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Trapping of surface plasmon waves in graded grating waveguide system

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We have proposed a graded grating plasmonic system with a significant slow-light effect for the propagation of high-confinement surface plasmon (SP) wave. Theoretical analysis and numerical simulations show that the localized position of SP wave in the plasmonic waveguide is dependent on the operating frequency. It is found that the slow-light effect exhibits an obvious enhancement with propagation. The proposed ultracompact configuration offers the advantage of a large trapping bandwidth of 90 THz, which may find excellent applications on slow-light systems, especially optical buffers. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4733477]

Surface plasmons (SPs) are waves that propagate along the surface of a conductor due to the interaction between the light waves and the free electrons of the conductor.[1,2] SPs are considered as one of the most promising candidate for concentrating and channeling light at subwavelength scale because of their ability to overcome the traditional diffraction limit.[2] In recent years, numerous devices based on SPs have been investigated theoretically and demonstrated experimentally, such as optical-switching,[3,4] plasmonic lens,[5] wavelength demultiplexer,[6,7] Bragg grating,[8] and coupler.[9]

To slow down the propagation speed of light and to coherently trap and store optical pulses, it has drawn a lot of attentions for its profound applications in optical communication and quantum information processing.[10] So it is highly important to investigate approaches and designs to slow down or even stop light. So far, a variety of structures have been reported experimentally or theoretically.[10–14] For instance, Gan *et al.* reported a kind of THz plasmonic graded metallic grating structures to reduce the speed of light over an ultra-wide spectral band[15] and realize "rainbow" trapping and releasing on metal surface.[16] However, previous investigations mainly focused on how to slow and trap light on metal surface. Slowing and trapping of SP wave on metal surface may bring about large scattering losses due to the poor confinement of light. It is very significant to trap light in plasmonic waveguides which have better confinement of light with an acceptable propagation length for SPs.[17]

In this letter, a plasmonic waveguide system based on graded grating structures is proposed and numerically investigated by using transmission line theory and finite-difference time domain (FDTD) method. Both the theoretical and simulation results show that this plasmonic structure can strongly slow down the propagation velocity of SP wave. We also find that the group index (defined as c/v_g) at a given frequency is dependent on the grating depth, which indicates that the SP wave can be significantly slowed down and localized at a specific position of the plasmonic waveguide. The slow-light plasmonic system can operate in a large frequency bandwidth. Such ultracompact configuration provides an effective method to slow or even trap the light signals.

Figure 1(a) shows the schematic diagram of the proposed plasmonic waveguide system. The system consists of a metal-insulator-metal (MIM) waveguide coupled with graded plasmonic stubs (forming a graded grating). When a TM-polarized plane wave is coupled into the waveguide, SP wave can be excited at the metal-insulator interfaces and confined in the insulator layer. The metal is selected as silver, whose frequency-dependent relative permittivity is characterized by the Drude model: $\varepsilon_m(\omega) = \varepsilon_\infty - \omega_p{}^2/[\omega(\omega + i\gamma)]$. Here ε_∞ is the dielectric constant at infinite angular frequency, ω_p is the bulk plasma frequency, and γ is the electron collision frequency. ω is the angular frequency of the incident wave in vacuum. The values of these parameters can be set as $\varepsilon_\infty = 3.7$, $\omega_p = 9.1$ eV, $\gamma = 0.018$ eV.[18]

We use an improved transmission model and transmission line theory[19] to account for the dispersion properties of the system. According to the transmission line theory, the system is equivalent to a parallel connection of an infinite transmission line with the characteristic impedance of $Z_{MIM} = K_0 w/\omega\varepsilon_0\varepsilon_{air}$ (representing the MIM waveguide) and a finite transmission line with the characteristic impedance Z_s terminated by a load Z_L (representing the stub). For simplification, the stub section can be replaced by an effective impedance described by $Z_{stub} = Z_s(Z_L - iZ_s\tan(K_s h))/(Z_s - iZ_L\tan(K_s h))$, where $Z_s = K_s w/\omega\varepsilon_0\varepsilon_{air}$ and $Z_L = (\varepsilon_m/\varepsilon_{air})^{1/2} Z_s$. $K_0 = \alpha_0 + i\beta_0$ and $K_s = \alpha_s + i\beta_s$ are the complex wave vector of the fundamental propagating TM mode in MIM waveguide and stub, respectively. p is the distance between adjacent stubs (i.e., the period of the grating). Using transmission line theory,[20,21] the dispersion relation between the frequency and Bolch wave number $K = \alpha + i\beta$ in the waveguide grating with a constant stub depth is found to be

