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# Non-specular reflection of a narrow spatially phase-modulated Gaussian beam

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11 Abstract: The lateral and angular Goos-Hänchen shifts undergone upon reflection on a dielectric plate by a spatially phase-modulated Gaussian beam are derived. It is shown that the 12 13 amplitude and the direction of both the lateral and angular shifts are very sensitive to the degree 14 of spatial phase modulation of the incident beam, so that such a modulation thus provides a 15 means to control those shifts. It is also shown that the modulation incurs some beam reshaping 16 upon reflection. Analytical calculations of the lateral shift are found to be in good agreement 17 with numerical simulations of the beam propagation before and after reflection. In these 18 simulations the required spatial transverse phase modulation is achieved by focusing a 19 microwave Gaussian beam onto the dielectric plate with a non-spherical lens or a flat-surfaced 20 thin lamella exhibiting a suitable gradient of its refractive index. The optimal parameters governing the spatial phase modulation are discussed in order to achieve: i) an enhancement of 21 22 the lateral shift of a spatially phase-modulated beam in comparison to that of a non-modulated 23 beam and ii) simultaneous large values of the reflectivity and of the lateral shift, while keeping 24 the reshaping of the reflected beam to a minimum.

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### 26 1. Introduction

Non-specular effects occurring upon the reflection of light wavepackets from various optical
structures have been intensively studied in the last two decades. These effects include both
lateral and transverse shifts of the reflected beams relatively to the position predicted by ray
optics (first described, in the context of the total internal reflection, as the Goos-Hänchen [1]
and the Imbert-Fedorov [2,3] effects, respectively) [4], as well as the corresponding angular
shifts in the plane of incidence or perpendicular to it, i.e., deviations of the reflection angle from
takes in the frame of geometric optics [5,6].

34 Although these effects are, as a rule, rather small, the beam shifts have nevertheless been 35 reported to take potentially significant values in many configurations, including upon total 36 internal reflection [1,7], but also at the vicinity of minima of the reflection coefficient, for 37 instance at Brewster and pseudo-Brewster incidence angles [8-10], near the edges of photonic 38 bandgaps in photonic crystals [11], or in a nanophotonic cavity [12]. In all cases, measurements 39 of the beam shifts can be made using conventional methods based on position sensitive 40 detectors, while charge-coupled device can give more detailed information about the profile of 41 the reflected beam [13]. More precise detection techniques include interferometric set-ups [14,15] or signal enhancement techniques [7,10,16–19]. 42

Far from being mere curiosities, such beam shifts can obviously be exploited in order to
yield information about the material(s) constituting the optical structure from which reflection
takes place or about the medium surrounding that structure. Indeed, as they can be shown to be
extremely sensitive to tiny variations of material properties (in particular, the permittivity) upon

47 any kind of external excitations (electric or magnetic fields, pressure, temperature, mechanical 48 strain,...), these effects are good candidates for the design of very precise sensors in particular, 49 which is one of the main reasons they have attracted much attention lately. Indeed, the lateral 50 shifts can be put to use for the design of bio- or chemical sensors [20,21], surface plasmon 51 resonance sensors [22] or simply for the precise measurement of refractive indices [23]. In 52 some systems, the dependence of the GH shift to temperature can be used for the design of 53 thermal sensors [24,25]. Beyond sensing applications, the principles of optical switches [26], 54 beam splitters [27], de/multiplexers [28], the monitoring of local electric and magnetic fields 55 [29] or optical differential operation and image edge detection [30] have been proposed on the basis of the GH effect. 56

57 To that intent, however, it is also desirable to be able to enhance, and particularly, control in a reversible way the beam shifts, as well as relate the values they assume with the changes 58 of permittivity of the materials the light beam encounters. The control of Goos-Hänchen beam 59 60 shifts has been studied in a variety of functional materials and structures. For instance, an external magnetic field can tune the Goos-Hänchen shift in magnetic media [17,31-36]. 61 62 Similarly, in combined magneto-optic and electro-optic systems the shift can be controlled via 63 external electric and magnetic fields [24,31,37,38]. A GH shift can be induced through the electro-optic effect [39] or by misfit strain [8]. 64

65 In all these instances, the focus has for the most part been set on ways to design the optical 66 system in which the beam shifts take place, as well as to select the properties of its constituents, 67 in order to achieve the desired control and enhancement of the effect and possibly use it for 68 applications. More rarely has the focus been set on the properties of the beam itself, specifically 69 on the way it can be tailored for an enhanced control of the Goos-Hänchen effect, but also on 70 the way the reflected beam can be distorted as a corollary to that effect. Among those rarer 71 studies, let us note the demonstration that the lateral Goos-Hänchen shift of light beams 72 reflected and transmitted through a layered dielectric structure can be effectively controlled by the focusing (and defocusing) of the incident beam [40], with an increase of the shift when the 73 74 beam is narrower. A significant reshaping of the reflected light beam has been discussed in a number of studies [41-44], including the observation that it can even split into two beams when 75 a giant shift occurs [45]. In multilayered structures, reshaping takes place due to the interference 76 77 between the waves reflected from all interfaces [46]. As a rule, beam distortion is also more 78 noticeable for narrow beams with waists of the same order of magnitude as their wavelength. 79 Thus, reshaping of the beam upon reflection requires additional studies.

