Ultrawide-Bandwidth Slow-Light System Based on THz Plasmonic Graded Metallic Grating Structures

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We explore a novel mechanism for slowing down THz waves based on metallic grating structures with graded depths, whose dispersion curves and cutoff frequencies are different at different locations. Since the group velocity of spoof surface plasmons at the cutoff frequency is extremely low, THz waves are actually stopped at different positions for different frequencies. The separation between stopped waves can be tuned by changing the grade of the grating depths. This structure offers the advantage of reducing the speed of the light over an ultrawide spectral band, and the ability to operate at various temperatures, but demands a stringent requirement for the temperature stability.

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It is known that light can be slowed down in the vicinity of resonances in dispersive materials [1]. In order to reduce the group velocity (v_g) of light coherently, there are primarily two major approaches employing either electronic or optical resonances. In the electronic scheme, drastic slowing down and complete stopping of light pulses can be accomplished by converting optical signals into electronic coherences [2–5]. The use of electronic states to coherently store the optical information, however, imposes severe constraints in the scheme, including narrow bandwidth, limited working wavelengths and strong temperature dependence. While promising steps have been taken towards slowing light in solid-state media and semiconductor nanostructures operating at room temperature [6], it still remains a great challenge to implement such schemes on a chip incorporating optoelectronic devices [5]. As a result there has been great interest in pursuing alternative approaches utilizing optical resonances in photonic structures, such as microcavities [7], photonic crystals [8], semiconductor waveguide ring resonators [9], etc. Recently, it was proposed that plasmonic structures and devices operating in the optical domain offer advantages for applications such as on-chip integration of optical circuits, surface or interface technology, and data storage [10]. What makes the plasmonic structure unique is its potential for spatial confinement of electromagnetic (EM) energy within subwavelength dimensions over a wide spectral range [11–13].

In this Letter, we investigate the slow-light properties of surface-plasmon polariton (SPP) modes by introducing just beneath the surface of a metal film a graded metallic grating of varying depth, as shown in the inset of Fig. 1. Compared to traditional approaches, our novel structure offers the advantage of reducing the speed of the light over a wide-bandwidth and the ability to work at ambient temperatures. We demonstrate that such a structure is capable of stopping light of different frequencies at different locations on a chip. The separation between the adjacent waves stopped by this structure can be tuned freely by changing the grade of the grating depths. It should be noted that some recent work on the so called ''trapped rainbow'' storage of light in metamaterials [14(a)] or graphene [14(b)] is related to the concept presented in this Letter.

Here we employ the *spoof SPP* theory in analytic form [11,15] to study the long-wavelength SPP dispersion behavior and slow-light characteristics, and use the THz domain as an example to illustrate all the unique features of our novel design. For simplicity, we first analyze the dispersion curves of the metallic surface with a constant grating depth, which consists of a one-dimensional (1D) groove array engraved in the metal surface, with a depth h, width d, and lattice constant p. In most of the theoretical studies for the metallic structures based on SPPs in THz and GHz domains, as an approximation the metals could be

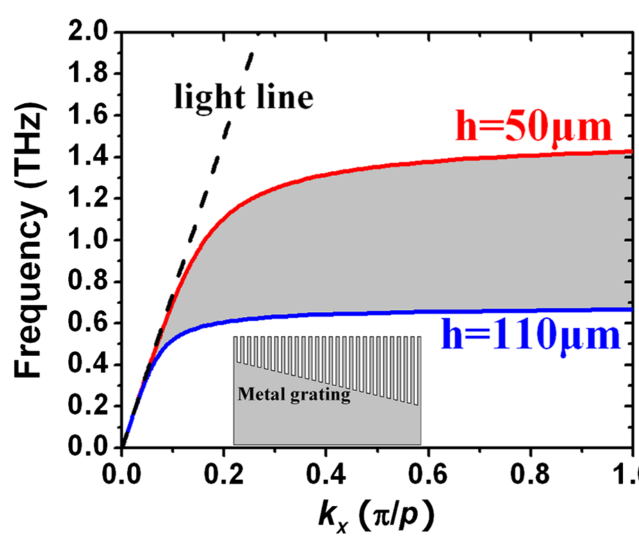

FIG. 1 (color online). Dispersion curves calculated for $d = 20$ μm and $p = 50$ μm with different groove depths ($h = 50$ and 110 μm). Inset: Schematic illustration of the graded grating structure.

