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# Enhancement of the Goos-Hänchen effect upon reflection of a Gaussian beam from a dielectric plate

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In this work, we present analytical and numerical calculations in order to investigate the effect of a transverse spatial modulation of the phase of a Gaussian beam on the spatial and angular lateral shifts, as well as the reshaping, it undergoes in its plane of incidence upon reflection off a dielectric isotropic plate.

The system under consideration consists of an isotropic, dielectric, nonmagnetic plate illuminated with an incident two-dimensional *s*-polarized Gaussian beam. The phase of the optical field of the Gaussian beam exhibits a parabolic spatial modulation described by the term  $\exp(-i\xi x'^2/w_0^2)$ , where  $x'$  is the coordinate perpendicular to the direction of propagation,  $w_0$  is the waist radius, and  $\xi$  is the parameter that quantifies the phase modulation. Such a transverse phase modulation can be achieved by using a refractive lens with a parabolically-shaped surface profile or a flat-surfaced thin lamella exhibiting a parabolic gradient of its refractive index. The simulations were carried out for a dielectric plate made of fused quartz (relative permittivity  $\varepsilon_p = n_p^2 = 3.8$  at vacuum microwave wavelength  $\lambda_0 = 2.912$  mm, and thickness  $d = 8.33$  mm) surrounded by air, and a beam waist  $w_0 = 3\lambda_0$ .

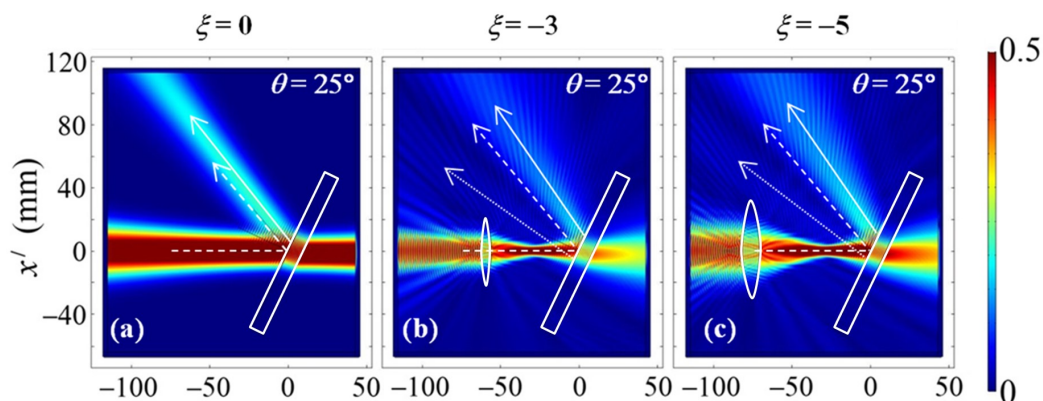


Fig. 1. Numerical simulation of the propagation of a phase-modulated Gaussian beam obtained for several various values of the phase modulation parameter  $\xi$ . The direction of the specular reflection is denoted by the dashed arrow. The solid and dotted arrows indicate two reflected beams (the former more intense than the other) after some reshaping upon reflection. The angle of incidence of the Gaussian beam on the plate is equal to  $25^\circ$ .

Such a phase-modulated Gaussian beam undergoes a significant transformation after reflection from the dielectric plate: its profile is distorted, which leads to a split of the reflected radiation into two beams of unequal intensity (see Fig. 1). Both reflected beams experience a lateral shift in the plane of incidence as well as an angular shift in the same plane, so that they propagate in directions different from the direction of specular reflection.

In our study, the spatial shift at the surface of the plate is calculated either through a purely analytical approach or by numerical solvation of Maxwell's equations, whereas the determination of the angular shift requires a numerical approach.

Angular and spatial shifts are also observed with an unmodulated Gaussian beam (the Goos-Hänchen effect), but in the case under study, they strongly depend on the value of the phase modulation parameter  $\xi$ . The results of an analytical and numerical analysis of the influence of the phase modulation parameter  $\xi$  on the spatial and angular shifts of the reflected beam are presented in Fig. 2.

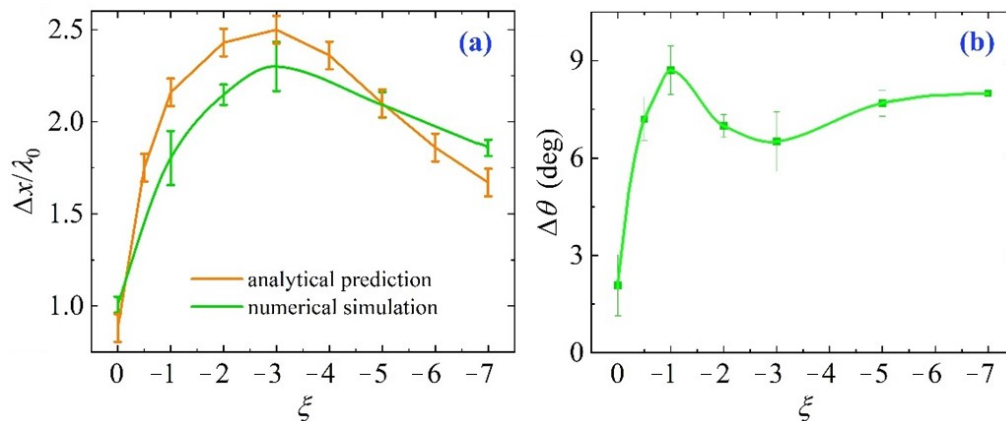


Fig. 2. Panel (a) represents a comparison of the results of numerical simulation (green curve) and analytical calculation (orange curve) of the lateral shift  $\Delta x / \lambda_0$  of the more intense reflected beam in dependence with the phase modulation parameter  $-7 \leq \xi \leq 0$ . Panel (b) shows the angular shift  $\Delta \theta$  of the same reflected beam for the same set of values  $\xi$  obtained by numerical simulation.

The analytical calculations of the lateral shift are in good agreement with the numerical simulations (Fig. 2(a)). The lateral shift of the brighter reflected beam is at least comparable to and can noticeably exceed the Goos-Hänchen shift that can be observed at the interface between semi-infinite media. The range of optimal values of the phase-modulation parameter  $\xi$  for which the lateral shift of the brighter reflected beam can be made to reach values 2.5 times larger than those observed with a non-modulated beam of the same wavelength and at the same angle of incidence is  $-4 \leq \xi \leq -2$ .

In the microwave domain, the lateral shift of the reflected beam thus enhanced and controlled by spatial phase modulation, can reach up to several millimeters, which means that its use in devices ranging from sensitive sensors to routers or de/multiplexers, is facilitated.

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