Angle-Independent Infrared Filter Assisted by Localized Surface Plasmon Polariton

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Abstract—A plasmonic infrared (IR) filter was experimentally and theoretically investigated. A localized surface plasmon polariton (LSPP) mode which was angle-independent in almost fully incident angle was observed. Through the use of the LSPP mode, an IR reflection-type notch filter with an ultrahigh immunity for the angular deviation was realized. An angle-independent reflection dip was designed at $\lambda = 6.2 \mu\text{m}$ with a full-width at half-maximum of $0.5 \mu\text{m}$. The experimental result shows that the position and the line shape of the resonant dip at $\lambda = 6.2 \mu\text{m}$ remain the same for an increasing incident angle from 20° to 60° . The optical properties can be engineered by tuning thickness of the cavity layer. The proposed notch filter presents a large angular tolerance means that the superior angular stability makes it more feasible as it is put into practical applications.

Index Terms—Filters, plasmonics.

I. INTRODUCTION

METALLIC surfaces with a subwavelength scale texturing are known to strongly modify their electromagnetic response. Moreover, a dielectric microcavity sandwiched with a perforated metal film and a flat metallic film performs strongly coupling effects via evanescent fields [1]. The coupling interaction strongly depends on the thickness of the metal film [2]. When the thickness of the metal film is small, the coupling interaction is strong, and new surface plasmon polariton (SPP) modes can be fully formed. Through the use of the SPP coupling behavior, substantial potential applications are opened up and have already been realized in the optical [3] and microwave regime [4].

A conventional optical filter was made by the thin-film technique. Versatile functions of the filter rely on a longitudinal stacked thin film. Narrow passband optical thin-film filters, for example, wavelength-division-multiplexing applications, often have hundreds or more individual layers, with stringent thickness tolerances for each layer [5]. To overcome this weakness, a transverse periodic grating stacked on a leakage

waveguide layer, named guided-mode resonant (GMR) filter, has recently been conceived owing to its relatively simple structure. It also performs functional optical properties, such as spectral selectivity for broadband [6] or narrowband [7] feasible band-tailoring for bandpass or bandstop [8]. However, suppressing the sideband of this kind of filter is still under investigation. In addition, most of these filters are very sensitive to the incident angle. This limits its applications to a filter.

In this letter, we study the reflection properties of a plasmonic multilayer structure which consists of a relief metallic grating, a cavity layer, and a metallic substrate. This plasmonic multilayer structure is demonstrated as a reflection-type notch filter. The proposed filter has a simple structure which can be fabricated easily. The stopband of the notch filter is achieved at the central wavelength of $6.2 \mu\text{m}$ with a full-width at half-maximum (FWHM) of $0.5 \mu\text{m}$. For the off-resonant condition, the sideband of the spectrum is flat and performs as a metallic plate. This nature makes the design of the proposed filter more flexible than a GMR filter. In addition, the resonant dip presents an ultrahigh immunity for the angular deviation through the use of the localized SPP (LSPP).

II. DEVICE DESCRIPTION AND FABRICATION

The plasmonic multilayer structure is presented in Fig. 1. It is comprised of a relief metallic grating, a cavity layer, and a metallic substrate. The grating periodicity is denoted by Λ , the filling factor is f , the depth is denoted by t_g , and its complex dielectric constant is denoted by ϵ_m , where $\epsilon_m = \epsilon_{mr} + i\epsilon_{mi}$. According to classical waveguide theory [14 + 1], narrow slits are able to support transverse-magnetic (TM) waveguide modes that have no cutoff in frequency. The cutoff wavelength of the transverse-electric (TE) modes is $2(1-f)\Lambda$ for a perfect metal hollow waveguide. Most of our investigating wavelengths are larger than $2(1-f)\Lambda$. Therefore, the TE modes are cut off and the optical properties are TM-dominated. Between and above the grating grooves the dielectric constant is denoted by ϵ_{Air} . The thickness of the SiO_2 cavity layer is assumed to be t_w and its dielectric constant is denoted by ϵ_w . The material of the metallic substrate is identical to the grating ϵ_m . The substrate thickness is assumed to be infinite. The structure is illuminated with an incident plane wave at an angle of θ_i . Here, the reflection properties are simulated by using rigorous coupled wave analysis. The input light is TM-polarized in which the magnetic vector is parallel to the grating grooves (i.e., parallel to the y -axis). The wavelength-dependent optical constants of the investigated materials are referred from [9].

