Photorefractive shooting stars

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Under certain conditions the direction of a beam diffracted from a photorefractive grating wanders as the grating decays. This phenomenon is due to competition between the original grating and those formed spontaneously by the Fabry–Perot modes produced by the crystal's surfaces. © 1998 Optical Society of America

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When two coherent light waves interfere inside a photorefractive crystal they produce a refractive-index grating that diffracts each of the incident waves into the other. When one of the beams, which we call the signal beam, is blocked, the grating diffracts the other beam, the reference beam, into a replica of the signal beam. The intensity of this re-created beam decays as the grating is erased by the incident reference beam. Under normal conditions the direction of propagation of the diffracted beam remains constant: It is fixed by the Bragg-matching conditions imposed by the direction of propagation of the reference beam and the photorefractive grating wave vector. We show in this Letter that, under certain conditions, the direction of propagation of the diffracted beam can stray from the original direction of propagation of the signal beam. When this wandering beam is observed on a screen it has the appearance of a shooting star. To the best of our knowledge, this is the first time that this phenomenon is reported. We explain this strange behavior in terms of a spatial mode-pulling effect produced by the cavity formed by the entrance and exit faces of the photorefractive crystal.

Figure 1 shows the experimental conditions under which this effect is observed. Two coherent, extraordinarily polarized laser beams of roughly equal intensity (≈ 1 W/cm^2) and $\lambda = 458$ nm intersect inside a nominally undoped and well-polished barium titanate crystal. The external angle θ_{ext} formed between the beams is approximately 25°, and the crystal is oriented such that energy is transferred from the reference to the signal beam by photorefractive two-beam coupling. A shutter is used to block the signal beam. The signal beam is almost ($\pm 2°$) normal to the entrance a face of the crystal.

Figure 2 shows an example of the time sequence of the diffracted beam. Figure 2a shows the original signal beam observed on a screen before it is blocked by the shutter. In Fig. 2b, the input signal beam is blocked, and what we observe is the reference beam diffracted by the previously recorded grating. Notice that the shape of the beam is essentially the same as in Fig. 2a, except that a small bulge appears on the upper right-hand side of the beam. Figures 2c and 2d show the evolution of the diffracted beam: The bulge grows and the beam wanders away from its initial position on the screen. Once the diffracted beam reaches the position shown in Fig. 2d , which takes 2–5 s after the input signal beam is blocked, it remains there and then decays. The direction into which the diffracted beam strays, as well as the time that it takes for the beam to move and the shape that the beam acquires, depends critically on the orientation of the signal beam and on the location of the beams on the entrance face of the crystal.

The key observations that provide insight into the explanation of this effect are, first, that the effect is observed only when the crystal is oriented such that energy is coupled from the reference beam to the signal beam and, second, that the signal beam is almost normal to the entrance surface. The explanation is the following: First the incident signal and reference beams record a grating. Once the signal beam is blocked, the grating recorded previously diffracts the reference beam into a replica of the signal beam. This replica is partially reflected by the exit surface of the crystal toward the entrance surface, where it is partially reflected again. Assuming that the faces of the crystal are perfectly parallel, the wave now propagates in the same direction as the original signal beam. The doubly reflected wave, which was diffracted at a time $t = t_0$, adds coherently with the

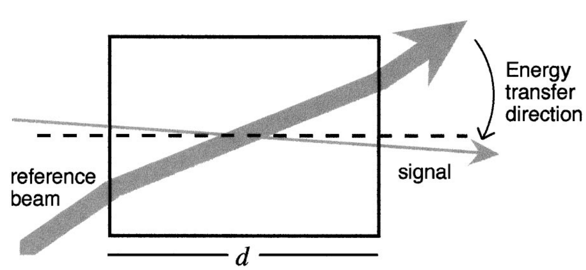

Fig. 1. Experimental setup. Crystal size, 3.85 mm × 5.36 mm × 5.12 mm.

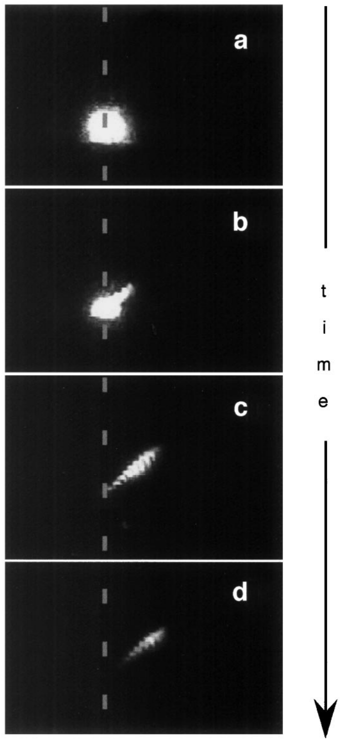

Fig. 2. Time evolution of the diffracted beam: a, original signal beam before it is blocked; b–d, evolution of the signal beam replica once the input signal is blocked. The vertical dashed line is an aid to the viewer.