80 In this paper, we discuss one such alternative method of exaltation of the lateral beam shift 81 related not to specific properties of the structure it interacts with, but to the properties of the 82 beam itself. Specifically, we present analytical and numerical calculations in order to 83 investigate the effect of a transverse spatial modulation of the phase of a narrow Gaussian 84 beam on the lateral and angular shifts, as well as the reshaping, it undergoes in its plane of 85 incidence upon reflection off a simple dielectric isotropic plate. Those calculations were carried out in the microwave domain. The paper is organized as follows. In Section 2, we provide an 86 87 analytical derivation of the reflected microwave electric field at the upper surface of the plate. 88 In Section 3, we show how it can be used for the calculation of the lateral beam shift for various degrees of phase modulation of the incoming wavepacket. In Section 4, we show the results of 89 90 the numerical simulations of beam propagation before and after reflection from the plate calculations and discuss the influence of the spatial phase modulation of the Gaussian beam on 91 92 its lateral and angular shifts, as well as its reshaping upon reflection. The conclusions of our 93 study (Section 5) are followed with an Appendix that describes ways to achieve the desired 94 phase modulation of the incoming Gaussian beam.

#### 95 2. Geometry and analytical description

96 In this study, we consider the reflection of a microwave Gaussian beam from a simple, 97 homogeneous, isotropic, dielectric, non-magnetic plate of refractive index  $n_P$  and thickness d, 98 as shown in Fig. 1. The refractive index of the surrounding medium is  $n_s$ . The upper and lower 99 surfaces of the plate are parallel to the (xy) plane of a Cartesian system of coordinates.

100 A two-dimensional (2D) monochromatic Gaussian s-polarized beam (wavelength  $\lambda_0$  in 101 vacuum and angular frequency  $\omega = 2\pi c/\lambda_0$  impinges on the top surface of the plate. The 102 propagation direction of the beam is determined by its central wavevector  $\mathbf{k}_c$ , with  $k_c = k_0 n_s$ , 103 where  $k_0 = 2\pi / \lambda_0$  is the wavenumber of the beam in vacuum. The incidence angle  $\theta$  is defined 104 as the angle between  $\mathbf{k}_c$  and the normal to the surface parallel to the z-axis. In the (xz) plane of 105 incidence, a system of x' and z' axes (obtained through a rotation of the x and z-axes by a rotation 106 of angle  $\theta$  around the v-axis) is associated to the beam, so that its central wavevector is parallel 107 to the z'-axis. The lateral dimensions of the plate, along the x- and y-axes, are supposed to be 108 much larger than the diameter of the Gaussian beam, so that side effects can be neglected. The 109 choice of a 2D beam description, in which the electric field profile does not depend on the y110 coordinate in the direction perpendicular to the plane of incidence (see Eq. (1) below) is 111 justified by the fact that this study is devoted to the non-specular effects (in particular the beam 112 shifts) that can be observed in that plane. Indeed, upon reflection, a Gaussian beam undergoes 113 a Goos-Hänchen lateral shift  $\Delta x$  in its plane of incidence (Fig. 1) that can be seen as a translation of the central wavevector of the reflected beam (solid red arrow) with respect to the direction 114 115 of specular reflection (dashed red arrow).



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Fig. 1. Schematic of the system. A 2D Gaussian microwave beam impinges on the upper surface of a dielectric plate of thickness *d*. The incidence plane is (*xz*) and  $\theta$  is the incidence angle. The lateral shift of the reflected beam is denoted  $\Delta x$ . Solid and dashed curves respectively show the profiles of the modulus and real part of the optical electric fields of the incident (blue curves) and reflected (red curves) beams. The dashed red arrow shows the direction of specular reflection without lateral shift.

123 In this paper, we specifically study the effect of a spatial modulation of the phase of the 124 incident Gaussian beam on the lateral (as well as angular) shift and the simultaneous reshaping 125 of the reflected beam. This modulation is quantified by the additional (in comparison with the 126 expression of the field for a usual Gaussian beam) complex exponential factor that depends on 127 the real-valued coefficient  $\xi$  in the following expression of the transverse electric field amplitude distribution  $E_{y}^{(i)}(x',z')$ , in which the origin common to the (xyz) and (x'y'z')128 129 Cartesian systems of axes coincides with the center of the incident 2D Gaussian beam in the 130 plane of its waist, and the time dependence of the propagating wavepacket is chosen as 131  $\exp(i\omega t)$ :

132 
$$E_{y}^{(i)}(x',z') = E_{0}\sqrt{\frac{w_{0}}{w(z')}}\exp\left[-\left(\frac{1}{w^{2}(z')}+i\frac{\xi}{w_{0}^{2}}\right)x'^{2}\right]\exp\left[i\eta(z')-ik_{c}\left(z'+\frac{x'^{2}}{2R(z')}\right)\right].$$
 (1)

133 In Eq. (1), z' is the algebraic axial distance from the waist, w(z') is the beam radius (defined 134 as the distance from the z'-axis for which the field amplitude falls to 1/e of its axial value), 135  $w_0 = w(0)$  is the waist radius, and  $E_0$  is the axial value of the field amplitude at the waist. An 136 important characteristic parameter of the Gaussian beam is its Rayleigh length 137  $z'_R = k_0 w_0^2 / 2$ , from which the z'-dependent beam parameters in Eq. (1) can be deduced, 138 namely the beam radius at position z',

139 
$$w(z') = w_0 \sqrt{1 + \left(\frac{z'}{z'_R}\right)^2}$$
, (2)

140 the radius of the wavefront curvature at position z',

$$R(z') = \frac{z'^2 + z_R'^2}{z'},$$
(3)

and its Gouy phase

141

143 
$$\eta(z') = \arctan\left(\frac{z'}{z'_R}\right). \tag{4}$$

It should be noted that although similar at first glance, phase factors  $\exp\{-i\xi x'^2 / w_0^2\}$  and 144  $\exp\{-ik_c x'^2 / 2R(z')\}$  in Eq. (1) are not equivalent, since the latter varies with the position z' 145 along the propagation axis of the incident beam and explicitly depends on the curvature radius 146 147 of the wavefront, especially so at large distances from the beam waist, and thus does not yield a parabolic modulation of the phase. It is also worth noting that the additional imaginary factor 148  $-i\xi x'^2/w_0^2$  in the spatial dependence of the field profile of a Gaussian beam is analogous to a 149 similar term describing linearly chirped Gaussian pulses in the time/frequency domain [47,48]. 150 The phase modulation parameter  $\xi$  is thus the spatial equivalent of the linear chirp parameter 151 152 of such a pulse.

