Coherent perfect absorption mediated anomalous reflection and refraction

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We show bending of light on the same side of the normal in a free-standing corrugated metal film under bidirectional illumination. Coherent perfect absorption (CPA) is exploited to suppress the specular zeroth order leading to effective back-bending of light into the "−1" order, while the "+1" order is resonant with the surface mode. The effect is shown to be phase sensitive, yielding CPA and superscattering in the same geometry.

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In recent years, there has been a great deal of interest in perfect absorption [1–4] motivated mostly by potential applications in light harvesting [5] and superluminescent light sources [6]. Many of such investigations focus on metallic gratings, which are known for their ability for near-perfect absorption both in resonant and in nonresonant regimes [7]. On the other hand, a great deal of research has gone into critical coupling (CC) and coherent perfect absorption (CPA), whereby all the incident coherent light energy can be coupled into the structure leading to null scattering (simultaneous zero reflection and transmission) [8–14]. In the context of a layered medium, CC and CPA result from single or multiple input beams, respectively, due to destructive interference [8,12]. In contrast, constructive interference can lead to superscattering (SS) [10,11]. Similar ideas were exploited as early as in 1966 by Evering [15], who showed that one can tune a grating from near-perfect absorption to SS by bringing in an additional coherent light and controlling its phase. In this Letter we explore theoretically analogous possibilities with a free-standing corrugated metal film [see Fig. 1(a)] illuminated from both sides at the same angles of incidence. The illumination geometry is analogous to the one used earlier [12] and the specular zeroth-order light (both reflected and transmitted) can be suppressed for suitable system parameters. Significant development in nanofabrication technology has made it possible to realize gratings with period comparable to wavelength. For gratings with $K = k_{\mathrm{SP}}$ [$K = 2\pi/\Lambda$ is the grating vector and k_{SP} is the surface plasmon (SP) wavevector], one can excite the SPs using the ± 1 diffraction orders for normal incidence [see Fig. 1(b)]. CPA with bidirectional incidence can then suppress the specular order and thus all the incident energy will be converted into the SPs in the $\pm x$ directions with half of the incident plane-wave energy in each direction. In our calculations we use the geometry shown in Fig. 1(c), where one of the surface waves (in the $-x$ direction) is changed to a propagating mode, while the $+1$ order can excite the SP satisfying the momentum matching condition $k_0 \sin(\theta) + K = k_{\mathrm{SP}}$ (k_0 is the vacuum wave vector, θ is the angle of incidence). Coupled with the CPA assisted suppression of the specular zeroth order, this manifests itself as counterintuitive scattering of light on the same side of the normal. We show that on either side (top or bottom) the −1 order scattered light intensity can be as high as 45% of the incident light.

Free-standing metal films have been studied both theoretically and experimentally [16,17]. It was shown that for shallow gratings, a perturbative method such as Rayleigh expansion is well suited and can lead to excellent agreements with the experimental results. For sufficiently thin films, the coupling was shown to lead to the long-range (LR) and short-range (SR) modes, which can be excited at different angles of incidence. In this Letter we use the same technique albeit with illumination by plane waves from both sides [see Fig. 1(a)]. We exploit one of the split modes to show CPA mediated anomalous scattering, though in principle, the other could have been used. We further show that the relative phase between the two incident waves can play an important role changing the character of interference from destructive (CPA) to constructive (SS).

Consider a corrugated metal film of dielectric constant ε_m suspended in air (dielectric constant ε_1) as shown in Fig. 1(a). The surface profiles are given by the following equations:

$$y_{\pm} = \pm d \pm a \sin Kx, \quad (1)$$

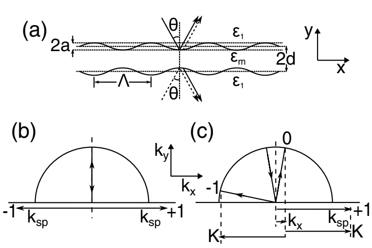

Fig. 1. (a) Schematics of the corrugated metal film and the illumination geometry (only the specular diffracted orders are shown). (b) Excitation of SPs under normal incidence of light in reciprocal space. (c) Excitation of 0 and −1 harmonics as propagating modes for small angle incidence. Figures are not drawn to scale.