treated as perfect electrical conductors (PEC) [11,13]. In our studies, we also assume a PEC. The dispersion relation for TM-polarized (E_x, E_z, and H_y) EM waves propagating in the x direction can be obtained to a first-order approximation [15]:

$$k_x = \frac{\omega}{c}\sqrt{\frac{d^2}{p^2}\tan^2\left(\frac{\omega}{c}h\right) + 1}, \qquad (1)$$

where c is the light velocity in vacuum. The dispersion relations for the 1D groove arrays with various parameters (h, d, p) can be obtained by solving Eq. (1). Figure 1 illustrates the solutions obtained for $d = 20$ μm and $p = 50$ μm, and $h = 50$ μm and 110 μm. One can see from Fig. 1 that for $h = 50$ μm the cutoff frequency of the dispersion curve is close to 1.4 THz. Therefore, the corresponding structure is capable of supporting the surface EM modes at the grating surface at such a frequency, as we have verified by finite-difference-time-domain (FDTD) simulations. For $h = 110$ μm, the cutoff frequency for the grating structure is reduced to about 0.6 THz. Therefore, the EM wave at 0.6 THz could be coupled into the grating structure and confined at the surface. It is worth noting that Eq. (1) is an approximate expression. According to FDTD simulation results, the cutoff frequency estimated from Eq. (1) is slightly larger than indicated above. By introducing an eigenvalue equation in the corrugated conducting plane of a periodic system and taking higher-order scattering components into account [16], the numerical value of the cutoff frequency is in a perfect agreement with the FDTD simulations [17]. Therefore, it is convenient for us to use the approximate expression to illustrate the principle of our design for slowing down the EM waves.

As illustrated by the ω-k relations in Fig. 1, our surface structures are capable of slowing down the EM waves since the v_g of the SPP modes are lower than that for the free-space EM wave. If an EM wave incident at a frequency slightly below the cutoff value is coupled into SPP modes, its v_g approaches zero. In this case, the 1D periodic structure with a subwavelength period functions as a waveguide for supporting slowly propagating EM modes [18]. However, such a metallic surface with a constant grating depth only works as a slow-light device for a very narrow range of frequencies near the cutoff value.

Next, consider a graded grating as shown by inset in Fig. 1, where the depth of the grating is now graded linearly from the left-hand side to the right-hand side. In such a case, the dispersion curves of the graded grating depths will differ from those for a constant grating depth. For example, considering that the depths of the grating in the left-hand side and the right-hand side are 50 and 110 μm, respectively, the dispersion curves between the two ends now lie in the gray region between the two lines in Fig. 1. Obviously, the cutoff frequency of the structure now increases from 0.6 to 1.4 THz.

The v_g for the surface waves may be derived from Eq. (1) and expressed as

$$v_g = \frac{d\omega}{dk_x} = \frac{c}{A + \frac{2d^2h\omega}{p^2cA}\tan(\frac{\omega}{c}h)\sec^2(\frac{\omega}{c}h)}, \qquad (2)$$

where $A = \sqrt{\frac{d^2}{p^2}\tan^2(\frac{\omega}{c}h) + 1}$. From Eq. (2), the group index for the SPP modes can be calculated to be $\frac{c}{v_g} = \frac{c}{d\omega/dk_x} = A + \frac{2d^2h\omega}{p^2cA}\tan(\frac{\omega}{c}h)\sec^2(\frac{\omega}{c}h)$. One can see from Fig. 2 that the v_g at the frequencies of 0.6, 0.7, 0.8, and 0.9 THz are reduced significantly from the speed of light in vacuum. If the grading of these grating depths is sufficiently small, the v_g at these four frequencies can be reduced to zero. This implies that the EM waves are completely "stopped" at the different locations along the surface grating, depending on the frequencies of the incoming EM waves. A broadband EM wave within a frequency band of 0.6–1.4 THz can be dramatically slowed down in a single graded-grating-depth structure, illustrating the ultra-wide-band capability of this approach. This structure has clear advantages compared with approaches based on the cold or warm atomic gases [3,4] or semiconductor nano structures and devices [6]. However, considering future experimental realization of this structure, only when the grating depth, whose cutoff frequency is corresponding to the incident light frequency, is reached can the SPP modes be stopped. Otherwise, they will be scattered or reflected back when the next grating cannot support them.

The effects of temperature on the properties of SPP modes have been studied for metal films in the visible to near infrared spectrum [19] and for doped semiconductor surface structures in the THz spectrum [20]. Temperature-dependent effects reported in these studies arose primarily from the temperature dependence of the dielectric properties. However, at THz frequencies, metals can be treated as PEC, and the SPP modes for these grating structures are