reference beam and with the wave diffracted by the grating at $t = t_0 + L/c$, where L is the optical path length of the round trip between the crystal's faces and c is the speed of light. The light-intensity pattern produced by the interference of these three waves records another photorefractive grating with the same wave vector as before. However, this new grating will, in general, be shifted with respect to the previously recorded grating because the phase difference between the waves diffracted at $t = t_0$ and $t = t_0 + L/c$ depends on the exact optical path length L, given by

$$L = 2dn \cos \theta_{\mathrm{int}} , \quad (1)$$

where d is the thickness of the crystal, n is the index of refraction of the medium, and θ_{int} is the internal angle between the signal beam's wave vector and the normal of the entrance face. In the special case when the waves diffracted at $t = t_0$ and $t = t_0 + L/c$ are in phase with each other, i.e., when the round-trip optical path length $L = N\lambda/n$, where N is an integer, the spatial phases of the old and the new gratings coincide such that the amplitude of the total photorefractive grating, old plus new, and consequently the degree of beam coupling are enhanced. The grating once again diffracts the reference beam, and the process is repeated continuously. This process is shown in Fig. 3. In short, the feedback of the signal beam replica lengthens the lifetime of the grating when $L = N\lambda/n$.

If the incident signal beam propagates at an angle at which $L \neq N\lambda/n$, which is generally the case, the multiply-reflected waves inside the crystal will not be in phase with one another, and consequently the grating that they record will be washed out rather than reinforced. Once the incident signal beam is blocked, any instability in the resonator, such as noise created by beam fanning, slight deviations from parallelism between the entrance and the exit surfaces, or changes in the optical path length of the resonator, will pull the signal beam replica into the natural modes of oscillation of the resonator, i.e., those for which $L = N\lambda/n$, continuously causing the beam to deviate into a direction in which the net gain is largest.

In the extreme case when the gain provided by the photorefractive coupling exceeds the losses produced by absorption and transmission by the entrance and exit faces, the grating should not decay; in fact, a grating can arise spontaneously from noise, without requiring an initial signal beam. This occurs when

$$R^2 \exp(\Gamma d) \exp(-2\alpha d) \geq 1 , \quad (2)$$

where R is the reflectivity of the entrance and the exit faces (assumed to be equal) and Γ and α are the photorefractive gain and the absorption per unit length, respectively. This situation is almost equivalent to that which arises in the linear self-pumped phase conjugator described by Cronin-Golomb *et al.*,[1] the only difference being the replacement of the external cavity mirrors by the flat surfaces of the crystal, and to the photogalvanically driven oscillations observed by Odulov in lithium niobate.[2] At $\lambda = 458$ nm the extraordinary index of refraction[3] is $n = 2.48$, so the Fresnel reflectivity of the surfaces is approximately 18%. The crystal used in these experiments has a thickness $d = 5.35$ mm; therefore, according to relation (2) and assuming that $\alpha \approx 0$, the threshold of spontaneous oscillation is attained when $\Gamma \approx 6.4$ cm^{-1}.

The threshold can be achieved in practice by choice of the appropriate angle of incidence of the reference beam. Assuming charge photoexcitation from a single trap site level, only one charge carrier type (holes), low light-intensity modulation, and charge transport driven exclusively by diffusion, the steady-state photorefractive coupling constant Γ predicted by the band conduction model[4] is given by

$$\Gamma = \frac{2\pi}{\lambda} n^3 \frac{k_B T}{e} \frac{k_g}{1 + (k_g/k_0)^2} r_{\mathrm{eff}}(\hat{\mathbf{k}}_g) , \quad (3)$$

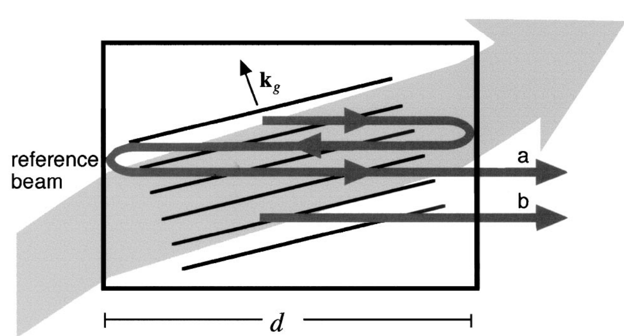

Fig. 3. Reinforcement of the grating by the reflected waves: a, wave diffracted at $t = t_0$; b, wave diffracted at $t = t_0 + L/c$.

