Deep subwavelength manipulation of terahertz (THz) waves by plasmonic surface

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Abstract

Deep subwavelength manipulation of terahertz (THz) wave is a key method to realize compact on chip THz devices. It is demonstrated that the refractive index change in a deep subwavelength region of a dielectric layer can effectively manipulate the surface THz wave propagation by the simulation study. The feature size of this area is only 10 μm (~1/8 λ). A slight change of refractive index, position or size of this region is enough to manipulate the surface THz waves with high efficiency, such as the transmissivity or reflectivity of different THz frequencies. Moreover, the change of the deep subwavelength region can be controlled by an ultrafast laser to achieve ultrafast dynamic manipulation of THz waves. This is a concise and efficient method of manipulating electromagnetic waves on the deep subwavelength scale and to fabricate more compact integrated optical devices.

1. Introduction

Guiding and manipulation of electromagnetic (EM) energy in the subwavelength range and beyond the diffraction limit is the main characteristic of plasmonic devices or structures, which can promote the development of many promising applications of integrated photonic circuits [1, 2], near-field optics and devices [3, 4], biosensors [5, 6], and photovoltaics [7, 8]. These plasmonic devices couple the EM waves into the electron oscillations and propagate them along the interface between the dielectric and metallic materials to enhance the interaction between light and matter at subwavelength scale by using their own subwavelength characteristics [9, 10]. At terahertz (THz) frequencies, various periodic perforated surfaces and waveguide structures have been used to control the transmission and propagation of EM fields based on the plasmonic effects [11–20], and promote many different THz applications including sensing [21, 22], imaging [23, 24], spectroscopy [25], communication [26, 27]. The typical plasmonic waveguide structure is a periodic grating on metal surface [13, 28–33]. The grooves of the periodic grating waveguide can have different profile shapes such as rectangular, oblique, trapezoidal, V-shaped, serrated and half-moon shaped to excite and control the properties of plasmonic waves [34–37]. In addition, the plasmonic waveguide with gradual depth [38–42], gradual period [43], and vertical or downward conical grooves [44] have also been used to slow down or capture the surface EM waves, called ‘trapped rainbow.’ In fact, the physical origin of the ‘trapped rainbow’ has been proved to be a kind of reflection and mode resonance, which provide a new method to control the surface EM waves through a deep subwavelength micro/nano structure [45, 46]. Another way to control the surface waves is to use metamaterials with large scale sub-wavelength periodic structures [47–51]. However, metamaterials must rely on the interaction of many periods, instead of using a single subwavelength structure to manipulate surface waves. In this paper, it is demonstrated that the propagation of surface THz waves can be effectively controlled by the changing the refractive index of the cover dielectric layer in a deep subwavelength area. In practical applications, the refractive index change in a small area can be controlled by many ways, such as ultrafast laser pulse, so as to realize the ultrafast manipulation of EM wave. At the same time, this mechanism can also be applied to deep subwavelength THz sensing.
2. Numerical simulation

The dispersion property of a metal grating with rectangular grooves (figure 1) is determined by its depth \(d\), width \(w\), and period \(p\). Hence, the metal waveguide can be designed to propagate and slow down EM waves of different frequency simply by adjusting the three parameters of depth \(d\), width \(w\), and period \(p\) \([11, 13, 45]\). In addition, the refractive index \(n\) of the groove material (like air or silica) is another factor to control the propagation of the surface waves. Here, the refractive index \(n\) in the grooves is not changed, but only the refractive index \(n\) of the layer attached on the metal grating is changed in a deep subwavelength region, which means only refractive index \(n\) of the covered dielectric layer is changed. The dielectric layer can be deposited on the metal grating to form a hybrid waveguide experimentally. The femtosecond laser pulses with different energies can be focused on the subwavelength region to change the local refractive index \(n\) dynamically, so as to control the surface wave in the order of femtosecond \([52, 53]\). The grating model with a special region that have different refractive index \(n\) and different positions \(P1, P2, P3\) is built (figure 1) and simulated via finite difference time domain (FDTD) modeling. The FDTD method is a rigorous solution to Maxwell’s equations and does not have any approximations or theoretical restrictions, which has been widely used as a propagation solution technique in integrated optics \([41–46]\). The size of this region is equal to the size of the grating groove. The meshed size or the uniform cell of the simulation model is \(\Delta x = \Delta z = 1 \mu m\). At THz frequencies, metals behave like a perfect conductor, and the negligible penetration of the EM fields leads to highly delocalized SPPs, which is also called spoof SPPs \([43]\). Hence, the material of the grating waveguide is modeled as a perfect electric conductor (PEC), and the whole simulation region is surrounded by a perfectly matched absorbing layer. The position and refractive index of the single deep subwavelength region are the main parameters to be studied. A p-polarized \((Hy, Ex, Ez)\) end fire excitation source is introduced at the beginning of the PEC model, which located at 1000 \(\mu m\) away from the single deep subwavelength region \((P1)\), to excite the surface plasmonic EM waves.

According to reference \([45]\), the cutoff frequency is below 4.6 THz for metal grooves with period of 20 \(\mu m\), width of 10 \(\mu m\), and depth of 10 \(\mu m\). Hence, a 3.75 THz (wavelength of 80 \(\mu m\)) excitation source is used to excite and generate the propagating surface EM wave along the periodic metal grating. The generated surface EM wave is propagated smoothly along the grating until it meets a special region with controllable refractive index \(n\) (marked with grey in figure 1). Here, only the refractive index and position of the special region are changed to run the simulation. Two monitors \((M1, M2)\) are located before and after the special region to record the before and after intensity of the surface EM wave, respectively.