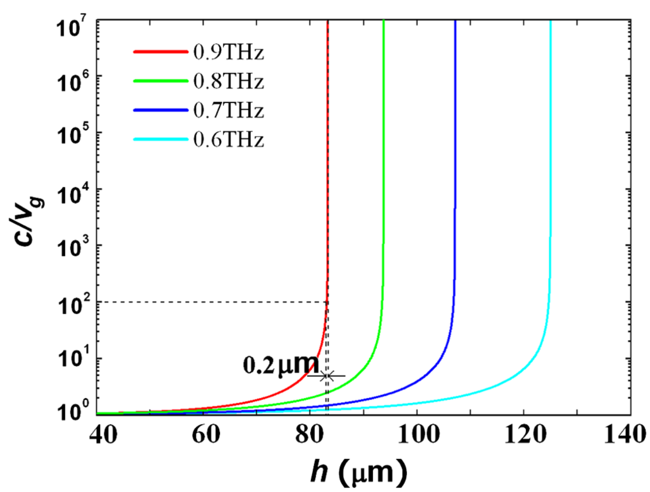

FIG. 2 (color online). Reciprocal of the v_g of the SPP modes are calculated according to the dispersion curves in the gray region in Fig. 1.

not expected to be as sensitive to temperature-dependent dielectric properties. Therefore, our slow-light structure should be capable of operating over a wide range of temperatures in the THz spectrum, unlike its counterparts based on atomic gases [3,4]. It should be noted that such slow-light structure still requires great thermal stability because a small change of the working temperature will introduce thermal expansion or contraction of the structure. As shown in Fig. 2, the dispersion curve and the v_g of the SPP modes are sensitive to the depth of the gratings. A depth change about 0.2 μm will cause the v_g to change from $c/10^7$ to $c/10^2$ at 0.9 THz (as shown by the line of 0.9 THz in Fig. 2). Because of the thermal expansion of the metal materials, a temperature shift will change the structure parameters and therefore dramatically affect the v_g of the SPP modes.

The thermal expansion expression of silver can be expressed as [21]

$$\Delta L/L_0 = -0.515 + 1.647 \times 10^{-3}T + 3.739 \times 10^{-7}T^2 + 6.283 \times 10^{-11}T^3. \quad (3)$$

Here, L_0 is the length or lattice parameter at room temperature, about 292.335 K. Assuming that the structure parameters are ($p = 50$ μm, $d = 20$ μm, $h = 83.335$ μm) at 292.335 K, the v_g of the SPP modes at 0.9 THz is about $10^{-5}c$ [according to Eq. (2)]. When the working temperature shifts by ± 0.1 K, the structure parameters will be ($p = 50.009$ μm, $d = 20.004$ μm, $h = 83.351$ μm) at 292.435 K and ($p = 49.991$ μm, $d = 19.996$ μm, $h = 83.319$ μm) at 292.235 K because of thermal expansion, and the v_g will be about $c/1229$ and $c/1506$, respectively. Clearly, the performance of the slow-light system is very sensitive to the temperature shifts. If stable performance is required, the temperature of the working structures has to be stable.

It is worth noting that the different frequencies are localized at various positions corresponding to different grating depths as shown in Fig. 2. For instance, the EM wave at the frequency of 0.9 THz is almost stopped at the location having the depth of approximately 83.335 μm, whereas that at 0.6 THz is localized at the grating depth of 125.000 μm. The process was simulated using a two-dimensional (2D) FDTD model. We have assumed the thickness of the metal to be 400 μm, the frequency of the incident wave to be within 0.6–0.9 THz. The period and width of the grating structure are 50 and 20 μm, respectively. In Fig. 3(a), the depth of the grating structure linearly changes from 50 to 150 μm. The total length of the grating structure is approximately 2 mm ($t_{\text{pass}} = 2$ mm$/c$), and the calculation time is set to $T = 7.5t_{\text{pass}} = 15$ mm$/c$. An EM wave propagating in free-space should be able to propagate from the left-hand side to the right-hand side of the simulation region within the calculation time.