$$\cosh(Kp) = \cos(K_0 p) - i\frac{Z_{MIM}}{2Z_{stub}}\sin(K_0 p). \qquad (1)$$

In Figs. 1(b) and 1(c), we show the dispersion relations for the plasmonic waveguide calculated by using transmission line theory. Our calculations reveal that the cutoff frequency has a red-shift with the increase of the grating depth. Figure 1(d) shows the group index c/v_g as a function of the frequency of incident wave at a given grating depth. The group velocity $v_g(\equiv \partial\omega/\partial\beta)$, which is given by the slope of the tangent line of the dispersion, can be slowed down significantly

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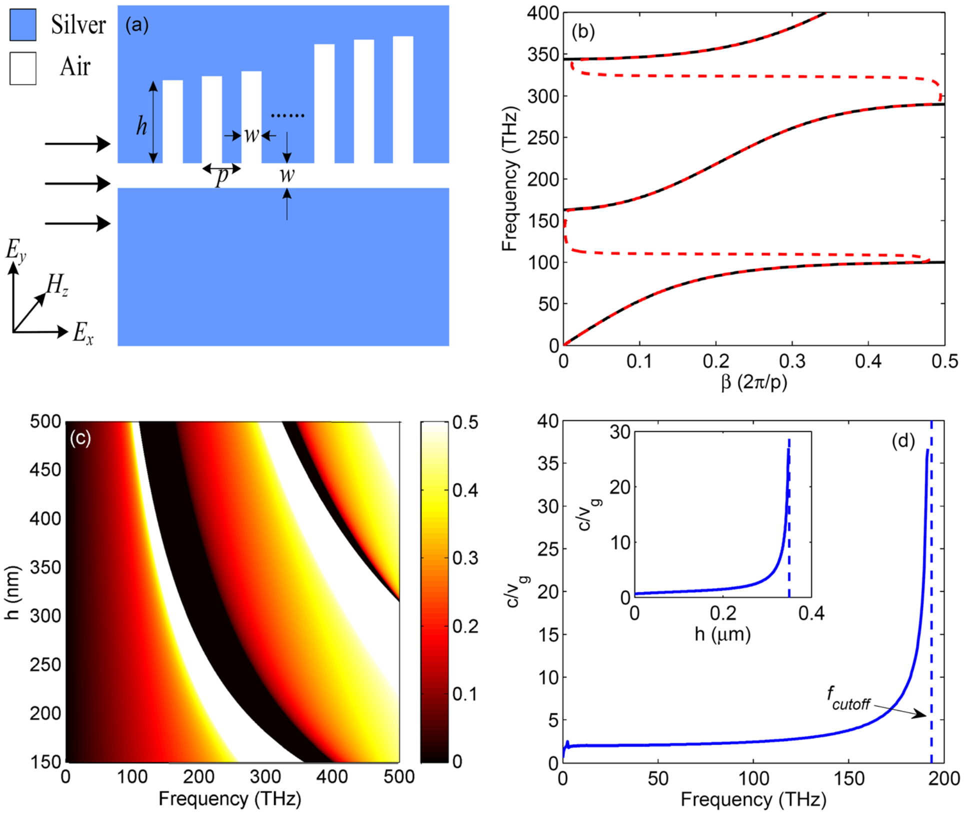

