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Giant enhancement in Goos-Hänchen shift at the singular phase of a nanophotonic cavity

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In this letter, we experimentally demonstrate thirtyfold enhancement in Goos-Hänchen shift at the Brewster angle of a nanophotonic cavity that operates at the wavelength of 632.8 nm. In particular, the point-of-darkness and the singular phase are achieved using a four-layered metal-dielectric-dielectric-metal asymmetric Fabry-Perot cavity. A highly absorbing ultra-thin layer of germanium in the stack gives rise to the singular phase and the enhanced Goos-Hänchen shift at the point-of-darkness. The obtained giant Goos-Hänchen shift in the lithography-free nanophotonic cavity could enable many intriguing applications including cost-effective label-free biosensors.

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Goos-Hänchen¹ (G-H) shift is a well-known phenomenon in geometrical optics that describes the lateral beam displacement of the reflected light from the interface of two media when the angles of incidence are close to the critical angle. In particular, this lateral beam displacement is proportional to the penetration depth, which usually occurs when the light is totally reflected from an interface of two media. In addition, the G-H shift has been observed at the interfaces when the light is partially reflected or transmitted.^{2,3} This fascinating concept has also been explored in different fields of physics including quantum mechanics,⁴ acoustics,⁵ nonlinear optics,⁶ and radio physics.⁷ Since the lateral shift is normally of the order of the operating wavelength, the direct observation of G-H shift is very challenging. Therefore, over the past few years, this concept has received intense theoretical^{8–10} and experimental^{11–13} research attention. Accordingly, different approaches¹⁴ have been demonstrated to enhance both positive and negative G-H shifts. The two important models to interpret the appearance of G-H shift are the stationary phase approach^{15,16} and energy propagation approximation.¹⁷ According to the stationary phase approach, a general formula relating G-H shift and the change in the complex reflection coefficient phase is¹⁵ $S = -\frac{1}{k} \frac{\partial \phi}{\partial \theta}$, with k being the wavevector of the incident medium and ϕ being the phase of the reflection coefficient.

The enhancement of G-H shift has theoretically and experimentally been demonstrated using numerous optical systems including structural resonances,¹⁸ absorptive materials,¹⁹ photonic crystals,^{20,21} metals,^{22–24} hyperbolic metamaterials,^{25–27} and negative refractive index media.²⁸ For the interfaces like “in the vicinity of the angle of total internal reflection,”²⁹ “near the Brewster angle,”³⁰ and “at the edge of the photonic bandgap,”³¹ the reported G-H shifts were less than 10 times the operating wavelength. This is due to the

small phase derivative at the resonant angle of their broad reflectance spectrum, where the resonant angle represents the incident angle at which minimum reflected intensity occurs. Moreover, a significant enhancement of G-H shift has been experimentally realized by exciting the surface plasmons (SPs) on metal surfaces^{22–24} and the surface electromagnetic waves (SEWs) in photonic crystals.²⁰ Since the excitation of surface waves provides narrow resonance in the angular reflectance spectrum, a large phase derivative occurs at the resonant angle, which enabled enhanced G-H shifts. However, the coupling techniques such as prism or grating are required to excite the surface waves of metals and photonic crystals.

While it is not possible to obtain a large phase derivative at the Brewster angle of a planar metal film,³⁰ we recently demonstrated that extreme phase singularity is possible at the point-of-darkness (perfect absorption) for a specific wavelength and angle of incidence³² (Brewster angle). This unusual behavior was realized by using a metal-dielectric planar nanophotonic cavity with an ultra-thin layer of a highly absorbing germanium (Ge) dielectric in the cavity.

In this letter, we report enhanced G-H shift at the point-of-darkness. We experimentally show the enhanced G-H shift of nearly 30 times the operating wavelength at the Brewster angle using a metal-dielectric nanophotonic cavity. However, the previously reported planar system³⁰ shows only less than 10 times the operating wavelength at the Brewster (pseudo) angle. The enhanced G-H shift observed in our system is due to the complete suppression of light reflection at the Brewster angle for p -polarization, which in turn provides singular phase (large phase derivative).