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where the + (–) sign refers to the top (bottom) interface and $2d$ and a give the width and the corrugation amplitude, respectively. Calculations were performed retaining 13 spatial harmonics and convergence was satisfactory for the grating parameters used in calculations. The following system parameters were chosen for most of the calculations: incident wavelength $\lambda = 780\ nm$, $d = 27\ nm$, and $\varepsilon_1 = 1.0$. We used silver as the film material with ε_m taken from the experimental work of Johnson and Christy [18]. Calculations were performed for two values of grating period Λ so as to lead to two near-normal angles of incidence, satisfying plasmon resonance conditions with the +1 diffraction order. The choice of parameters is not arbitrary, and they needed to be adjusted such that CPA condition is met for the zeroth specular order. Thus we used different values of the modulation depth a for the same grating period Λ in order to meet the CPA condition at the LR and SR modes. Moreover, in order to demonstrate the phase sensitivity, we introduced a delay in one of the incident beams. The delay will be assumed to be zero unless otherwise stated. It will be shown below how a change in this delay from zero to π can change the character of scattering from SS to CPA.

Let r_m and t_m represent the mth amplitude reflection and transmission diffraction orders for unit amplitude p-polarized plane wave incidence. Let $\Delta\phi_m$ represent the phase difference (normalized to π) between r_m and t_m. In the context of the zeroth order, the role of these quantities in CPA was discussed in detail in [12], highlighting the importance of destructive interference, when $|r_0| = |t_0|$ and $\Delta\phi_0 = \pm 1$. The results for CPA with the LR mode are shown in Fig. 2, where we have plotted $|r_0|$ and $|t_0|$ [Fig. 2(a)], $\Delta\phi_0$ [Fig. 2(b)], and total scattered intensity on either side $\log_{10}|r_0 + t_0|^2$ [Fig. 2(c)] for $\Lambda = 826\ nm$ and $a = 7.2\ nm$. One can easily see that at $\theta \sim 4°$ the CPA condition is met along with simultaneous excitation of the LRSP and one has near-null scattering at that angle.

It may be noted that for a thin planar metal film the LR and SR modes differ by a phase difference of π, though perturbation of the surface in a corrugated film slightly offsets this value (1.08π for parameters of Fig. 2). Otherwise, the same system parameters yielding CPA for the LR mode would lead to the SS at the SR mode. Because of the offset we had to pick a slightly different system parameter, namely, $a = 8.9\ nm$ for the same grating period $\Lambda = 826\ nm$ as in Fig. 2 for demonstrating both SS and CPA with the SR mode. In particular the SR mode was picked for demonstrating CPA, since without interference it can never lead to null reflection. The results for $|r_m|$ and $|t_m|$, $\Delta\phi_m$ (normalized to π), and the log of the total scattered intensity $\log_{10}|r_m + t_m|^2$ for two different orders, namely $m = 0$ and $m = -1$, are shown in Fig. 3. The results for $m = +1$ (not shown) confirms the SP-mediated local field enhancement. All other harmonics (not shown) are evanescent and their excitation efficiency is low due to shallow corrugation. It can be seen from Fig. 3(a) that $|t_0| = |r_0|$ for an incident angle of 5.3° implying that both CPA and SS can be realized provided that the phase difference is adjusted accordingly. It can be seen from Fig. 3(c) that for a phase delay of π between the incident plane waves (dashed curve) the necessary conditions for CPA are met at the SR plasmon resonance since $\Delta\phi_0 = \pi$ ensuring destructive interference. In contrast, incident waves with the same phase result in $\Delta\phi_0 \sim 2$ yielding constructive interference leading to SS (solid curve for $m = 0$ in Fig. 3). Both these features can be read from Fig. 3(e) where we used a log plot to stress the null of scattering for CPA. The right column in Fig. 3 shows the results for the $m = -1$ diffraction order, which displays a dramatic change when the LR and SR modes are excited. In fact, for a phase delay of π between the input beams at $\theta = 5.3°$ (CPA for zeroth order) there can be significant scattering in the –1 order [see right peak in Fig. 3(f)] at the SR resonance.