153 With the choice of origin for both systems of axes mentioned above, the center line of the 154 Gaussian incident beam crosses the upper surface of the plate at the point  $\{x = x' = 0, y = y' = 0, z = z' = 0\}$  and the center of the beam in the waist plane thus coincides with z' = 0 on that 156 surface. In oblique incidence (for  $\theta \neq 0$ ), the other points of the beam waist are located above 157 or below the upper surface of the dielectric plate. Using Eq. (1) and the relations 158  $x' = x \cos \theta, z' = x \sin \theta$ , (5)

159 the complex amplitude of the incident electric field on the upper surface of the plate (z = 0) in 160 the (x,y,z) system of coordinates is:

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$$E_{y}^{(i)}(x,z=0) = E_{0}\sqrt{\frac{w_{0}}{w(x)}}\exp\left[-\left(\frac{1}{w^{2}(x)}+i\frac{\xi}{w_{0}^{2}}\right)x^{2}\cos^{2}\theta\right] \times \exp\left[i\eta(x)-ik_{c}\left(x\sin\theta+\frac{1}{2R(x)}x^{2}\cos^{2}\theta\right)\right],$$
(6)

162 where 
$$w(x)$$
,  $R(x)$  and  $\eta(x)$  are thus calculated for  $x = z' / \sin \theta$ .

163 In the paraxial approximation, in the vicinity of the beam waist (*i.e.*, when  $z' \ll z'_R$ ), one 164 can see from Eqs. (2)–(4) that  $w(z') \approx w_0$ ,  $R(z') \rightarrow \infty$ , and  $\eta(z') \approx 0$  for all points inside the beam 165 spot at the upper surface of the plate (*i.e.*, for z = 0). Thus, the electric field distribution of the 166 incident beam on that surface can be written as

167 
$$E_{y}^{(i)}(x, z=0) = E_{G}^{(i)}(x) \exp(-ik_{cx} x), \qquad (7a)$$

168 with

$$E_{G}^{(i)}(x) = E_{0} \exp\left[-\frac{(1+i\xi)x^{2}\cos^{2}\theta}{w_{0}^{2}}\right]$$
(7b)

170 and where  $k_{cx} = k_c \sin \theta$  is the x-component of the central wavevector of the incident beam in 171 the surrounding medium.

172 The spatial profile  $E_y^{(r)}(x)$  of the reflected beam at the upper surface of the plate can then 173 be obtained using the inverse spatial Fourier transform [8,24]:

174 
$$E_{y}^{(r)}(x) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} E_{y}^{(i)}(K) \Re(K + k_{cx}) \exp(iKx) dK,$$
(8)

175 where 176

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177 
$$E_{y}^{(i)}(K) = \int_{-\infty}^{\infty} E_{y}^{(i)}(x) \exp(-iKx) dx = E_{0}\sqrt{\pi}\sqrt{\frac{w_{0}^{2}}{(1+i\xi)\cos^{2}\theta}} \exp\left[-\frac{1}{4}\frac{w_{0}^{2}K^{2}}{(1+i\xi)\cos^{2}\theta}\right]$$
(9)

is the incident field distribution in the spatial frequency domain. In Eqs. (8) and (9), the spatial Fourier variable K is defined as  $K = k_x - k_{cx}$ , where  $k_x$  is the x-component of the wavevector **k** of any given spatial Fourier component of the incoming field distribution  $E_y^{(i)}(x)$ , and the corresponding  $\Re(K + k_{cx}) = \Re(k_x)$  is the complex reflection coefficient of the system at a given position x across the beam at the surface of the plate. This reflection coefficient  $\Re$  is deduced from Maxwell's equations and from the boundary conditions at each interface in the system as [49]:

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$$\Re(k_x) = \frac{r \left[ 1 - \exp(2ik_{tz}d) \right]}{1 - r^2 \exp(2ik_{tz}d)}, \text{ with } r = \frac{k_z - k_{tz}}{k_z + k_{tz}},$$
(10)

186 where, for any given spatial Fourier component of the incoming field distribution, 187  $k_z = k_0 n_S \cos \theta'$  and  $k_{tz} = k_0 n_P \cos \theta'_t$  are the components along the z-axis of its wavevector 188 **k** and of its corresponding refracted wavevector  $\mathbf{k}_t$ . The angles  $\theta'$  and  $\theta'_t$  are thus the incidence angle and the refraction angle in the plate respectively associated to  $\mathbf{k}$  and  $\mathbf{k}_t$  and 189 they are related by Snell's law  $n_S \sin \theta' = n_P \sin \theta'_t$ . The spread of values assumed by the 190 191 angles  $\theta'$  and  $\theta'_t$  reflects the divergence of the incoming Gaussian beam. Equations (8)–(10) 192 lead to the determination of the reflected beam intensity profile from which, after comparison 193 with the incoming beam intensity profile, the value of the lateral shift at the upper surface of 194 the plate, denoted  $\Delta x$ , can be numerically deduced. As a rule, an angular shift  $\Delta \theta$  with respect 195 to the specular geometry can also be observed. Its value cannot be deduced from the analytical 196 approach described above and discussed below in Section 3 (as that approach yields the field 197 distribution at the surface of the plate only), but it can be obtained from numerical simulations 198 of the propagation of the Gaussian beam after reflection (see Section 4).