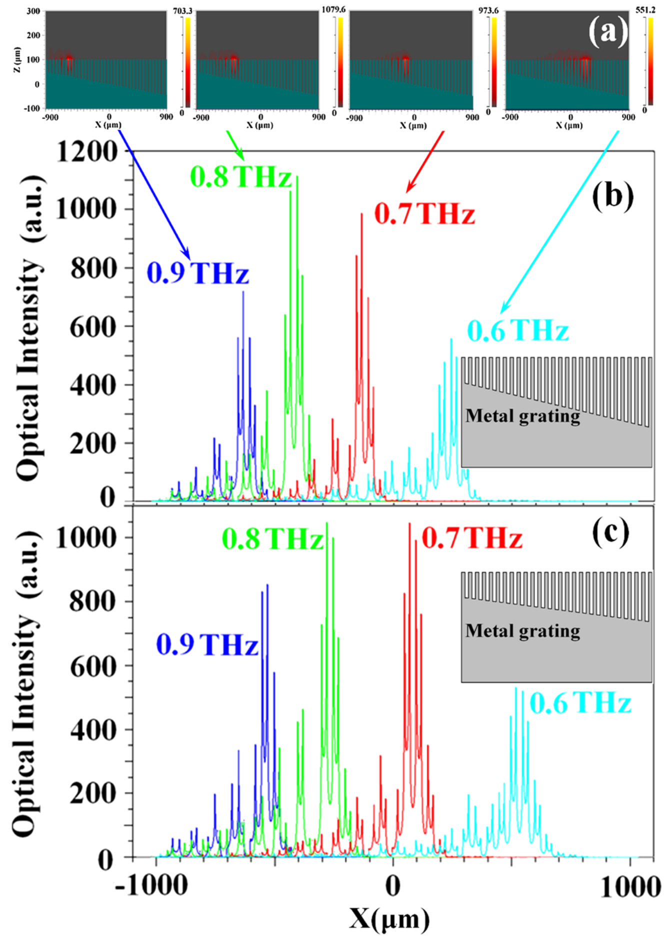

FIG. 3 (color online). Results obtained by using 2D FDTD simulations: (a) corresponds to the 2D field distribution at four different frequencies of 0.6, 0.7, 0.8, and 0.9 THz. (b) and (c) represent 1D optical intensity ($|E|^2$) distribution 2 μm above the structured metal surface. The depth of the grating structure in (b) and (c) changes from 50 to 150 μm linearly [the inset in (b)] and from 50 to 130 μm linearly [the inset in (c)] from the left-side end to the right-side end, respectively. The dimension of the simulated region is 3600 μm $\times$ 800 μm with a uniform cell of $\Delta x = 2$ μm and $\Delta z = 2$ μm. This simulated region is surrounded by a perfectly matched layer absorber.

2D FDTD simulation results indicate that different frequencies within the range of 0.6–0.9 THz are localized at different locations along the surface after a calculation time, $T_1 = 7.5t_{\text{pass}}$. When the calculation time is longer, e.g., $T_2 = 15t_{\text{pass}}$, $50t_{\text{pass}}$, and $100t_{\text{pass}}$, the locations of these frequencies more or less stay unchanged (data not shown here), confirming that the v_g of the SPP modes have been reduced drastically. These characteristics are also reflected in the 1D steady-state wave intensity at a location of 2 μm above the metal surface; see Fig. 3(b). These results clearly show that the graded grating depths can be used to slow down the EM wave packet and even stop it at different locations on the surface depending on the frequency of the incoming EM wave. It should be noted that every peak amplitude of the electric field in Figs. 3(b) and

3(c) is located right at each edge of the grating ridge. In other words, for the modes guided by the graded grating structure the electromagnetic fields are most intense at the edges of the ridges, which is consistent with the previous result about SPP modes supported on the grating structures [22]. Such a structure could be used to disperse different frequency components of the incoming EM pulse, i.e., to function as a spectrometer. If our surface grating structure is incorporated into a chip, the wavelength or frequency of the EM wave can be readily analyzed by monitoring the localized evanescent waves. If different waves at different locations can be coupled out, a novel plasmonic wavelength-division multiplexing is also realizable. Interestingly, if the grade of the grating depths is changed, the separations between the adjacent waves can be tuned freely. For example, if the depth of the grating structure changes linearly from 50 to 130 μm from left to right across the structure, the peak locations of the different frequencies will be expanded horizontally [as shown in Fig. 3(c)]. It is worth noting that the micrometer-scale dimensions of the structure for THz waves can be easily realized by current fabrication technologies.

Finally, the coupling issue is an important problem in SPP studies, both theoretical and experimental. In recent related publications [13(a)], novel symmetric metallic structures did suffer from low coupling efficiency [13(c)]. Actually, some coupling approaches have been reported, which might be helpful for coupling enhancement on our single side grating structures, such as tapered waveguide [17], perpendicular razor blade [13(b)], and so on. Consequently, we believe that coupling enhancement approaches for our structures are ready based on these reports.

In conclusion, we have proposed a metal surface structure with graded grating depths that supports THz SPP modes. When the grating depths are graded, the dispersion curves of the surface structure are spatially inhomogeneous. Such graded-grating-depth structures are capable of slowing down or even stopping EM waves within an ultrawide spectral band at different locations along the surface. The separation between the adjacent localized frequencies can be tuned freely by changing the grade of the grating depths. Importantly, the propagation characteristics of these *spoof SPP* modes can be controlled by the surface geometry. Such a feature could open a door to the control of the EM wave on-a-chip or even realize novel applications such as a spectrometer integrated on a chip for chemical diagnostics, spectroscopy and signal processing applications. Compared to the traditional slow-light approaches currently under investigation, this structure offers the advantages of slowing down and stopping the EM waves over an ultrawide spectral band and the ability to operate at various temperatures.

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