A schematic of the fabricated asymmetric Fabry-Perot (F-P) cavity is shown in Fig. 1(a), which consists of a top silver layer (20 nm), optically thick lossless methyl methacrylate (MMA) as the second layer (400 nm), a highly absorbing ultrathin layer of germanium (8 nm) as the third layer, and a

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FIG. 1. (a) Schematic of the fabricated four-layered nanophotonic cavity. (b) FE-SEM image of the thermally evaporated 8 nm thick Ge film.

silver film as the bottom layer (80 nm). These films were deposited on a $700\ \mu\text{m}$ thick silicon substrate. The Ag and Ge layers were deposited by thermal evaporation (Oerlikon Leopold vacuum system) of Ag and Ge pellets at a deposition rate of $0.2\ \text{\AA/s}$ and $0.1\ \text{\AA/s}$, respectively, and a common base pressure of $<5 \times 10^{-6}$ mbar. The MMA (8.5MMAEL 11, MICROCHEM) layer was spin coated at 5000 rpm. The optical constants and thickness of all films were determined using spectroscopic ellipsometry (J. A. Woollam Co., Inc, V-VASE). We confirmed from the field emission scanning electron microscopy (FE-SEM) image that the thermally evaporated ultra-thin layer (8 nm) of Ge has a uniform surface texture and morphology, which is shown in Fig. 1(b).

To experimentally demonstrate the point-of-darkness and singular phase in an asymmetric F-P cavity at a specific wavelength and incident angle, we recorded a pair of ellipsometric parameters such as ψ (ellipsometric reflection) and Δ (phase shift) as a function of wavelength [Fig. 2(a)] and angle of incidence [Fig. 2(c)] using the VASE ellipsometer. The wavelength and angular resolution of the measurements were set to be 1 nm and 1° , respectively. We found that the cavity shows point-of-darkness at a wavelength of 633 nm and an incident angle of 65.5° , where the measured $\psi < 1$. It is also evident that an abrupt phase change is obtained at the point-of-darkness (633 nm and 65.5°). The emergence of the

singular phase from the stack is due to the presence of a highly absorbing ultra-thin layer of Ge within the stack, since a Ge layer with thickness much smaller than the operating wavelength on a thin Ag film rapidly attenuates the incident light.³²

We then validated the obtained experimental results using a numerical simulation model based on the transfer matrix method (TMM).³³ The pair of ellipsometry parameters and reflection spectra were numerically computed with Matlab. In the simulations, the Fresnel reflection coefficients ($r_{p,s}$) for an N -layer model were solved, where the experimentally determined dielectric constants of films were used.³² The ψ spectra were obtained using $\tan \psi = |r_p/r_s|$, where r_p and r_s are the Fresnel reflection coefficients for p - and s -polarizations, respectively. Since Δ is the phase difference between s - and p -polarizations, $\Delta = \phi_s - \phi_p$ with values of ϕ_s and ϕ_p were extracted from the Fresnel reflection coefficients, $r_s = |r_s| \exp(i\phi_s)$ and $r_p = |r_p| \exp(i\phi_p)$. The simulated ψ and Δ spectra as a function of wavelength and angle of incidence are shown in Figs. 2(b) and 2(d), respectively. The simulated and measured spectra match shows good agreement.

To show that the point-of-darkness and singular phase are obtained at the Brewster angle for the p -polarization, we measured the reflectance spectrum for the p - and s -polarizations

FIG. 2. (a) Measured and (b) simulated ψ and Δ spectrum as a function of wavelength at 65.5° angle of incidence. (c) Measured and (d) simulated ψ and Δ spectrum as a function of incident angle at 633 nm wavelength.