### Analytical study of the effect of phase modulation on the reflected beam at the surface of the plate

In this Section, we apply the previous analytical description to a Gaussian beam in the
microwave domain, for which the lateral and angular beam shifts are expected to reach large
and easily measurable values. Note that the intermediate Fourier transforms expressed in Eqs.
(8) and (9) require numerical calculations.

205 Our simulations were carried out for a dielectric plate made of fused quartz (relative 206 permittivity  $\varepsilon_P = n_P^2 = 3.8$  at vacuum wavelength  $\lambda_0 = 2.912$  mm [44], and thickness d = 8.33207 mm) surrounded by air ( $n_s = 1$ ). For that value of thickness d, the reflection coefficient  $\Re$  208 deduced from Eq. (10) can be shown to reach a zero minimum at an incidence angle of 209 approximately 18.5°. Around that incidence angle, for small but non-zero values of  $\Re$ , beam 210 shifts are known to reach large values [9]. The waist of the incident Gaussian beam is chosen 211 as  $w_0 = 3 \lambda_0$ . In this case, the Rayleigh length is  $z'_R \approx 84.5$  mm, so that we can neglect the 212 variations of the beam diameter across the thickness of the plate.

213 The transverse spatial distribution of the normalized Gaussian amplitude  $E_G^{(0)}(x)/E_0$  of the electromagnetic field at the upper surface of the plate (z = 0) is shown in Fig. 2 as a function of 214 the incidence angle and for the spatial modulation parameter  $\xi = -5$ . Panels (a), (b), and (c) 215 present the modulus  $|E_G^{(i)}/E_0|$ , real part  $\text{Re}[E_G^{(i)}/E_0]$ , and imaginary part  $\text{Im}[E_G^{(i)}/E_0]$  of the 216 normalized amplitude, respectively, and panel (d) shows the cross-sections of distributions (a)-217 218 (c) for an incidence angle  $\theta = 20^{\circ}$ . As expected from Eq. (7b), the distribution of the Gaussian 219 field amplitude is symmetrical with respect to the x-axis (position x = 0 corresponds to the 220 center of the incident beam waist). Although the phase modulation of the Gaussian beam (for 221  $\zeta \neq 0$ ) does not affect the envelope (modulus) of the field amplitude it does, however, modify the real and imaginary parts of  $E_G^{(i)}(x)$ , and an increase of the modulation parameter  $\xi$  leads to 222 increasingly fast oscillations of  $\operatorname{Re}[E_G^{(i)}/E_0]$  and  $\operatorname{Im}[E_G^{(i)}/E_0]$  along the x-axis. In accordance 223 with Eq. (7b), a reversal of the sign of  $\xi$  reverses the sign of the imaginary part of the Gaussian 224 225 field amplitude. As a whole, the phase modulation of the field can be expected to exert a 226 noticeable influence on the overall reflected beam, as the latter results from the interference 227 between multiple waves reflected from the upper and lower surfaces of the dielectric plate.



beam at the upper surface of the plate (at z = 0) as a function of the incident spatially incoduced Gaussian beam at the upper surface of the plate (at z = 0) as a function of the incidence angle and for spatial modulation parameter  $\xi = -5$ : (a) modulus  $|E_G^{(i)}/E_0|$ , (b) real part  $\text{Re}[E_G^{(i)}/E_0]$ , and (c) imaginary part  $\text{Im}[E_G^{(i)}/E_0]$ . Panel (d) shows the cross-section of panels (a)-(c) for incidence angle  $\theta = 20^\circ$  (horizontal black dashed lines), where the red solid, blue dotted and green dashed curves denote the modulus, real and imaginary parts of the normalized field, respectively.

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236 This is clearly illustrated in Fig. 3, where the transverse distribution along the x-axis of the 237 normalized modulus  $|E^{(r)}/E_{\rm p}|$  of the reflected field at the upper surface of the plate (z = 0), 238 deduced from Eqs. (1)-(10), is shown as a function of incidence angle  $\theta$  and for different values 239 of the spatial modulation parameter  $\xi$ . The black curves follow the position of the maximum of 240 the beam intensity, *i.e.*, a departure of those lines from x = 0 indicates and quantifies the lateral beam shift  $\Delta x$ . In the absence of spatial modulation ( $\xi = 0$ , Fig. 3(a)), the reflected beam already 241 242 exhibits a significant distortion, with respect to the Gaussian profile of the incident beam, in particular in the vicinity of incidence angles corresponding to minima of the modulus of 243 reflection coefficient  $\Re$  — specifically, around  $\theta = 18.5^{\circ}$  and  $\theta = 60^{\circ}$  (the precise values of 244 245 those angles are determined using Eqs. (10)). Indeed, near  $\theta = 18.5^{\circ}$ , the reflected wave splits into two beams with almost equal maxima. With an increase of the absolute value of the spatial phase modulation parameter  $\xi$  (Fig. 3(b)-(g)), the distortion of the reflected field becomes stronger, and larger intervals of  $\theta$  appear for which the profile of the reflected field is split and exhibits two peaks. Due to this beam reshaping, the determination of the lateral shift, as calculated analytically at the surface of the plate, is sometimes ambiguous, since both maxima of the split beam can be of comparable amplitudes — this is especially true in the case of a nonmodulated beam, as evidenced by the black lines in Fig. 3.

