Observation of the Goos-Hänchen Effect in a Phase-Conjugate Mirror

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The Goos-Hänchen shift between a supercritically incident beam and its reflection in a total-internal-reflection mirror comprising a material interface is well established. We experimentally demonstrate that the Goos-Hänchen effect can also occur between the probe beam and the phase-conjugate beam in a phase-conjugate mirror. Controlled lateral displacements of up to 218 μm were measured using photorefractive four-wave mixing with a frequency-detuned Gaussian probe beam. [S0031-9007(98)07104-X]

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The notion that an optical beam may be laterally displaced upon reflection from an interface that presents a complex-valued reflection coefficient with an angle-dependent phase has been held since Newton's time [1]. A beam can be decomposed into a collection of uniform plane waves with different angles, and each of these components may be reflected differently. The beam displacement is the result of various small but different phase changes in the constituent plane waves of the incident beam—the sum of these slightly phase-shifted waves is a laterally displaced reflected beam [2]. Physically, there is a flow of wave energy parallel to the shift direction.

The measurement of such a displacement was first performed by Goos and Hänchen in an optical experiment involving total internal reflection at the boundary between high- and low-refractive-index media [3]. This lateral displacement of a reflected beam, which is not accounted for by simple geometrical considerations [see Fig. 1(a)], has since come to be known as the Goos-Hänchen effect. A variety of theoretical and experimental examinations of the Goos-Hänchen effect in total-internal-reflection mirrors have now been performed, including refinements of the theory [4]; optical studies of the effect in semiconductors [5], at curved interfaces [6], and at boundaries involving nonlinear media [7,8]; and in microwave and acoustical systems [9].

It has been conjectured that the Goos-Hänchen effect is not restricted to total internal reflection at the interface between different media—the phase conjugation of a probe beam by an angularly dispersive medium with a complex phase-conjugate reflection coefficient should laterally shift the conjugate beam relative to the incident probe beam [see Fig. 1(b)] [10]. In this Letter we present the first experimental demonstration of such spatial shifts generated by a phase-conjugate mirror [11].

Photorefractive phase-conjugate mirrors based on four-wave mixing are excellent candidates for the observation of the spatial beam shifts. During photorefractive four-wave mixing, a probe beam interacts with a pair of counterpropagating pump beams in a nonlinear medium to produce a beam that is the phase conjugate of the probe. When the pumps are undepleted monochromatic plane waves, the Fourier components of the phase-conjugate beam can be described as reflections of the components of the conjugated probe beam, which has reversed wave fronts [10]. Importantly for beam shifts, the phase-conjugate reflectivity depends on the probe angle, i.e., there is angular dispersion, as a consequence of the nonlocal nature of the wave mixing [12,13]; and the reflectivity is complex when there is a detuning between the probe- and pump-beam frequencies or if there is an applied or photovoltaic electric field across the photorefractive material [14,15]. These dependences permit the complex reflectivities of the Fourier components of the conjugated probe beam, and therefore the magnitude and direction of the phase-conjugate beam shift, to be controlled (the shift also depends on the physical properties of the medium and the specific four-wave mixing geometry) [10].

Measurements of the lateral displacements that occur in the photorefractive phase conjugation of an ordinary-polarized frequency-detuned Gaussian probe beam were performed using the setup shown in Fig. 2. An argon ion laser operated at 514.5 nm in a single longitudinal mode and with a Gaussian transverse profile was used to generate the probe and pump beams. To produce planar

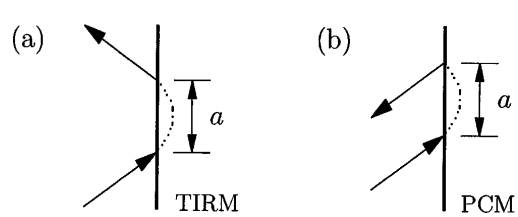

FIG. 1. Simplified illustrations of the Goos-Hänchen effect with lateral displacement a in (a) a total-internal-reflection mirror (TIRM) and (b) a phase-conjugate mirror (PCM). Beam centroids and propagation directions are represented by the arrows and flow within the mirrors is represented by the dotted curves.

wave fronts within the crystal, a lens pair was placed in each of the pump paths so that each beam had a 2.5 mm diameter waist at their intersection. The $5 \times 6 \times 7$ mm^3 45°-cut $BaTiO_3$:Ce photorefractive crystal was thereby pumped by two ordinary-polarized counterpropagating Gaussian beams with forward and backward pump powers $P_f = 47$ mW and $P_b = 56$ mW, respectively. The probe detuning was produced by a Doppler shift upon reflection from a piezoelectrically controlled moving mirror. The probe beam diameter was 2.2 mm, the probe power was 1.2 mW, and the angle between the probe and the forward pump was 12°.

For each detuning frequency Ω, a set of 25 conjugate-beam pictures was taken, with a 300-ms interval between pictures. The average centroid location of each set was calculated. Two groups of such measurements were obtained under identical conditions but with the CCD array placed at two different distances from the crystal. These allowed us to geometrically extract the lateral displacement a at the entrance to the crystal, as well as any angular tilt, from the measured conjugate-beam centroid locations. The overall beam-location error of our detection system was measured to be approximately ± 8 μm.

The lateral displacement of the conjugate-beam centroid as a function of the probe-beam detuning frequency is shown in Fig. 3. This result demonstrates the Goos-Hänchen effect in a phase-conjugate mirror over a wide range of detuning frequencies. The maximum lateral displacement was 218 μm. The spans of the measured centroid locations, represented in Fig. 3 by error bars, arose principally from frequency-detuning-dependent distortions of the phase-conjugate transverse beam profile; the distortions became more pronounced with increasing frequency detuning.