FIG. 3. (a) Measured and (b) simulated reflectance spectra for p - and s -polarizations at 65.5° angle of incidence.

separately. The measured reflectivity spectrum at an angle of incidence of 65.5° for both polarizations is shown in Fig. 3(a). The recorded reflected intensity for p -polarization at 633 nm is 0.07% ($R \sim 0$). It indicates that p -polarized light provides almost zero reflectance at 633 nm, confirming that the incident angle (65.5°) at which zero reflectance was obtained is the Brewster angle. The simulated results ($R_{p,s} = |r_{p,s}|^2$) for both polarizations are shown in Fig. 3(b), which accurately reproduced the experimental spectra.

The confined intensity ($I = |E|^2$) distribution along the planar multilayer stack was further simulated. We used the transfer matrix method (by writing Matlab code) to calculate the intensity distribution.³⁴ For the point-of-darkness condition at 633 nm and 65.5° , the simulated intensity distribution for the p -polarized light is shown in Fig. 4. It can be seen from the 2D map [Fig. 4(a)] and line profile [Fig. 4(b)] that the intensity remained tightly confined in the ultra-thin Ge layer at the point-of-darkness. This further indicates that the Ge layer heavily attenuates the incident light at 633 nm wavelength to achieve point-of-darkness and phase singularity at the Brewster angle.

Since the fabricated cavity shows a large phase derivative at the point-of-darkness, enhanced G-H shift is expected at the Brewster angle. To experimentally investigate the G-H shift, a home-built differential phase-sensitive setup was used.³⁵ A schematic of the home-built setup is shown in Fig. 5(a). Since p -polarized light only enhances the G-H shift in the cavity, we recorded the differential G-H shift between p - and s -polarized light. In particular, s -polarized light acts as a reference signal in the setup. Since the point-of-darkness and phase singularity are obtained at a 633 nm wavelength, we

used a He-Ne laser with a wavelength of 632.8 nm and a power of 4 mW as the excitation source. The light from the source was separated into p - and s -polarized light using a polarized beam splitter (PBS). The p -polarized light travels along the original light path, while the s -polarized light travels in parallel with the p -polarized light by using two mirrors. Afterwards, the second mirror and PBS are used to change the path of s -polarized light to that of the p -polarized light. In this way, both p - and s -polarized light impinge onto the sample surface. A position sensitive detector (or lateral position sensor, Thorlabs, PDP90A) was used to collect the reflected light. The T-Cube controller is an accessory of the detector for recording the spot position. The overall measurement was operated by the LabVIEW program with a computer. It should be noted that the chopper between the two PBS and mirrors has two functions: (i) to confirm that only one beam of s - and p -polarized light can shine onto the sample surface at one time and (ii) the detector can collect the signal of p - and s -polarized light alternately when the chopper is rotated. The position data of p - and s -polarized light were used to obtain the target results of the differential G-H shift. The sample was immobilized on a rotating translation stage. The position of the reflected p - and s -polarized light as a function of incident angle was recorded using the position sensitive detector with a data acquisition card for further processing.

The differential G-H shift was obtained after data processing using Matlab. Since the position detector can record the exact position of the light spot [i.e., for p -polarized light as $P(x_p, y_p)$ and for s -polarized light as $S(x_s, y_s)$], the target data of differential G-H shift were calculated as $\Delta GH = |x_p - x_s|$. It should be noted that the incident sample surface was kept

FIG. 4. (a) Simulated intensity distribution for the p -polarization along the four-layered system at 633 nm and 65.5° . (b) Its magnitude as a function of depth along the multilayer.

FIG. 5. (a) The sketch of the home-built setup for the G-H shift measurement. (b) Measured and (c) simulated G-H shift as a function of incident angle at 632.8 nm wavelength. Data points represent the error bar.

parallel to the x-axis of the detector; therefore, only the x-axis value of the spot position was used. Since the sampling frequency of the detector is 50 Hz, a total of ~ 1500 points in 5 min of the signal was recorded for each angle of incidence. We first calculated the standard deviation of these 1500 points of data and then we filtered the original data by using 2 times the standard deviation. From the filtered data, we calculated the average value of both polarizations to be as the desired results. Finally, the differential G-H shift was obtained as the absolute difference between the two averages. The noise level of the measurement was less than $0.3 \mu\text{m}$.

