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Resonances in a single thin dielectric layer: enhancement of the Goos–Hänchen shift

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Abstract. We report experimental results on a new type of resonance induced in a single dielectric film. In our system, a single dielectric layer, evaporated onto a prism base, acts as a Fabry–Perot-type cavity, with narrow resonances around the cut-off frequency. Near a resonance, this device, which is simpler than those based on a multilayered structure, has been used for amplifying the Goos–Hänchen shift.

1. Introduction

Optical resonances which can be excited in thin dielectric layers are usually accompanied by an accumulation of energy in the layer, resulting in an increased sensitivity to perturbations. The finesse of the resonances can be very large when high reflection coefficients at the interfaces of the layer are used. In a waveguide this is obtained by using total internal reflections which also give rise to evanescent waves. In such guiding structures the electric field amplitude is enhanced when the transverse resonance condition is fulfilled. In order to analyse these resonances, the thin dielectric layer is deposited on a prism base which allows light from a monochromatic source to be coupled to the modes of propagation of the waveguide. For the reflection coefficient to be close to unity, one usually uses a gap layer, which separates the waveguide layer from the prism base. The coupling to the waveguide is then achieved by optical tunnelling through this gap layer. It is thus possible to obtain narrow resonances by adjusting the thickness of this gap layer.

In this paper we show that it is possible to obtain narrow resonances without a gap layer. Using an incidence angle of the laser in the prism close to the critical angle between the prism and the waveguide layer one can achieve reflection coefficients close to unity. This system is equivalent to a guiding structure with losses, with the different modes appearing at different incidence angles. With this system one can choose the width of a resonance for a specific application. In contrast to the double-layer structure which has been used for atomic mirror experiments [1] (where the intensity of the evanescent wave can be orders of magnitude larger than the incident intensity [1]) the single-layer structure described in this paper yields an evanescent wave which has an intensity comparable to the incident intensity. However, the electric field inside the layer can be enhanced by several orders of magnitude and the phase shift of the reflected laser undergoes a very rapid change across a resonance. We have used these characteristics to enhance the Goos–Hänchen [2] shift at total internal reflection.

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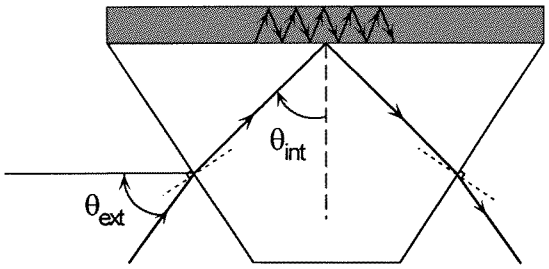

Figure 1. Thin film structure. A 5.9 μm layer of SiO_2 ($n_2 = 1.45$) evaporated on a SF11 prism base ($n = 1.78$) acts as a build-up cavity. We use external incidence angles θ_{ext} corresponding to internal incidence angles θ_{int} close to the critical angle $\theta_{12}^{cr} = \arcsin(n_2/n_1)$.

2. Principle of the resonance

The thin film structure studied in this paper is illustrated in figure 1. A thin dielectric layer (index of refraction $n_2 = 1.45$, thickness $d_2 \sim 6$ μm) is evaporated onto a prism base (index $n_1 = 1.78$). The two interfaces of the thin layer act as the mirrors of a Fabry–Perot-type cavity. For an incidence angle of the laser in the prism above the critical angle θ_{13}^{cr} for a prism–air interface ($n_1 \sin\theta_{13}^{cr} = 1$) the thin layer–air interface acts as a mirror with unit reflectivity, as the condition for total internal reflection at this interface is fulfilled ($n_2 \sin\theta_2 = n_1 \sin\theta_1 > 1$). When the incidence angle of the laser in the prism base is close to the critical angle θ_{12}^{cr} between the prism and the thin layer ($n_1 \sin\theta_{12}^{cr} = n_2$) the reflection coefficient at this interface is close to unity. This allows the prism–layer interface to act as a good coupling mirror and leads to a high finesse for the cavity [3]. In contrast to a standard Fabry–Perot cavity, our set-up does not have two identical mirrors because the layer–air interface acts as a perfect mirror. The transverse resonance condition for the modes of our cavity is given by