We now show that the closer it is to normal incidence, the larger will be the anomalous scattering in the –1 diffraction order. We reproduce the bottom panel of

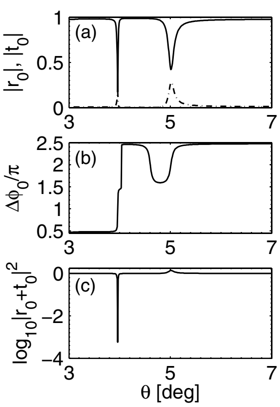

Fig. 2. (a) Absolute values of zeroth order reflected (solid line) and transmitted (dash-dotted line) amplitudes $|r_0|$ and $|t_0|$, (b) phase difference $\Delta\phi_0$, and (c) total scattered intensity on each side $\log_{10}|r_0 + t_0|^2$ as functions of angle of incidence for $\lambda = 780\ nm$, $\Lambda = 826\ nm$, $a = 7.2\ nm$, $d = 27\ nm$, and $\varepsilon_1 = 1.0$. The incident plane waves have a null phase delay.

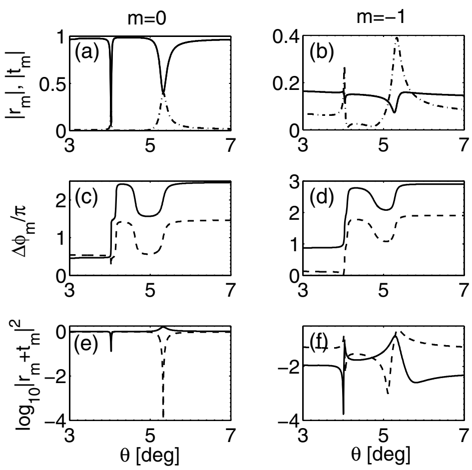

Fig. 3. Absolute values of reflected (solid line) and transmitted (dash-dotted line) amplitudes $|r_m|$ and $|t_m|$ [top row: (a) and (b)], phase difference $\Delta\phi_m$ [middle row: (c) and (d)], and total scattered intensity on one side $\log_{10}|r_m + t_m|^2$ [bottom row: (e) and (f)], as functions of angle of incidence θ for the 0 order (left column) and –1 order (right column). The solid and dashed lines in (c)–(f) are for null and π phase delay, respectively, between the incident waves. The other parameters are as in Fig. 2, except that now $a = 8.9\ nm$.

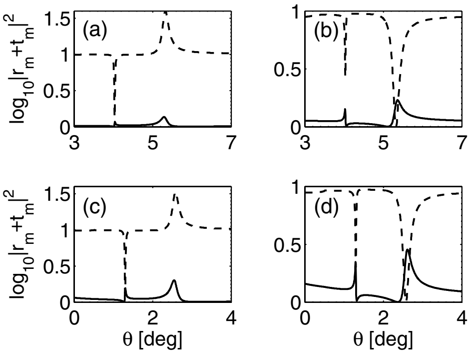

Fig. 4. Total scattered intensity as a function of angle of incidence, for an initial phase delay of 0 [(a),(c)] and π [(b),(d)]. (a),(b) and (c),(d) are for $\Lambda = 826\ nm$ and $\Lambda = 787\ nm$, respectively. Dashed and solid lines in each panel are for 0 and −1 harmonics, respectively. The other parameters are as in Fig. 3.

Fig. 3 for two different values of grating period, namely, $\Lambda = 826\ nm$ [Figs. 4(a), 4(b)] and 787 nm [Figs. 4(c), 4(d)] with parameters meeting the CPA/SS conditions for the SRSP. Note that Λ closer to λ corresponds to smaller angles for the excitation of the SRSP. Dashed (solid) lines show the results for $m = 0$ ($m = -1$) order. Figures 4(a), 4(c) and Figs. 4(b), 4(d) correspond to phase delays 0 and π, respectively, between the incident waves. For the zeroth order, null phase delay corresponds to SS [dashed curve peak in Figs. 4(a) and 4(c)], while a delay of π results in CPA at the SR mode resonance [dashed curve, right dip in Figs. 4(b) and 4(d)]. It is thus clear that the character of interference plays a very important role. A comparison of Figs. 4(b) and 4(d) clearly reveals that for the shorter grating period one has larger total scattering in the $m = -1$ order and it can be as high as 45%. Thus near the SR resonance the zeroth order gets suppressed due to CPA, while there is enhanced scattering in the only other propagating order, namely the $m = -1$ order. In other words light bends in the “wrong” direction on the same side of the normal.

In conclusion, we have exploited CPA in a free-standing corrugated metal film for near normal illumination from both sides to show apparent bending of light on the same side of the normal. Recent advances in nanofabrication techniques render the realization of such gratings (free-standing or embedded in a dielectric) possible. Reported effects can be experimentally observed and they can have varied applications in nanoantennae and in other areas of plasmonics.

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