The experimentally obtained G-H shift as a function of incident angle is shown in Fig. 5(b), which was performed on different positions of the sample to ensure the reproducibility of the results. Since the singular phase behavior is only visible at the point-of-darkness, we recorded the G-H shift close to the point-of-darkness angle (64° to 68°). As expected, maximum G-H is obtained at the Brewster angle (65.5°), which is nearly 30 times the excitation wavelength (632.8 nm). The error bars (data points) reflect the slight variation in the obtained G-H shift on different positions of the sample. The numerical results demonstrating the G-H shift for the proposed experimental system are shown in Fig. 5(c), which was obtained by using the transfer matrix method. The G-H shift was calculated by using numerical differentiation of the formula $s = -\frac{1}{k} \frac{d\phi}{d\theta}$ with θ being the angle of incidence and ϕ the phase angle of reflection coefficient ($\tilde{r}$). The general form of the reflection coefficient can be written as $\tilde{r} = re^{i\phi}$, whereas the reflection amplitude is obtained as $R = |\tilde{r}|^2$. Thus, the phase angle ϕ can be obtained from $\phi = \arctan\left(\frac{\text{Im}(\tilde{r})}{\text{Re}(\tilde{r})}\right)$. The simulations accurately reproduce the key results that maximum G-H shift is obtained at the Brewster angle, again supporting our claim that enhanced G-H at the point-of-darkness. The experimentally determined³² dielectric constants of thin films were used in the numerical model; however, the thickness of thin films was slightly varied from the measured

values in order to get a good match with the value at the Brewster angle. The thickness of the layers used in the simulations was top Ag (18 nm), MMA (400 nm), Ge (8.1 nm), and bottom Ag (80 nm). In contrast to simulation results, the observed variation in the experimental G-H shift curve near the Brewster angle is attributed to the limitation of the measurement apparatus. Note that the incident beam position on the sample surface may not be the same for larger angles of incidence. A slight increase or decrease in $\psi_{\min}$ due to surface roughness change significantly affects the phase change.³² In particular, the phase change varies with this slight displacement of the beam position, which in turn affects the absolute difference between the two average G-H shifts.

To summarize, enhanced Goos-Hänchen shift was realized at the Brewster angle of an asymmetric Fabry-Perot cavity. Since it is known that the large phase derivative is the main requirement for obtaining an enhanced G-H shift, we have experimentally demonstrated an abrupt phase change at the reflection-less point in a four-layered metal-dielectric-dielectric-metal asymmetric Fabry-Perot cavity. The experimentally obtained G-H shift shows thirtyfold enhancement compared to the operating wavelength at the Brewster angle; however, this enhancement is not possible at the Brewster angle of a planar metal film due to the small phase derivative.³⁰ All experimental results were validated using an analytical simulation model based on the transfer matrix method. The giant Goos-Hänchen shift observed in the lithography-free design of the nanophotonic cavity could find various cost-effective photonic device applications including ultra-sensitive biosensing based on G-H shift-sensitive detection.

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¹F. Goos and H. Hänchen, *Ann. Phys.* **436**, 333–346 (1947).

²L. G. Wang, H. Chen, and S. Y. Zhu, *Opt. Lett.* **30**, 2936 (2005).