This ambiguity, however, is less of a difficulty for incidence angles far from those for which 253 254  $|\Re|$  nears a minimum. In this case, the reflected field is still split in two, but one maximum is 255 visibly larger than the other one (see for example Figs. 3(e)-3(g), as well as the discussion of 256 Fig. 4 in the next Section), and for all intents and purposes the lateral beam shift  $\Delta x$  can be 257 defined as the shift in position of the brighter part of the reflected wave. The analytical 258 calculations depicted in Fig. 3 show that, for such incidence angles, an increase of the spatial phase-modulation (increase of  $|\xi|$ ) leads to an increase of the lateral beam shift. It can also be 259 260 noted that for  $0 \le \theta \le 15^\circ$  and  $\theta \ge 20^\circ$ , the lateral shift experienced upon reflection by a spatially phase-modulated beam is coupled with significantly larger values of the reflected field than is 261 the case for a non-modulated beam ( $\xi = 0$ ). This fact makes spatially phase-modulated beams 262 263 particularly useful for so-called weak measurements of the lateral beam shifts [7,17,19]. For 264 increasing absolute values of the modulation parameter, however, the reflected beam also 265 experiences an increased reshaping - see Figs. 3(d) and 3(g), so that a compromise, when choosing the value of the phase modulation parameter, must be found between increased lateral 266 267 shift, large reflected intensity and distortion of the beam.



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Fig. 3. Distribution of the normalized modulus  $|E_y^{(r)} / E_0|$  of the reflected field at the upper

surface of the plate (at z = 0) as a function of the *x*-coordinate and the incidence angle  $\theta$  for values of the spatial phase modulation parameter equal to: (a)  $\xi = 0$ , (b)  $\xi = +3$ , (c)  $\xi = +5$ , (d)  $\xi = +7$ , (e)  $\xi = -3$ , (f)  $\xi = -5$ , and (g)  $\xi = -7$ . Black lines follow the position of the absolute maximum of the field amplitude when  $\theta$  varies. The horizontal dotted and dashed lines in panels (a), (e), (f), and (g) correspond to incidence angles  $\theta = 20^{\circ}$  and  $\theta = 25^{\circ}$  and refer to the cases depicted in Fig. 4 and discussed in Section 4. The vertical white lines show the position of the center of the incident beam (x = 0).

Finally, Fig. 3 also shows that the general tendency for the dependence of the lateral shift on the angle of incidence is that its evolution when  $\theta$  increases is reversed (although nonsymmetrically with respect to x = 0) upon a sign reversal of the spatial modulation parameter  $\xi$ , as can readily be seen when comparing Figs. 3(b) and 3(e), Figs. 3(c) and 3(f), or Figs. 3(d) and 3(g). However, as should be expected, for incidence angles around normal incidence 282  $(\theta = 0)$ , calculations show that the distribution of the Gaussian beam field is symmetric with 283 respect to x = 0 for any value of  $\xi$ .

Overall, the results shown in Fig. (3) clearly highlight the marked sensitivity of the lateral
shift of the Gaussian beam upon a spatial modulation of its phase and the way a thoughtful
choice of the parameter governing that modulation provides a control of both the amplitude and
the sign of the shift.

288 It must be noted, however, that the lateral GH beam shift upon reflection is, as mentioned 289 earlier, coupled to an angular shift, also in the plane of incidence, with respect to the purely 290 specular direction, for which the central wavevector of the reflected beam would make the exact 291 same angle  $\theta$  (in absolute value) with the normal to the surface as the central wavector of the 292 incoming beam. In reality, the reflection of the beam departs from this simple behaviour 293 familiar to ray optics, and an angular shift  $\Delta \theta$  is indeed observed that can, in some cases, reach 294 several degrees and thus cannot be neglected, as it must be taken into account for the design of 295 any device exploiting the measurement of the GH effect for sensing purposes. The analytical calculations presented in this Section do not allow a simple evaluation of  $\Delta \theta$ . Estimates based 296 297 on numerical simulations of the propagation of the reflected beam, however, can be carried out, 298 and are presented and discussed below.

## A. Numerical simulation of the propagation of the reflected phase-modulated Gaussian beam

In this Section, we show the results of numerical simulations of the production of a phase modulated Gaussian beam and its propagation after reflection on the dielectric plate. These
 simulations were carried out using the COMSOL Multiphysics solver.

304 Several routes can be followed in order to obtain the transverse spatial phase modulation of 305 the form  $\exp(-i\xi x'^2)$  that appears in Eq. (1) in addition to the longitudinal phase term 306  $\exp(-ik_0 n_s z')$  of a conventional Gaussian beam. We propose here two ways of achieving that 307 goal by focusing a non-modulated Gaussian beam: 1) with a lens with one (plano-convex lens) 308 or two (biconvex lens) parabolically-shaped surface profile(s) in the (x'z') plane; or 2) with a 309 flat-surfaced thin lamella exhibiting a parabolic gradient of its refractive index also acting as a 310 converging lens (see the Appendix for details). In both cases, the constitutive parameters of the lens were chosen so that it produces a spatially phase-modulated beam with a negative 311 312 modulation parameter ( $\xi < 0$ ).

313 Figure 4 shows the results of numerical simulations where a spatial phase modulation is added to an initially non-modulated Gaussian beam when it is focused with a symmetrical 314 315 biconvex lens whose thickness (in the direction of the z'-axis) follows a parabolic dependence as a function of x' (see Eq. (14) in the Appendix Section). In order to properly assess the 316 317 influence of the resulting phase modulation, the position of the lens relatively to the plate as 318 well as the waist of the incoming (non-modulated) Gaussian beam were adapted for each value 319 of the resulting negative modulation parameter  $\xi$ , in such a way that the focused (phase-320 modulated) beam keeps the same waist  $w_0$  at the upper surface of the dielectric plate in all cases. 321 Note that the height h of the lens should be significantly larger than the diameter  $2w_0$  of the 322 incoming beam in order to reduce non-paraxial aberrations. Thus, for each value of  $\xi$ , the height 323 of the lens must be adapted in addition to its curvature.