$$2\frac{2\pi}{\lambda} n_2 d_2 \cos\theta_2 - 2\Phi_{23} = 2m\pi \qquad (m \text{ integer}) \tag{1}$$

where $-2\Phi_{23}$ is the phase shift at the reflection at the waveguide–air interface and λ is the wavelength of the laser in air. In this equation θ_2 is the angle of incidence of the wavevector in the guiding structure. This condition is an intermediate situation between the resonance condition for waveguides and a Fabry–Perot cavity without total reflection. For a waveguide configuration as described in a previous paper [1] the cavity is separated from the prism base by a gap layer. Optical tunnelling through this gap layer acts as a coupling mirror into the cavity and the reflections at each 'mirror' of the cavity are obtained by internal reflection. The resonance condition for such a waveguide is

$$2\frac{2\pi}{\lambda} d_3 n_3 \cos\theta_3 - 2\Phi_{34} - 2\Phi_{321} = 2m\pi \qquad (m \text{ integer}) \tag{2}$$

where n_3 and d_3 are the index and thickness of the waveguide. The two total internal reflections at each boundary lead to two phase shifts $-2\Phi_{34}$ and $-2\Phi_{321}$ and θ_3 is the angle of incidence of the wavevector in this guiding structure. In the case of a Fabry–Perot or Lummer–Gehrke interferometer [3] without total internal reflection, only the geometrical phase shift accounts for the resonance condition:

$$2\frac{2\pi}{\lambda} d_3 n_3 \cos\theta_3 = 2m\pi \qquad (m \text{ integer})\,. \tag{3}$$