- ³C. F. Li, *Phys. Rev. Lett.* **91**, 133903 (2003).
- ⁴C. W. J. Beenakker, R. A. Sepkhanov, A. R. Akhmerov, and J. Tworzydło, *Phys. Rev. Lett.* **102**, 146804 (2009).
- ⁵R. Briers, O. Leroy, and G. J. Shkerdin, *Acoust. Soc. Am.* **108**, 1622 (2000).
- ⁶O. Emile, T. Galstyan, A. Floch, and F. Bretenaker, *Phys. Rev. Lett.* **75**, 1511 (1995).
- ⁷A. Matthews and Y. Kivshar, *Appl. Phys. Lett.* **93**, 131901 (2008).
- ⁸C. K. Carniglia and K. R. Brownstein, *J. Opt. Soc. Am.* **67**, 121 (1977).
- ⁹B. R. Horowitz and T. Tamir, *J. Opt. Soc. Am.* **61**, 586 (1971).
- ¹⁰T. Paul, C. Rockstuhl, C. Menzel, and F. Lederer, *Phys. Rev. A* **77**, 053802 (2008).
- ¹¹M. Merano, J. B. Götte, A. Aiello, M. P. van Exter, and J. P. Woerdman, *Opt. Express* **17**, 10864 (2009).
- ¹²Y. Wan, Z. Zheng, and J. Zhu, *J. Opt. Soc. Am. B* **28**, 314 (2011).
- ¹³F. Bretenaker, A. Le Floch, and L. Dutriaux, *Phys. Rev. Lett.* **68**, 931 (1992).
- ¹⁴K. Y. Bliokh and A. Aiello, *J. Opt.* **15**, 014001 (2013).
- ¹⁵K. Artmann, *Ann. Phys. (Leipzig)* **437**, 87 (1948).
- ¹⁶K. W. Chiu and J. J. Quinn, *Am. J. Phys.* **40**, 1847 (1972).
- ¹⁷R. H. Renard, *J. Opt. Soc. Am.* **54**, 1190 (1964).
- ¹⁸R. Yang, W. Zhu, and J. Li, *Opt. Express* **22**, 2043–2050 (2014).
- ¹⁹E. Pfléghaar, A. Marseille, and A. Weis, *Phys. Rev. Lett.* **70**, 2281 (1993).
- ²⁰Y. Wan, Z. Zheng, W. Kong, X. Zhao, Y. Liu, Y. Bian, and J. Liu, *Opt. Express* **20**, 8998–9003 (2012).
- ²¹I. V. Soboleva, V. V. Moskalenko, and A. A. Fedyanin, *Phys. Rev. Lett.* **108**, 123901 (2012).
- ²²C. Bonnet, D. Chauvat, O. Emile, F. Bretenaker, and A. Le Floch, *Opt. Lett.* **26**, 666 (2001).
- ²³X. Yin, L. Hesselink, Z. Liu, N. Fang, and X. Zhang, *Appl. Phys. Lett.* **85**, 372 (2004).
- ²⁴X. Yin and L. Hesselink, *Appl. Phys. Lett.* **89**, 261108 (2006).
- ²⁵C. Xu, J. Xu, G. Song, C. Zhu, Y. Yang, and G. S. Agarwal, *Opt. Express* **24**, 21767–21776 (2016).
- ²⁶C.-W. Chen, T. Bian, H.-P. Chiang, and P. T. Leung, *J. Opt.* **18**, 025104 (2016).
- ²⁷Y. Xu, C. T. Chan, and H. Chen, *Sci. Rep.* **5**, 8681 (2015).
- ²⁸P. R. Berman, *Phys. Rev. E* **66**, 067603 (2002).
- ²⁹H. G. L. Schwefel, W. Köhler, Z. H. Lu, J. Fan, and L. J. Wang, *Opt. Lett.* **33**, 794 (2008).
- ³⁰M. Merano, A. Aiello, G. W. t'Hooft, M. P. van Exter, E. R. Eliel, and J. P. Woerdman, *Opt. Exp.* **15**, 15928 (2007).
- ³¹D. Felbacq, *Opt. Lett.* **28**, 1633 (2003).
- ³²K. V. Sreekanth, S. Sreejith, S. Han, A. Mishra, X. Chen, H. Sun, C. T. Lim, and R. Singh, *Nat. Commun.* **9**, 369 (2018).
- ³³K. V. Sreekanth, S. Zeng, K.-T. Yong, and T. Yu, *Sens. Actuators B* **182**, 424–428 (2013).
- ³⁴C. C. Katsidis and D. I. Siapkas, *Appl. Opt.* **41**, 3978–3987 (2002).
- ³⁵L. Jiang, S. Zeng, Z. Xu, Q. Ouyang, D.-H. Joo Chong, P. Coquet, S. He, and K.-T. Yong, *Small* **13**, 1700600 (2017).