The fabrication processes of the plasmonic multilayer structure were described as follows. An Ag metal film with an optically thick thickness was deposited on the front side of a Si sub-

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Fig. 1. Basic geometry of the investigated filter. It is a plasmonic multilayer structure consisting of a relief metallic grating, a waveguide layer, and a metallic substrate.

Fig. 2. Measured reflection spectra under oblique incidence for $\theta_i = 20^\circ$ to $\theta_i = 60^\circ$ in step of 10° .

strate followed by a SiO_2 layer deposited with the electron beam evaporator. Then a grating structure of 100-nm-thick silver film was patterned onto the SiO_2 layer by deposition and lift-off techniques. The reflection spectrum of the device was measured by a Perkin Elmer 2000 Fourier transform infrared (FTIR) spectrometer system with a wave number resolution of 8 cm^{-1} .

III. ANGLE-INDEPENDENT NOTCH FILTER

Fig. 2 shows the reflectance spectrum of the proposed structure. The geometric parameters of the plasmonic multilayer structure were denoted as follows: $\Lambda = 3000 \text{ nm}$, $\Lambda f = 1500 \text{ nm}$, $t_g = 100 \text{ nm}$, and $t_w = 50 \text{ nm}$. The spectra under oblique incidence (from 20° to 60° in step of 10°) are measured to investigate the angular stability. Because of the limitation of the FTIR system, the normally incident case is not measured. The reflectance for each incident angle is individually shifted 0.3 for a clear expression. It can be seen that the reflectance is high as a metallic behavior with a wide spectral range from 3 to $9 \mu\text{m}$ for off-resonant condition. Two clear resonant reflection dips can be found at $\lambda = 3.4 \mu\text{m}$ and $\lambda = 6.2 \mu\text{m}$. The resonant wavelength is almost independent of θ_i . In addition, there is a resonant dip located at $\lambda = 3.9 \mu\text{m}$ for $\theta_i = 20^\circ$ which is corresponding to the grating-coupled SPP at the air–Ag interface. It can be seen that the resonant dip is shifted to a longer wavelength as an increasing θ_i .

The two resonant reflection dips located at $\lambda = 3.4 \mu\text{m}$ and $\lambda = 6.2 \mu\text{m}$ present different properties while the incident angle increases. The contrast of the resonant dip at $\lambda = 3.4 \mu\text{m}$ is increased for an increasing θ_i . The contrast of the resonant dip

Fig. 3. Angle-dependent reflection spectra of the IR filter in the (a) measurement and, (b) simulation. The geometric parameters were: $\Lambda = 3000 \text{ nm}$, $\Lambda f = 1500 \text{ nm}$, $t_g = 100 \text{ nm}$, and $t_w = 50 \text{ nm}$.

at $\lambda = 6.2 \mu\text{m}$ with an FWHM of $0.5 \mu\text{m}$ almost maintains in a steady manner with an increasing θ_i . It has to mentioned that we used an unpolarized black body emission light as a probe beam. Thus, the contrast of the dips will be limited. By using a polarized light, the dips will be sharper. The resonant dip at $\lambda = 6.2 \mu\text{m}$ shows a large angular tolerance meaning that the superior angular stability of the proposed notch filter makes it more feasible for practical applications. The mechanism of the angle-independent dip will be discussed in detail in Section IV.

IV. ANGLE-RESOLVED REFLECTANCE SPECTRUM

Fig. 3(a) and 3(b) shows the angle-resolved reflectance spectra in the measurement and simulation, respectively. The red and blue color, respectively, represents high and low reflectance. The geometric parameters of the plasmonic multilayer structure were denoted as follows: $\Lambda = 3000 \text{ nm}$, $\Lambda f = 1500 \text{ nm}$, $t_g = 100 \text{ nm}$, and $t_w = 50 \text{ nm}$. Because of the limitation of the FTIR system, we can only measure the reflection spectrum for an incident angle from 12° to 65° . It can be seen that the simulated spectrum has a good agreement with the measured results. The deviation between the experimental and simulated results may partly result from the structural variations in fabrication.