324 In practice, the lateral beam shift measurements are easier to realize at relatively small incidence angles. Here we show in Fig. 4 the reflection of the Gaussian beam simulated for two 325 326 values of the incidence angle:  $\theta = 20^{\circ}$  (top panels) and  $\theta = 25^{\circ}$  (bottom panels). The first of 327 these values is close to the minimum of reflectivity  $|\Re|$  of the plate, as was discussed above, 328 whereas for the second value reflection is characterized by both large values of the lateral shift 329 and large values of  $|\Re|$ . The analytically calculated profiles of the field modulus at the surface 330 of the plate for those angles of incidence correspond to the horizontal dotted and dashed white 331 lines in Fig. 3.

As was predicted by the calculations based on the analytical model described in Section 3, the Gaussian beam undergoes a reshaping of its field profile even when its phase is not spatially modulated ( $\xi = 0$ , Figs. 4(a) and 4(e)). As can be seen in all panels of Fig. 4, the reflected intensity is split between two beams as a result of this reshaping, one of which corresponds to a positive lateral shift  $\Delta x$  (solid arrows) with respect to the specular direction (dashed arrows) and the other corresponds to a negative lateral shift  $\Delta x$  (dotted arrows). In what follows, these two beams will be referred to as the *first* and *second* reflected beams, respectively.



Fig. 4. Numerical simulation of the total electric field amplitude distribution (normalized with respect to  $E_0$ ) for values of the spatial phase modulation parameter equal to (a) and (e)  $\xi = 0$ , (b) and (f)  $\xi = -3$ , (c) and (g)  $\xi = -5$ , (d) and (h)  $\xi = -7$ , and for incidence angle  $\theta = 20^{\circ}$  (top panels) and  $\theta = 25^{\circ}$  (bottom panels), in the case where the phase of the incident Gaussian beam is spatially modulated using a parabolically-shaped biconvex lens. The white dashed line denotes the center of the incoming beam and the white dashed arrow indicates the direction of its specular reflection. The solid and dotted arrows show the propagation directions of the first and second reflected beams, respectively. Note that the color scale for the normalized field amplitude has been truncated to the [0; 0.5] interval in order to enhance the readability of the graphs.

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At incidence angle  $\theta = 20^{\circ}$  (Fig. 4(b)-(d)), these two beams are of comparable amplitudes for all values of the modulation parameter  $\xi$  (with the first reflected beam corresponding to  $\Delta x > 0$  only slightly brighter), but as mentioned above, the overall reflected intensity is low, as this incidence angle coincides with low values of  $|\Re|$ .

For all intents and purposes, the case where incidence angle  $\theta$  is equal to 25° (Fig. 4(f)-(h)) 353 is more interesting, since the detection of beam shifts is bound to be easier in this case due to 354 355 the larger values of the reflected intensity. At that incidence angle, the intensities of the two reflected beams greatly differ, with the first beam (solid arrow, for  $\Delta x > 0$ ) much brighter than 356 357 the second one (dotted arrow, for  $\Delta x < 0$ ), and thus more suitable to potential applications. The 358 position of the center (defined as the location where intensity is maximum) of the first reflected 359 beam at the surface of the plate can be numerically deduced from the simulations and its comparison with that of the incoming beam yields the positive value of the lateral shift  $\Delta x$  it 360 361 undergoes. Similarly, the direction of propagation of either first or second reflected beam, 362 obtained through a numerical determination of its center, can be compared to the specular 363 direction, which leads to the value of the angular shift  $\Delta \theta = \theta_r - \theta_r$ , where  $\theta_r$  denotes the absolute 364 value of the angle between the central propagation axis of a reflected beam and the normal to the top surface of the plate. The angular shift thus determined is positive for the first reflected beam, whereas it is negative for the less bright second reflected beam — meaning that  $\theta_r > \theta$ and  $\Delta \theta > 0$  for the first reflected beam, and  $\theta_r < \theta$  and  $\Delta \theta < 0$  for the second one (whereas  $\theta_r = \theta$  in the case of the specular reflection).



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370Fig. 5. (a) Comparison of the normalized lateral spatial shift  $\Delta x/\lambda_0$  of the first reflected beam as371a function of the phase modulation parameter  $\xi$  (for  $-7 \le \xi \le 0$ ) obtained with the analytical372calculation (orange curve) and with the numerical simulation (green curve). (b) Angular shift  $\Delta \theta$ 373of the first reflected beam for the same set of values of  $\xi$  obtained using the numerical simulation.374The incidence angle is  $\theta = 25^{\circ}$ .

375 The results of the analytical and numerical determinations of the normalized lateral spatial 376 shift  $\Delta x/\lambda_0$  of the brighter first reflected beam are compared in Fig. 5(a) as functions of  $\xi$  for 377  $-7 \le \xi \le 0$  and for  $\theta = 25^{\circ}$ . The error bars are those of the numerical procedure used for the 378 determination of the reflected beam center at the upper surface of the plate (z = 0), with an 379 uncertainty related to the reshaping of that beam (as shown in Fig. 3). The values of  $\Delta x$  obtained 380 with both approaches are in a satisfactorily good agreement for all values of  $\xi$  considered in 381 our calculations, and, for  $-3 \le \xi \le 0$ , indicate a steady increase of the shift (by a factor that can 382 slightly exceed 2) when the absolute value of parameter  $\xi$  increases, *i.e.*, when the transverse 383 modulation of the phase of the incoming Gaussian electric field increases. For larger values of  $|\xi|$  (for  $-7 \le \xi \le -3$ ), both methods seem to indicate a general tendency for  $\Delta x$  to decrease 384 385 slightly. This can be related to the fact that the reshaping undergone by the reflected beam 386 becomes markedly stronger when the modulation parameter increases in absolute value. Thus, 387 for an effective control of the enhancement of the lateral shift, one should retain values of the 388 modulation parameter within the interval  $-5 \le \xi \le -1$ . Overall, our calculations show that the 389 lateral shift  $\Delta x$  can exceed twice the value of the wavelength in vacuum of the incoming beam, 390 that is, reach values of the order of 1 cm.