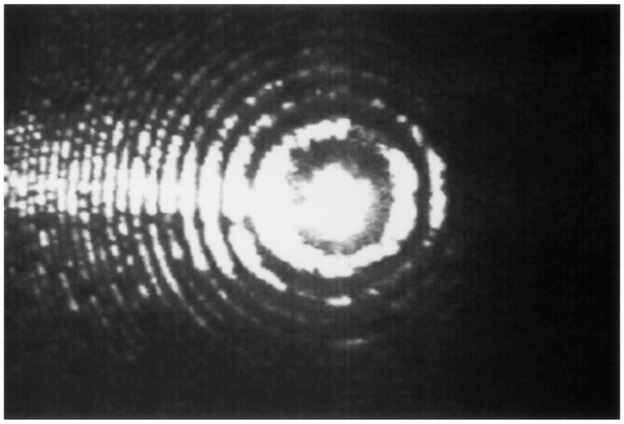

Fig. 4. Far-field pattern of a spontaneously formed oscillation when only the reference beam is incident. The separation between rings corresponds to the separation expected for a Fabry–Perot interferometer of the same thickness as the crystal.

where k_B is Boltzmann's constant, T is the absolute temperature, e is the unit charge, $\mathbf{k}_g$ is the grating wave vector, and r_{eff} is the effective electro-optic coefficient. The material parameter k_0 is the inverse Debye screening length, which depends, among other things, on the crystal's effective trap density N_{eff} that is available to create a photorefractive grating and on the dielectric constant of the medium. Since the absorption of the sample used in these experiments is low ($\alpha < 0.8\ \text{cm}^{-1}$), we assume that $N_{\text{eff}} \approx 2 \times 10^{16}\ \text{cm}^{-3}$, in accordance with measurements made previously of samples with low absorption.[5] Because of the anisotropy of the medium, both r_{eff} and k_0 vary in a complicated way with the orientation of the grating wave vector with respect to the crystallographic axes. Using the angular dependences of the electro-optic coefficient and the dielectric constant given in Ref. 6, we find that the gain reaches the threshold value of $\Gamma = 6.4\ \text{cm}^{-1}$ at $\theta_{\text{ext}} \approx 5°$ and reaches a maximum of $\Gamma = 31\ \text{cm}^{-1}$ at $\theta_{\text{ext}} = 32°$. However, in barium titanate the experimentally observed gain is always less (~30–~60% lower) than what is predicted by Eq. (3) because the effects of secondary trap centers (shallow traps) and electron–hole competition have not been taken into account in the derivation of relation (2). Furthermore, the value of r_{eff} obtained from Ref. 6 is valid for $\lambda = 515$ nm, which may differ from the value at $\lambda = 458$ nm. Nevertheless, we can expect that close to $\theta_{\text{ext}} = 32°$ the real photorefractive gain will be above the threshold for self-sustained oscillation, as we shall now prove.

Figure 4 shows the far-field pattern of a spontaneously formed oscillation when only the reference beam is incident, at $\theta_{\text{ext}} = 31°$. The pattern is identical to the output of a high-finesse Fabry–Perot interferometer: well-defined, narrow concentric circles with radii proportional to $\sqrt{j}$, where j is the order of the ring. The reason for the appearance of the rings is simple: Only those waves that propagate at an angle for which the round-trip optical path length is exactly an integer number of wavelengths will record and continuously reinforce stationary gratings; all other directions of propagation will create running gratings that eventually wash out.[7] It is interesting that although for a conventional, linear Fabry–Perot interferometer the finesse, defined as the separation between adjacent rings divided by their width, depends on the reflectivity of the reflecting surfaces, in this spontaneously formed resonator the finesse is always high, regardless of the reflectivity of the surfaces, as long as R is large enough for oscillation to occur. The finesse is limited by the homogeneity of the crystal and the flatness of its surfaces and ultimately by the relaxation of the Bragg-matching condition that is due to the finite width, collimation, and spectral purity of the reference beam.

Finally, a close inspection of Figs. 2c and 2d reveals that the wandering spot observed on the screen is not a smooth, round Gaussian beam, as in Fig. 2a, but rather an elongated spot with ring structure. This structure is nothing more than segments of the Fabry–Perot modes shown in Fig. 4. The wandering beam temporarily excites these oscillation modes, which later decay because of competition with other adjacent modes of higher net gain.

In conclusion, we have observed that under certain experimental conditions the direction of propagation of a beam diffracted from a photorefractive grating can wander as the grating decays. We have explained this phenomenon in terms of a competition between the original grating and other gratings formed spontaneously by the Fabry–Perot modes produced by the crystal's surfaces.

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References

1. M. Cronin-Golomb, B. Fischer, J. White, and A. Yariv, Appl. Phys. Lett. **41,** 689 (1982).
2. S. G. Odulov, Sov. J. Quantum Electron. **14,** 360 (1984).
3. K. Buse, S. Riehemann, S. Loheide, H. Hesse, F. Mersch, and E. Krätzig, Phys. Status Solidi A **135,** K87 (1993).
4. N. V. Kukhtarev, V. B. Markov, S. G. Odulov, M. S. Soskin, and V. L. Vinetskii, Ferroelectrics **22,** 949 (1979).
5. R. M. Pierce, R. S. Cudney, G. D. Bacher, and J. Feinberg, Opt. Lett. **15,** 414 (1990).
6. M. Zgonik, K. Nakagawa, and P. Günter, J. Opt. Soc. Am. B **12,** 1416 (1995).
7. R. A. Rupp, J. Marotz, K. H. Ringhofer, S. Treichel, S. Feng, and E. Krätzig, IEEE J. Quantum Electron. **QE-23,** 2136 (1987).