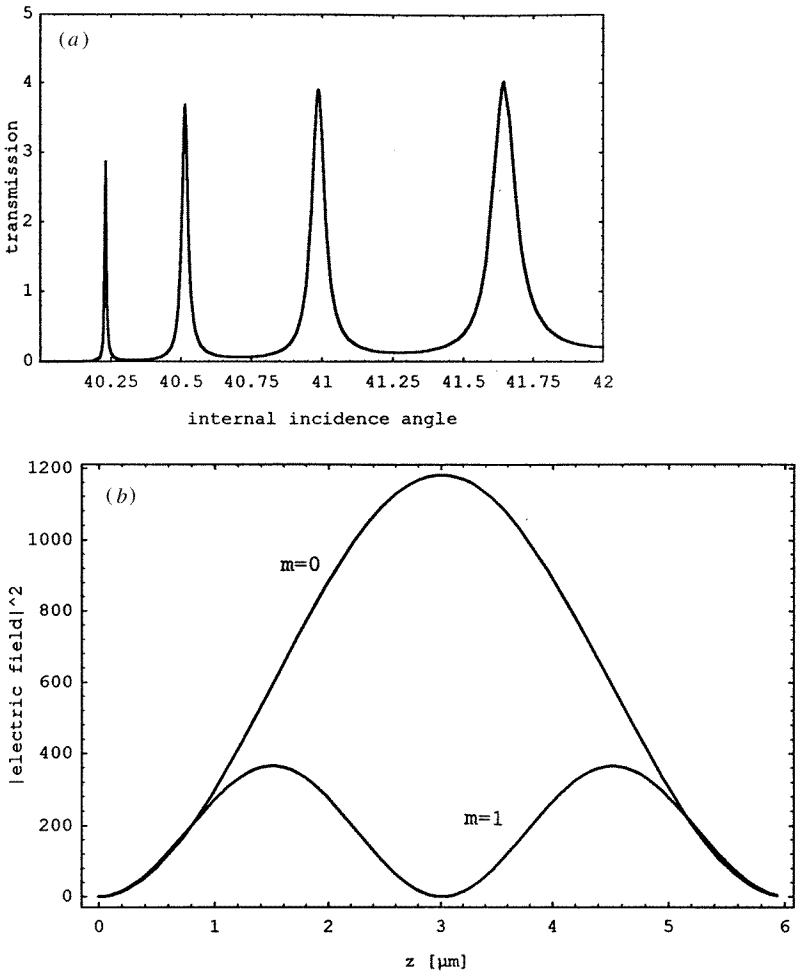

Figure 2. (*a*) Square of the amplitude of the electric field at the layer–air interface as a function of the internal incidence angle. Resonances appear when condition (1) is fulfilled. (*b*) Profile of the electric field amplitude across the layer for the $m = 0$ and $m = 1$ modes of the TE polarization.

As the phase factors due to the total internal reflection in equations (1) and (2) depend on the polarization of the laser, the resonance condition for TE (or s) and for TM (or p) polarized light is different in waveguides as well as in our type of cavities. The different modes of the cavity corresponding to integer m can be scanned by varying the incidence angle of the laser in the prism. The angular width of the resonances is lowest for the $m = 0$ resonance (close to the critical angle between the prism base and the dielectric layer) and increases as the reflection coefficient at the prism–layer interface decreases (corresponding to increasing m values). When the resonance condition (1) is fulfilled the amplitude of the evanescent wave in the medium above the cavity is larger than outside the resonances (see figure 2(*a*)). However, even though the width of the $m = 0$ resonance is narrower than that of larger m values, the amplitude of the evanescent wave is not correspondingly larger. Indeed, in the system studied in this paper, it is not the amplitude of the evanescent wave

which is proportional to the inverse of the width of the resonance, but the peak amplitude of the electric field inside the dielectric layer (see figure 2(*b*)).

3. Experimental detection of the resonances

The set-up used to analyse the resonances in our thin-layer cavity is the same as previously described in [1]. In a perfect system without losses, the reflection coefficient of the thin layer is equal to one, even at resonance, because of the reflection at the layer–air interface. However, due to losses in the dielectric layer, it is possible to observe the resonances by measuring the reflection coefficient as a function of the incident angle of the laser in the prism. The high intensity of the electric field in the thin layer (see figure 2(*b*)) indeed also enhances the scattering and the absorption of light, thus yielding enhanced losses. These enhanced losses are thus revealed as dips in the reflectivity recorded as a function of the incidence angle of the laser. A He–Ne laser ($\lambda = 633$ nm) undergoes total internal reflection in the prism at the surface where a thin SiO_2 film of 5.9 μm thickness has been deposited by thermal evaporation on a high refractive index prism (SF11, $n = 1.78$ at $\lambda = 633$ nm). The film is in contact with air ($n \simeq 1$). Figure 3 shows the measured reflection coefficient for a TE polarized He–Ne laser as a function of the external incidence angle θ_{ext}.

As our dielectric layer is 5.9 μm thick, the geometrical phase factor $2\frac{2\pi}{\lambda}d_2 n_2 \cos\theta_2$, which is independent of the polarization, is larger than the polarization dependent phase shift at total reflection $-2\Phi_{23}$ for the incidence angles considered in this paper. Furthermore, the