Similarly, Fig. 5(b) represents the variations of the angular shift  $\Delta \theta$  of the first reflected beam for the same incidence angle  $\theta = 25^{\circ}$  and over the same range  $-7 \le \xi \le 0$  of the phase modulation parameter. Here again, the error bars stem from the procedure used for the determination of the central axis of the primary reflected beam. The angular shifts deduced from the numerical simulations are noticeably enhanced when the incoming Gaussian beam is phase-modulated (by a factor larger than 4 when  $\xi$  increases from 0 to 7 in absolute value) and reach several degrees, which makes them easy to detect for potential applications of lateral shift measurements. Note that similar tendencies for the lateral and angular shifts can be obtained for the second, much less intense, reflected beam.

400 As mentioned earlier, similar results can be obtained when the spatial modulation of the 401 Gaussian beam is achieved using a flat-surfaced thin lamella with a spatial gradation of its refractive index  $n_{gr}(x')$  obeying a parabolic law along the x'-axis. For the case  $\xi < 0$ , the 402 refractive index profile of such a thin lamella is described by Eq. (A5) in Section 6. Again, 403 404 simulations show a split of the reflected field in two separate beams with different propagation 405 directions (on either side of the specular direction), one being markedly more intense than the 406 other. Figure 6 illustrates this approach with the example of numerical simulations of beam 407 propagation carried out when the refractive index at the center of such a focusing lamella is  $n_{orc} = n_P$  and for  $\xi = -3$ . The other parameters are identical to those used in Figs. 3 and 4. In 408 409 this case the refractive index in the lamella decreases parabolically along the x'-axis from the 410 center of the lamella to its extremities, so that  $n_{gr}(x' = \pm H/2) = 1.5$ , where H = 33.4 mm is the 411 total height of the lamella, whose thickness is chosen as D = 9.2 mm. For this set of structural 412 parameters, calculations lead to values of the lateral spatial shift  $\Delta x$  of the first (*i.e.*, brighter) 413 reflected beam, estimated as previously at the surface of the plate coinciding with the (xy) plane, 414 approximately equal to 2.82  $\lambda_0$  for incidence angle  $\theta = 20^\circ$  and 2.33  $\lambda_0$  for  $\theta = 25^\circ$ , which is in 415 a good agreement with the corresponding values estimated with a parabolic lens.





#### 426 5. Conclusions

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We have shown theoretically and numerically that a spatial transverse modulation of the
phase of a Gaussian beam provides a way to control the amplitude and direction of the lateral
Goos-Hänchen shift to which the reflected beam is subjected with respect to the conventional
specular reflection geometry of geometrical optics. We show in the Appendix how, in practice,
such a modulation can be achieved by placing a parabolic lens, or a dielectric lamella with a
parabolic gradient of its refractive index distribution, in front of a usual Gaussian beam.

433 Our theoretical analysis and numerical simulations show that the spatial lateral shift of the
434 reflected beam is of the order of one wavelength of the incoming non-modulated Gaussian
435 beam, and that it can be increased up to 2.5 times by introducing a spatial modulation to the
436 beam. For the chosen waist of the microwave beam used for the calculations, this translates into

an exaltation of the spatial shift from 2.9 mm to 7.3 mm, which would facilitate its detection inthe context of practical applications.

439 Our numerical simulations of the beam propagation indicate that the angular shift that 440 typically accompanies the lateral Goos-Hänchen shift in the plane of incidence is also sensitive 441 to the modulation of the phase of the beam. Specifically, we have shown that the angular shift 442 can be increased more than four times by the phase modulation of the Gaussian beam and can 443 reach up to 9°, which, again, makes the measurement of such a shift easier.

444 We have established the optimal range [-5, -1] of values of the dimensionless parameter  $\xi$ 445 that governs the spatial phase modulation for which the lateral shift of the reflected beam is 446 significantly larger than that of a non-modulated beam, but also coincides with large values of 447 the reflection coefficient, while the reshaping of the reflected beam remains limited and thus 448 does not prevent practical application of beam shift measurements.

Such applications can for example be found in the microwave domain, where our
calculations have shown that the lateral shift of the reflected beam, enhanced and controlled by
a well-chosen phase modulation, can reach up to several millimeters and its experimental
measurement in devices such as sensitive sensors, routers, or de/multiplexers, is thus facilitated.

453 It should be noted that the conclusions presented here remain valid for other spectral ranges, 454 for instance in the visible or near-infrared domains. However, the required precision of the 455 techniques used for the detection of the spatial and angular beam shifts in those domains would 456 be higher.

### 457 6. Appendix: Obtaining a spatially phase-modulated gaussian beam

458 We discuss here two ways of achieving a transverse spatial phase modulation of the electric

459 field of a Gaussian beam of the form  $\exp(-i\xi x'^2/w_0^2)$ , as indicated in Eq. (1).