FIG. 1. (a) Schematic diagram of the plasmonic waveguide system: w, the width of the waveguide and stubs; p, the period of the grating; h, the grating depth. (b) Dispersion curves calculated using transmission line theory (red dashed line). The results are shown for a waveguide structure with a constant grating depth of $h = 500$ nm, $w = 50$ nm, and $p = 200$ nm. Also shown are the dispersion curves for lossless metal (black solid line). (c) Evolution of propagation constant β at different frequencies with the grating depth of $w = 50$ nm and $p = 200$ nm. (d) Group index of SP wave as a function of frequency for $h = 320$ nm. The cutoff frequency f_{cutoff} is about 193.5 THz (i.e., $\lambda_{\mathrm{cutoff}} \approx 1.55\,\mu$m). The inset shows group index versus the grating depth for the incident frequency of 193.5 THz.

when the incident frequency approaches to the cutoff frequency. We also calculate the group index as a function of the grating depth at a given incident frequency. As shown in the inset of Fig. 1(d), the group index is greatly increased and exhibits a significant slow-light effect when the incident frequency is 193.5 THz with grating depth of 320 nm. Such waveguide with a constant grating depth only slow down the group velocity within a very narrow range near the cutoff frequency. To enlarge the slow-light frequency range, we design a plasmonic waveguide system based on graded metallic gratings. If the grade is small enough, the dispersion relations are supposed to change gradually along the waveguide with the ascending grating depth. The group velocity of incident light with certain frequency can be greatly reduced at a specific location. Thus, SP waves can be trapped at the corresponding waveguide positions, leading to the ultra-wide operation bandwidth.

To clearly show the dynamic evolution of the SPs propagation and validate the above analysis, we present the dependence of SP intensity in the stubs on the propagation time and distance by using FDTD method. In Fig. 2(a), the incident light is a TM-polarized Gaussian pulse with duration of 100 fs and central frequency of 160 THz. It is found that the SP wave propagates along the x direction with an increasingly slower group velocity, and the strongest intensity corresponds to the localized position of SPs. From Fig. 2(a), it can be seen that the SP wave is trapped at the position of $\sim$7.5 μm, where the grating depth is about 300 nm. By using transmission line theory, the cutoff frequency of the grating with the depth of 300 nm is calculated to be 155.4 THz, which is very close to the FDTD results.

The small difference of the transmission line theory may be attributed to the errors in the phase of the reflection coefficient at the two grating interfaces, which have been discussed in Ref. 22. Inset of Fig. 2(a) shows the relation between the propagation distance and time for SP wave. The curve becomes steeper through the waveguide system, which confirms that the group velocity of SP wave is gradually slowed down.

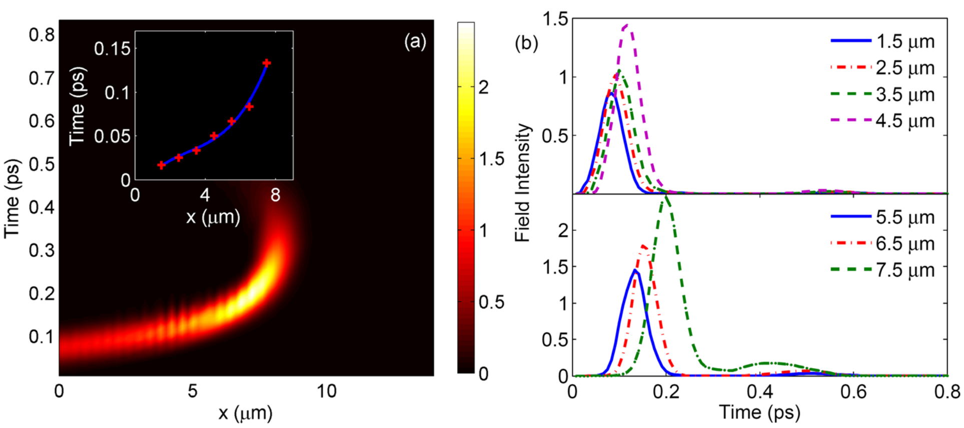

FIG. 2. (a) Time-dependent field intensity ($|H_z|^2$) in the stubs. Inset: arrival time of SP wave at different spatial positions. (b) Intensity evolution of SP wave at different spatial positions of the proposed structure. In calculations, the incident light is a TM-polarized Gaussian pulse with a width of 100 fs and central frequency of 160 THz. The grating depth of the structure changes from 150 nm to 500 nm linearly in a 16 μm region. The period and width of the grating structure are 200 nm and 50 nm, respectively.