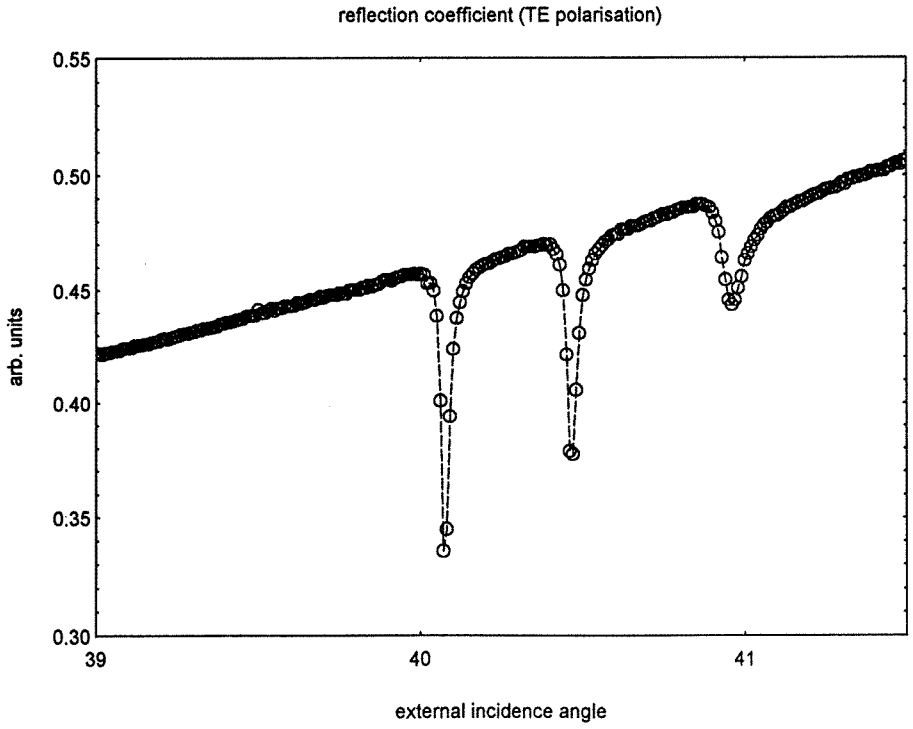

Figure 3. Reflection coefficient of the TE polarized light as a function of the external incidence angle. The dips in the reflectivity correspond to the resonances of the cavity resulting in enhanced losses.

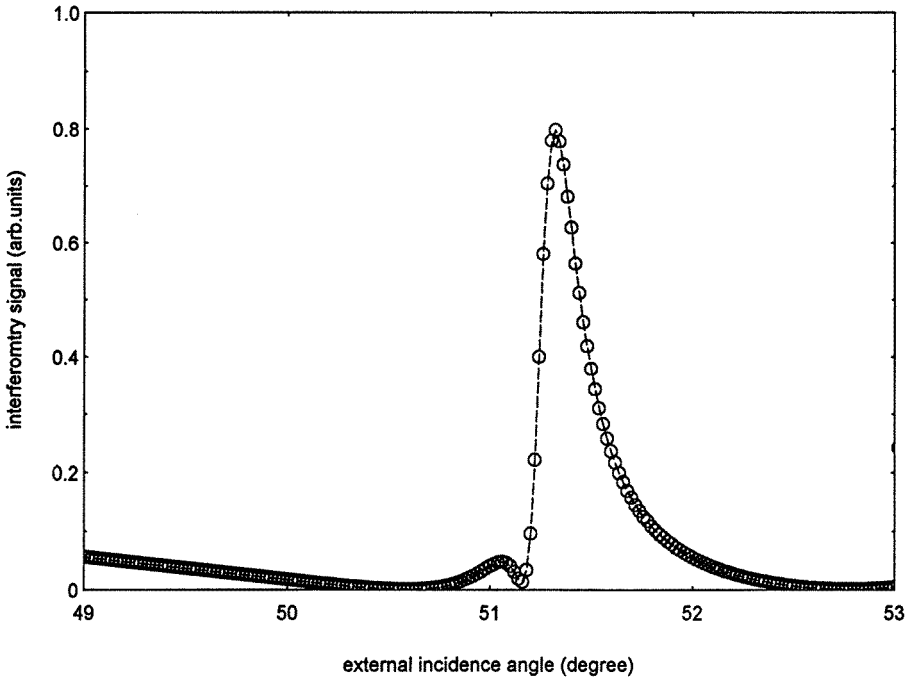

Figure 4. Interferometry signal as a function of the external incidence angle for a 3 μm layer. The incident light is polarized at 45° between the TE and the TM polarizations and a crossed analyser is placed in front of the detector. The zeros of this signal correspond to angles where the phase of the TE polarized light undergoes the same phase shift as the TM polarized light.