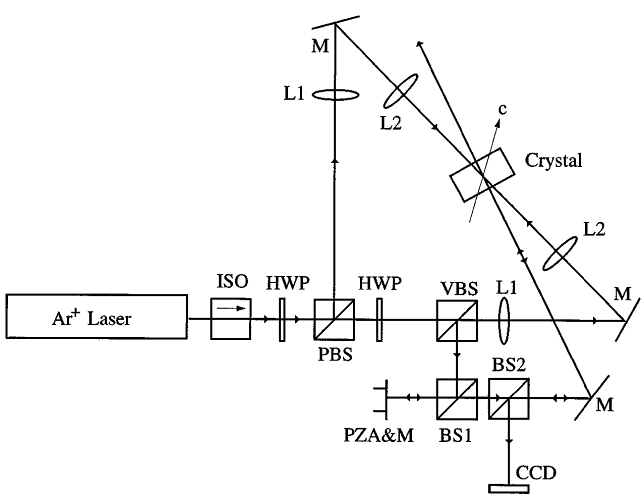

FIG. 2. The nondegenerate photorefractive phase-conjugate mirror experiment. After traversing an optical isolator (ISO), the laser beam was divided into two beams by rotating the polarization with a half-wave plate (HWP), dividing the beam with a polarizing beam splitter (PBS), and rotating the direct beam's polarization by 90° with another half-wave plate. A mirror (M) and a pair of lenses (L_1 and L_2) were placed in each of the pump paths. The probe beam was obtained by splitting the forward pump with a variable beam splitter (VBS) and directing it with a beam splitter (BS1). The probe beam was Doppler detuned by reflection from a moving mirror attached to a piezoelectric actuator (PZA), reflected back through BS1, and directed into the crystal. The conjugate beam, which propagated in a direction nearly opposite to that of the probe beam, was isolated using a beam splitter (BS2) and detected with a charge-coupled-device (CCD) array.

We now compare our results with those obtained from the undepleted uniform plane-wave-pump four-wave mixing theory [10]. The theory predicts the observed shape of the dependence of the displacement on the detuning frequency surprisingly well: The theoretical curve is nonmonotonic with a small dip, a characteristic maximum, and a gradual taper with increasingly large $|\Omega|$. However, the size of the shift computed for a 0°-cut undoped $BaTiO_3$ crystal, which has well-known parameter values but a lower wave-coupling efficiency than our crystal in the same four-wave mixing configuration, is about 2 orders of magnitude smaller than the measured shift. The theory also showed that the lateral shift increases with increasing coupling and diverges near self-oscillation, where the reflectivity is very sensitive to the parameter values [16]. Consequently, the relatively large size of the displacement in our case may originate from the stronger wave coupling and larger phase-conjugate reflectivity provided by our system. Nonlinear effects, such as the propagation of the phase-conjugate beam within a photorefractive self-focused channel when there is an appropriate intrinsic photovoltaic or externally applied electric field [17], could also play a role in phase-conjugate-beam shifts since the existence of a self-focused channel at a nonlinear interface has been predicted to permit an unusually large Goos-Hänchen effect in total-internal-reflection mirrors [7].

Furthermore, we have experimentally verified that the beam shift is antisymmetric with respect to the sign of the

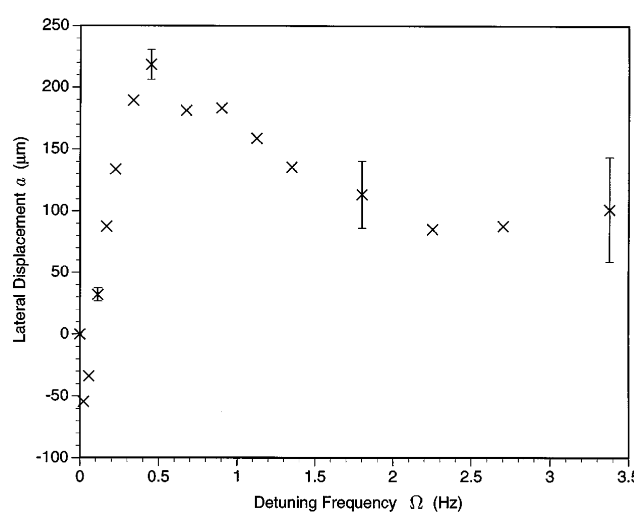

FIG. 3. Measured lateral displacement a of the conjugate-beam centroid as a function of the probe-beam detuning frequency Ω.

detuning frequency, as expected from the theory, and that the detuning frequency required for maximum shift, which depends on the response time of the material and therefore on the total incident optical irradiance, closely matches the theoretical value over a range of irradiances extending nearly 2 orders of magnitude [11]. However, whereas the simplified theory predicts no angular tilt, we found that the conjugate beam was indeed slightly tilted, with a dependence on the detuning frequency and a maximum angle of 0.16 mrad [11]. This tilt likely arises from effects associated with our use of transversely nonuniform Gaussian-profiled pump beams [18].

Although our results were obtained with a detuned probe beam in a photorefractive phase-conjugate mirror, any process that results in a complex phase-conjugate reflection coefficient with an angle-dependent phase can produce such displacements. Hence, similar shifts should be present in other types of phase conjugators, including those based on the Kerr effect. Furthermore, the readily controllable shifts demonstrated here are likely to be useful for phase-conjugate-beam steering and alignment. They also can impact the spatiotemporal dynamics of the optical fields within phase-conjugating systems, such as phase-conjugate resonators [19]. Consequently, these results have significant implications for the myriad applications that incorporate phase-conjugate mirrors [20–22].

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