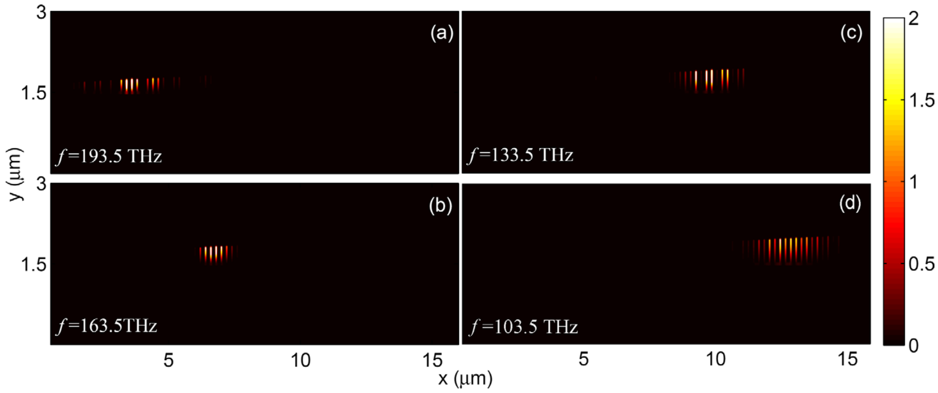

FIG. 3. Field distributions of the trapped waves with the frequencies of (a) 193.5 THz, (b) 163.5 THz, (c) 133.5 THz, and (d) 103.5 THz. The incident light is TM-polarized Gaussian pulses with the duration of 100 fs. The grating depth of the plasmonic waveguide system is linearly increased from the left-hand side ($h = 150$ nm) to the right-hand side ($h = 500$ nm) (enhanced online) [URL: http://dx.doi.org/10.1063/1.4733477.1].

Figure 2(b) shows the intensity evolution of SP pulse along the propagation direction at seven different positions and also distinctly illustrates the gradually slowing down of SP wave. For instance, it takes about 13 fs to pass from the position of 1.5 μm to 2.5 μm. While it takes about 50 fs from the position of 6.5 μm to 7.5 μm. It should be noted that in practical, however, the SP wave can never be completely trapped due to the metallic absorption.[23] In order to realize the real trap of SPs, one can incorporate a gain media in the structure to compensate for the metal loss. Thus, the group velocity v_g of SP wave is expected to be further slowed down or even to be zero.

Finally, to confirm that our structure can trap SP wave in an ultra-wide frequency bandwidth, the distributions of magnetic field intensity ($|H_z|^2$) are simulated by FDTD method. Figure 3 depicts that SP waves with four different frequencies (i.e., 103.5 THz, 133.5 THz, 163.5 THz, and 193.5 THz) are trapped at different positions along the waveguide. These frequencies correspond to the cutoff frequencies of the grating depths at these positions. The four frequencies are trapped at the positions of 3.57 μm, 6.24 μm, 9.98 μm, and 13.82 μm, which correspond to the grating depth of about 220 nm, 275 nm, 355 nm, and 440 nm, respectively. The proposed waveguide system possesses the ability to trap SP wave over a large frequency bandwidth of about 90 THz.

In summary, we have proposed a graded plasmonic grating waveguide system, which supports slow-light modes and exhibits a small group velocity to realize the trapping of SP wave. Different from previously proposed structures which trap SPs on metal surface, our structure can trap SP wave in plasmonic waveguide with better confinement of light. Both the transmission line theory and FDTD results show that the waveguide system exhibits a large slowdown effect over a broad frequency range, which are highly desirable for practical applications of chip-based optical buffers and slow-light devices.

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