phase shift at total internal reflection at the layer/vacuum interface approaches 180° as the incidence angle approaches the critical angle θ_{12}^{cr} and becomes independent of polarization. Therefore the TE and the TM modes are very close to each other and do actually overlap. It is possible to detect the difference between the TE and the TM modes by a polarization interferometry measurement where the incident laser beam is polarized at 45° from the TE direction. As the phase of the reflected light undergoes a π phase across each resonance, a small difference in the angular position of the TE and the TM resonances can be detected by using a crossed analyser after the reflection in the prism. The double-bump structure observed in this experiment (see figure 4) is explained by the phase difference between the TE and the TM polarized light being zero twice when scanning the resonance.

An alternative way to observe the modes of this thin cavity is to use a laser focused onto the thin layer (m-line method [4]). In the reflected far field each position then corresponds to a different incidence angle of the laser in the cavity. For each resonant angle we have observed a dark line in the reflected beam. In such a focusing experiment the dark line is easily observed, even in the presence of fluctuations of the laser intensity. It is also possible to combine polarization interferometry with this m-line technique. We have also observed the resonances by using a white light source at a fixed incidence angle. As the resonance condition also depends on the wavelength, we have used a spectrograph in such a white light experiment to observe the different resonances.

4. Goos–Hänchen shift

The cavity described above has been used to amplify the Goos–Hänchen shift. It is well known that in total reflection of a light beam at a plane interface separating two dielectric media, the reflected beam is shifted in the incidence plane with two eigenmodes corresponding to TE and TM polarizations. Generally, these eigenvalues of the longitudinal shift are small and multiple successive total reflections are needed to measure a noticeable displacement of the reflected beam. An alternative way can be performed by using a single total reflection on a resonant cavity. Leaky-wave structures [5] can produce a displacement of the reflected beam orders of magnitude larger than the Goos–Hänchen shift on a single interface. The calculation of the longitudinal shift may be obtained by using both the stationary phase [6] and energy flux [7] methods. A more rigorous approach, starting from the Maxwell equations, allows us to provide a comprehensive study of the Goos–Hänchen shift observed on any interface configuration [8]. Using the first approach, the longitudinal shift Δx_{GH} in the prism is expressed as

$$\Delta x_{\mathrm{GH}} = \frac{\lambda}{2\pi}\frac{\partial \Phi}{\partial \theta_1} \tag{4}$$

where Φ is the phase shift of the reflected beam which depends on the polarization state TE or TM and λ is the wavelength in the incident wave medium. It appears clearly from this expression that the shift Δx_{GH} is proportional to the slope $\partial\Phi/\partial\theta_1$ which may be very high in a resonant structure. The higher the slope, the lower the angular resonance width. Outside the resonances, the slope is very small and the amplification of the longitudinal shift may only be observed when the incident angle is chosen close to the resonance angle of the particular mode. This resonance character has been used for determining the enhancement of the Goos–Hänchen shift. A linear object AB (sharp wedge of a thin glass plate) is placed

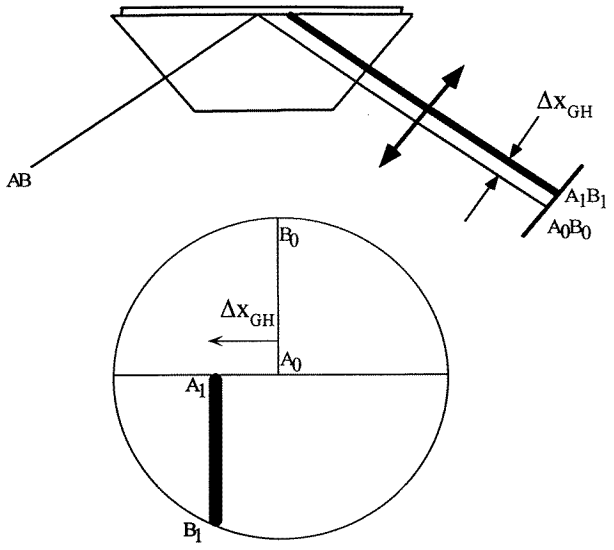

Figure 5. Schematic observation of the Goos–Hänchen shift. The lower part of the object AB is illuminated by a light beam coupled to a resonance mode of the cavity and thus the enhanced longitudinal shift Δx_{GH} of this part of the beam is compared to the reference line of the upper part, illuminated out of resonance.

