transforming oscilloscope for determination of the frequency shift.

First, we observe that the fringes are indeed moving smoothly in a well-defined direction perpendicular to the fringes. This observation proves that the fanning light *is* shifted in frequency, as expected from the previous observations. Second, the direction of propagation reverses when the sign of the applied electric field is changed. This implies that the sign of the frequency shift is determined by the direction of the applied electric field. Third, the magnitude of the frequency shift exhibits a linear dependence on the intensity of the input beam. This is shown in Fig. 4.

Similar experimental results concerning frequency shifting have been observed previously in the so-called photorefractive resonator.[7,8] In this case an external cavity forms a resonator and a photorefractive crystal placed in the cavity acts as a gain medium and, hence, the fanning light is amplified to form the self-oscillation beam. Also in this case a frequency shift of the self-oscillating beam is observed. However, "both the sign and the magnitude of the frequency shift exhibit a one-to-one correspondence to the cavity-length detuning."[7] So in this case the frequency shift is determined completely by the cavity length because the resonator condition has to be fulfilled. In the present case, however, no resonator is present. So the present results are, to our knowledge, the first that demonstrate a frequency shift in a pure beam-fanning experiment, i.e., without any resonator. Conclusively, because of the absence of a resonator, some alternative physical explanation has to be found to explain the appearance of the frequency shift.

No beam fanning is observed if no electric field is applied. This means that the diffusion space-charge field is not sufficient to start the process. Therefore we have to apply an electric field to increase the space-charge field. However, application of a dc

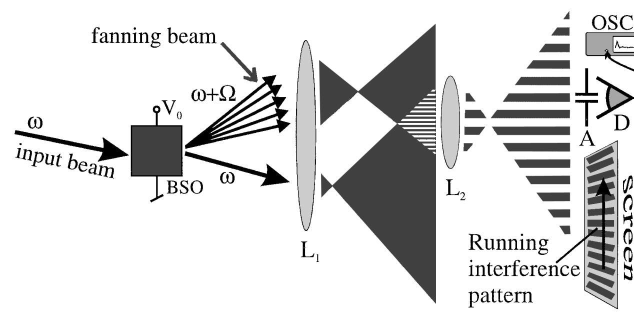

Fig. 3. Experimental setup for measuring the frequency shift of the fanning beam, Ω. ω, frequency of the incident beam; L_1, 100-mm lens; L_2, 10-mm lens; A, aperture; D, photodetector; OSC, fast Fourier transforming oscilloscope; V_0, applied voltage.

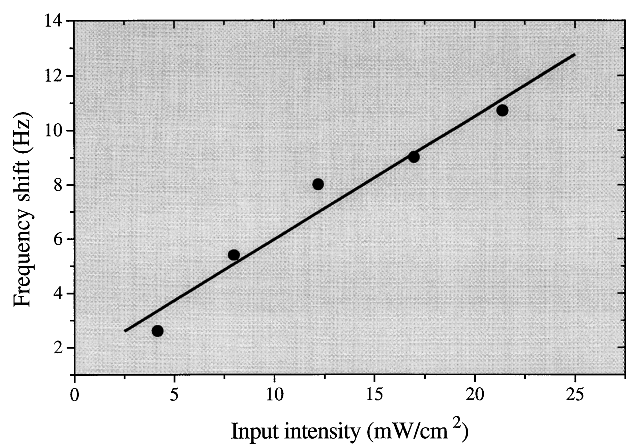

Fig. 4. Measured frequency shift of the fanning beam Ω versus the intensity of the input beam I_0. Circles, measured values; solid line, best linear fit.