Both of the simulated and measured angle-resolved reflection spectra show two kinds of resonant dips: angular dependent and independent. The angular dependent dips shown in this letter are corresponding to the grating-coupled SPP which highly depends on the incident angle. Typically, the dispersions present the resonances due to the excitation of SPPs at either the SiO_2 –Ag (SA) or air–Ag (AA) interfaces of the metal film. The resonant dip of the dispersion is denoted according to the conservation of momentum for SPPs: $k_{\text{SPP}} = k_x + G$, where k_{SPP} is the wave vector of the SPP; $G = 2\pi m/\Lambda$ is the reciprocal lattice vectors of the grating; and m is an integer. As shown in Fig. 3, the grating-coupled SPP AA mode for $m = +1$, $m = -1$, and $m = -2$ are, respectively, denoted as AA[+1], AA[−1], and AA[−2]. From the angular-dependent reflection spectra, we can recognize that the resonant dip at $\lambda = 3.9 \mu\text{m}$ and $\theta_i = 20^\circ$ is the AA[−1] mode.

Except the angular-dependent AA modes, there are some angle-independent resonant reflection dips shown in Fig. 3. Here, we discuss the resonant modes located at 0.19, 0.3, and 0.42 eV which can be, respectively, referred to the resonant dip ($\lambda = 6.2 \mu\text{m}$, $\lambda = 5.1 \mu\text{m}$, and $\lambda = 3.4 \mu\text{m}$) shown in Fig. 2. These resonant dips are almost independent of the

Fig. 4. Center wavelength and Q -value of the angular-independent resonant dip as a function of SiO_2 thickness. The incident angle is 20° . The solid line and dot represent the simulation and measurement results, respectively.

incident angle. Especially for the dip at 0.19 eV, the dip is angle-independent for almost the full incident angle. Similarly, in 1999, Porto *et al.* theoretically found that a narrow band of wavelengths may be transmitted over the whole range of incident angles for deep enough metallic gratings with very narrow slits [10]. In our structure, the width of the slit $(1-f)\Lambda$ is comparable to the investigated wavelength. Therefore, the resonant Fabry-Pérot modes inside the 1-D slit are relatively weak meaning that generation of our angle-independent resonant dip is not resulted from the resonant Fabry-Pérot mode.

Fig. 3 shows that the group velocity at the x -direction of these resonant modes $\partial\omega/\partial k_x$ is zero. This implies that the fields of LSPP modes are confined at the Ag-dielectric interface but not confined at the slits. In other words, the fields are standing waves resonant along the x -direction.

Owing that the LSPP mode is localized at the Ag- SiO_2 interface, the resonant properties can be modified by tuning the geometric parameters of the Ag- SiO_2 interface. Fig. 4 shows the center wavelength and the FWHM of the angle-independent resonant dip as a function of SiO_2 thickness t_w . The solid line and dot represent the simulation and measurement results, respectively. It can be seen that the center wavelength is blue-shifted from 6.5 to 5.5 μm as t_w is increased from 20 to 140 nm. The FWHM is increased from 0.25 to 6.5 μm as t_w is increased from 20 to 140 nm.

For a thin t_w , the coupling effects between the grating and flat Ag surface are strong. At this time, the eigen mode at the sandwiched SiO_2 layer can be seen as a combination of two exponentially decaying SPPs on the two SA interfaces. The thinner the t_w , the higher the propagation constant inside the Ag- SiO_2 -Ag cavity [11]. For a thick t_w , the propagation constant inside the resonant cavity is decreased to approach 1. Therefore, the resonant wavelength is blue-shifted. In addition, it is also found

that the resonant wavelength is blue-shifted for a decreasing f , which is not shown here. Therefore, through tuning the parameters of the Ag- SiO_2 interface, one can engineer the optical properties of the angle-independent dip.

V. SUMMARY

The reflection properties of a plasmonic IR filter were experimentally and theoretically investigated. The filter is a plasmonic multilayer structure consisting of a relief metallic grating, a waveguide layer, and a metallic substrate. An LSPP mode, which is angle-independent in almost full incident angle, is observed. Through the use of the LSPP mode, an IR reflection-type notch filter with an ultrahigh immunity for the angular deviation is realized. A reflection dip is designed at $\lambda = 6.2 \mu\text{m}$ with an FWHM of 0.5 μm . For off-resonant condition, the side-band of the spectrum is flat and performs as a metallic plate. It is also shown that the center wavelength and the bandwidth can be easily designed through tuning the parameters of the Ag- SiO_2 interface. In addition, for an increasing θ_i , the position and the line shape of the resonant dip at $\lambda = 6.2 \mu\text{m}$ remain the same. This large angular tolerance means that the superior angular stability of the proposed notch filter makes it more feasible for practical applications.

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