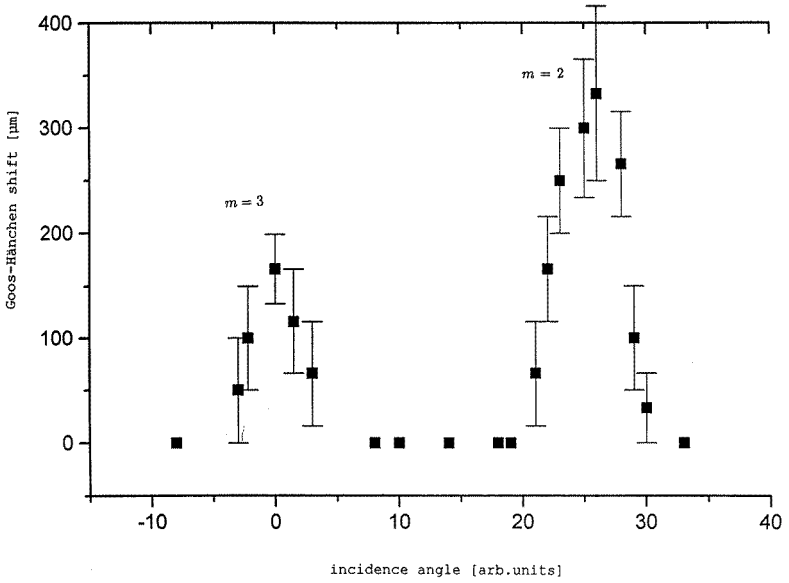

Figure 6. Observed Goos–Hänchen shifts for the TE polarized light as a function of incidence angle. The two peaks corresponds to the $m = 2$ and $m = 3$ resonances of the 5.9 μm thick cavity.

at the entrance face of the prism and an image is formed on a screen with a 60 times magnification lens. A half part of the linear wedge is illuminated with a quasi-parallel beam far from the resonance angle, whereas the second part is illuminated with parallel rays of incidence close to the resonance angle. Consequently, the resulting observed image is made with two linear components as shown in figure 5. The non-shifted upper image A_0B_0, considered as a reference, is formed with the rays of incidence greater than the resonant angle. The lower part is a shifted image A_1B_1 corresponding to the rays which are incident at the resonant angle and go through the amplifying layered prism. This particular illumination is obtained by using a slightly prismatic plate, placed on the half section of the parallel incident light beam. Figure 6 shows the Goos–Hänchen shift for TE polarized light at the $m = 2$ and $m = 3$ resonances. Even though the amplitude of the shift is reduced because of a convolution by the laser beam divergence, we observe shifts as large as 400 μm. The first mode ($m = 0$) which should give rise to even larger shifts induces a very strong broadening of the shifted image. This broadening, accompanied by a strong distortion of the image, makes quantitative measurements more difficult to perform.

5. Conclusion

We have explained the principle of resonance obtained with one thin dielectric layer evaporated on a prism base. The cavity is of the Fabry–Perot type, with one mirror obtained by total internal reflection, the other being used slightly below the critical angle, thus yielding a reflection coefficient close to unity. One thus has a cavity including an evanescent wave. We have used this type of cavity to enhance the longitudinal Goos–Hänchen shift. As the resonances for the TE and the TM polarizations overlap, such a cavity seems promising for studying the lateral shifts of a laser at total reflection [8, 9]. Other applications of the narrow

resonances may include sensitive detection of changes of the cavity parameters (thickness, index of refraction). Using a doped layer in this scheme should allow small nonlinear effects in thin doped films to be studied.

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