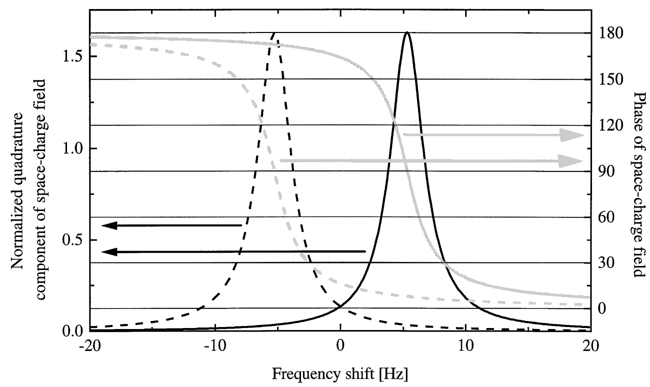

Fig. 5. Normalized quadrature component of the space-charge field (dark curves) and the phase between space-charge field and intensity distribution (light curves) versus frequency shift Ω for negative (dashed curves) and positive (solid curves) applied electric field.

electric field does not practically affect the two-wave mixing gain that is responsible for the fanning process. This is because only the quadrature part of the space-charge field, i.e., the part that is 90 deg out phase with respect to the interference pattern, contributes to the gain. Application of a dc electric field increases, however, mainly the in-phase component of the space-charge field. Consequently, an additional mechanism is needed to yield a proper exploitation of the applied field. This mechanism appears to be frequency shifting of the fanning beam.

In this case the normalized complex amplitude of the induced space-charged field is given by[9]

$$e_1 = \frac{1}{2}\, m\, \frac{E_q}{E_0} \times \frac{E_0 + iE_D}{\dfrac{\Omega}{\omega_0}(E_0 + iE_D + iE_M) - (E_q + E_D - iE_0)}, \quad (1)$$

where the normalization is obtained by division by the applied field, E_0. In Eq. (1) m is the intensity modulation coefficient, Ω is the angular frequency shift of the framing beam, ω_0 is a constant that is proportional to the dc intensity in the medium, I_0, and E_q, E_D, and E_M are characteristic fields.[9]

By inserting material parameters relevant to BSO[9] along with $m = 1$,[10] $I_0 = 12.5\ \mathrm{mW/cm^2}$, $E_0 = 9\ \mathrm{kV/cm}$, and a fringe spacing $\Lambda = 7\ \mu\mathrm{m}$ into Eq. (1) we obtain the curves shown in Fig. 5. Here the quadrature space-charge field component (i.e., the imaginary part of e_1) and the phase between the space-charge field and the interference pattern are plotted versus the frequency shift. As one can see, the quadrature component is significantly enhanced when a frequency shift is introduced. At resonance (approximately at $\Omega = \pm 5$ Hz) it is seen that the phase assumes exactly the desired 90 deg. So introduction of a frequency shift has the effect of shifting the phase of the induced space-charge field by the exact amount needed to produce maximum gain. According to Fig. 4 the measured frequency shift at $I_0 = 12.5\ \mathrm{mW/cm^2}$ is approximately 7 Hz, which is very close to the theoretically predicted resonance peak shown in Fig. 5. In conclusion, the fanning beam experiences an optimum spontaneous frequency shift in order to obtain the maximum gain leading to maximum beam fanning.

In the observations mentioned above it was stated that the sign of the frequency shift is controlled by the direction of the applied field. This agrees perfectly with the results in Fig. 5 because the resonance peak is shifted from $\Omega \approx 5$ Hz to $\Omega \approx -5$ Hz when the sign of E_0 is changed. Moreover, the observed linear dependence of frequency shift on dc intensity, shown in Fig. 4, is also expected from theory. This is seen by inspection of Eq. (1), where the term Ω/ω_0 (= constant × Ω/I_0) describes the linear dependence; i.e., increasing I_0, say, by a factor of 2 leads to a similar increase in Ω so that the system remains at resonance.

In conclusion, we have shown that beam fanning in BSO is highly dependent on the polarization state of the illuminating beam. Rotating the state of polarization by 90 deg changes the fanning angle completely from −30 deg to 30 deg. Moreover we have demonstrated, for the first time to our knowledge, that beam fanning in a crystal of BSO with a dc electric field applied to it is possible only because the fanning beam experiences a spontaneous frequency shift. This causes the phase between the induced space-charge field and the illuminating interference pattern to assume the desired 90 deg required for maximum gain. The observed dependencies of the frequency shift on the direction of the applied electric field and on the intensity of the illuminating beam show excellent agreement with our theoretical expectations.

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10. The choice of the modulation coefficient, m, is not essential to the present investigations because according to Eq. (1) m acts only as an overall scaling coefficient (i.e., for all frequencies Ω).