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A first way consists in focusing a conventional (*i.e.*, without phase modulation) Gaussian 460 461 beam with a non-spherical lens tailored to yield the required phase modulation. Let us consider 462 such a lens, made of a transparent material with refractive index  $n_{L}$  and immersed in an homogeneous medium with refractive index  $n_S$  (with  $n_S < n_L$ , which is the case when the 463 surrounding medium is vacuum or air). Its optical axis coincides with the z'-axis (the central 464 465 axis of the incoming beam, see Fig. 1), i.e., the incoming conventional Gaussian beam is 466 incident along the optical axis of the lens. The lens is located close to the waist of the beam, 467 that can thus be considered to be collimated and its wavefront to be plane across the lens, provided the latter's thickness is at all points much smaller than the Rayleigh length  $z'_R$  of the 468 469 beam.

470 Let us first consider the case of a symmetrical biconvex lens (Fig. 7(a)), introduce the 471 function  $\rho_{bc}(x')$  describing the lens thickness profile and denote  $\rho_{bc0} = 2 \rho_{bc}(0)$  its total thickness 472 on the optical axis. In the paraxial approximation, the additional transverse spatial phase 473 modulation introduced by the lens verifies:

$$\frac{\xi}{w_0^2} x'^2 + 2m\pi = 2k_0(n_L - n_S)\rho_{bc}(x'), \ m \in \mathbb{Z}.$$
(11)



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476 Fig. 7. Schematic of (a) a biconvex lens and (b) a plano-convex lens with a parabolic thickness 477 profile, height h and refractive index  $n_L$  surrounded by a medium with refractive index  $n_S$ . Note

478 that the actual origin of the (x'y'z') Cartesian system of axes is the same as in Fig. 1.

479 As a result, the dependence of  $\rho_{bc}$  on the distance x' from the optical axis is thus parabolic 480 (for  $-h/2 \le x' \le h/2$ , where h is the height of the lens), with

481 
$$\rho_{bc}(x') = \frac{\xi x'^2 + 2m\pi w_0^2}{4\pi (n_L - n_S) w_0^2} \lambda_0 = \frac{\lambda_0}{4\pi (n_L - n_S) w_0^2} \xi x'^2 + \frac{\rho_{bc0}}{2}.$$
 (12)

482 For  $\xi < 0$ , the lens is at its thickest at its center and it is thus converging. The numerical 483 simulations discussed in Section 4 (Figs. 4 and 5) were carried out for such a symmetrical 484 biconvex lens, made of the same fused quartz as the dielectric plate  $(n_L = n_p)$  and surrounded 485 with air  $(n_s = 1)$  as well.

486 Of course, other types of converging lenses can be considered in order to obtain the required 487 phase modulation, for instance a plano-convex lens (Fig. 7(b)). Now the lens profile function, 488 denoted  $\rho_{pc}(x')$ , verifies, in the paraxial approximation:

489 
$$\frac{\xi}{w_0^2} x'^2 + 2m\pi = k_0 (n_L - n_S) \rho_{pc}(x'), \ m \in \mathbb{Z},$$
(13)

490 which, for  $-h/2 \le x' \le h/2$ , yields

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$$\rho_{pc}(x') = \frac{\xi x'^2 + 2m\pi w_0^2}{2\pi (n_L - n_S) w_0^2} \lambda_0 = \frac{\lambda_0}{2\pi (n_L - n_S) w_0^2} \xi x'^2 + \rho_{pc0}, \qquad (14)$$

492 where  $\rho_{pc}(0) = \rho_{pc0}$  is the thickness of lens on its optical axis. Again, for  $\xi < 0$ , the lens is 493 converging.

494 Yet another way to achieve the desired spatial modulation of the phase of the incident 495 Gaussian beam is to use a flat dielectric lamella whose refractive index  $n_{gr}$  exhibits a parabolic 496 gradient in the direction x' perpendicular to the beam propagation direction z' (Fig. 8). It is 497 assumed that the local refractive index  $n_{gr}(x')$  exceeds the ambient refractive index  $n_s$  for all 498  $x' \in [-H/2, H/2]$ , where *H*, the height of the lamella, must be larger than the diameter 2  $w_0$ 499 of the incoming Gaussian beam.



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Fig. 8. Schematic of a flat dielectric lamella (thickness D, height H and parabolic gradient  $n_{re}(x')$ of its refractive index) acting as a converging lens and surrounded by a medium with refractive index  $n_s$ . The color variations inside the lamella schematically illustrate the change in the refractive index along the x'-axis.

505 In order to induce the desired parabolic phase term in Eq. (1),  $n_{or}(x')$  must vary as

$$n_{gr}(x') = n_{gr,c} + \frac{\lambda_0}{2\pi w_0^2 D} \xi x'^2, \qquad (15)$$

where D is the thickness of the lamella and  $n_{gr,c}$  is its refractive index at x' = 0. The minimal 507 size of such a graded flat lens along of the x'-axis is dependent on the width of the incident 508 509 Gaussian beam. As can be seen from Eq. (15), the rate of change  $(n_{gr}(x') - n_{gr,c})/x'^2$  of the 510 local refractive index along the transverse dimension of the lamella is determined by both the 511 beam parameters ( $\lambda_0, w_0, \xi$ ) and the lamella thickness D.

For  $\xi < 0$  the local refractive index decreases with the distance |x'| from the plane x' = 0, 512 513 which is the plane of symmetry of the lamella. The calculations shown and discussed in Section 4 (see Fig. 6) were made for  $n_{gr,c} = n_p = 1.95$ ,  $n_{gr} (\pm H/2) = 1.5$ , H = 33.4 mm, and D = 9.2 mm. 514 515 Such a graded-index flat lens can be obtained for different spectral ranges by using additive manufacturing technologies (3D-printing), resulting in the fabrication of a composite material, 516 517 or of a perforated gradient index lamella, that provide the required refractive index gradient 518 [50-54].

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