3. Simulation results and discussion

According to the FDTD simulation results (figure 2), the surface wave intensities before (reflection) and after (transmission) the special region are all controllable with the increase of refractive index \(\Delta n\) or positions \(P1, P2, P3\). Here, \(\Delta n\) means the increase of refractive index relative to air \((n = 1)\).

At the zero point of figure 2, \(\Delta n = 0\), the grating becomes a uniform waveguide grating, and the intensity of \(M1\) and \(M2\) are all approximately equal, which is a base intensity of the surface wave that is propagated on the uniform waveguide. When the refractive index \(\Delta n\) gradually increases, the intensity of \(M1\) increases and the intensity of \(M2\) weakens, which can be attributed to the reflection of the surface wave by the special deep

![Figure 1. Schematic of metal grating showing width (w), period (p), depth (d), and refractive index (n) in the deep subwavelength region of the cover layer. This deep subwavelength region with controllable refractive index (n) can be located at different positions (P1, P2, P3). The surface EM waves propagate along the direction of the X axis.](image-url)
subwavelength region. The intensity of reflection wave can be more than 2 times of base values and reach at ‘1’ (square dotted black line in figure 2(a)). The reason is the intensity we monitored is localized near field intensity that can be enhanced by interference and localized SPPs as shown in figure 3. If the special region is located at position 1 (square dotted black line), the intensity of M1 and M2 show the most dramatic change, which means that a small change of refractive index (∆n ∼ 0.3) is enough to control the transmissivity or reflectivity of different THz frequencies. Hence, if people want to manipulate the surface EM wave with high efficiency, the most effective position to change the refractive index (∆n) is position 1 (P1). When the refractive index (∆n) increases to ‘0.4’, the M2 intensity (square dotted black line in figure 2(b)) drops to nearly ‘0’, which means that the special deep subwavelength region can approximately block all the surface waves. If the special region moves to other positions like P2 (circle dotted red line) and P3 (triangle dotted blue line), the intensity of M1 and M2 change more and more slow. The mechanism for effective THz wave control at different groove position (P1, P2, P3) is the excitation of resonant modes. The change of refractive index in the dielectric layer forms a new localized dielectric EM mode. At P1, the refractive index changing area is covered on a single groove and forms a new cavity. The resonant modes between the new localized dielectric mode and groove mode are excited in the new cavity. At P2, only half of cavity is working, so the efficiency is slightly lower. At P3, the controlling efficiency becomes much lower. Because, there is no cavity any more, and the controlling of surface waves only depends on the dielectric mode. This mechanism can be also used for the surface refractive index sensing with high spatial sensitivity.

Figure 3 shows the two-dimensional surface EM wave distribution obtained through the metal waveguide with a deep subwavelength region at position P1 of varying refractive index. ∆n = 0.0 (a); ∆n = 0.2 (b); ∆n = 0.4 (c).

Figure 2. Intensity of surface EM wave with a frequency of 3.75 THz before (a) and after (b) the special deep subwavelength region of varying refractive indices (∆n) and positions (P1, P2, P3).

Figure 3. Two-dimensional EM wave distribution with a frequency of 3.75 THz obtained through metal waveguide with a deep subwavelength region at position P1 of varying refractive index: ∆n = 0.0 (a); ∆n = 0.2 (b); ∆n = 0.4 (c).
changing refractive index ($\Delta n$). Importantly, the changing refractive index ($\Delta n$) can be controlled by an ultrafast laser to realize the ultrafast manipulation of surface EM wave [52, 53]. In addition, the position and size of the special region also can be controlled by simply moving the position and size of the laser focal point.

The surface EM waves with different frequencies can also be controlled by the refractive index. For example, a source of 3 THz (wavelength of 100 μm) is tested (figure 4) for comparison. The control effect of the deep subwavelength region for longer wavelength (lower frequency) is reduced. Thus, the refractive index or size of the special deep subwavelength region must be increased to obtain a high efficiency manipulation. For the frequency of 3 THz, the most efficient blocking effect occurs at the refractive index ($\Delta n$) of ‘$\sim$0.75’ (square dotted black line in figure 4(b)), which is larger than that of 3.75 THz.

4. Conclusion

The numerical results demonstrate that the propagation of plasmonic EM waves can be efficiently controlled by a single deep subwavelength region ($< 1/8 \lambda$) with changing refractive index or positions, which has advantages over metamaterials or photonic crystals that rely on large-scale periodic structures. The refractive index, position, and size of the region can be controlled by an ultrafast laser to manipulate the EM waves of different frequencies at a high speed and high efficiency. For example, the femtosecond laser pulses with different energies can be focused on the subwavelength region to change the local refractive index ($n$) dynamically, so as to control the surface wave in the order of femtosecond. In addition, the intensity of the reflected waves is enhanced by the localized SPPs and interfering of incoming and reflected waves. When coupling with the composite antennas [54], the dynamic controllable subwavelength waveguide can become a more effective on-chip platform for THz applications. It can be used in fast optical switch or high sensitivity detection. This control method of surface EM waves can also be combined with semiconductor-based plasmonic waveguides that is compatible with the current complementary metal-oxide-semiconductor (CMOS) fabrication technique [55–58], for subwavelength THz transmission and manipulation in a real CMOS plasmonic platform. Hence, controlling plasmonic EM waves and fabricating more compact integrated optical devices such as nonlinear wave switches, local enhanced slowing waveguides, dynamic filters, and amplifiers for future integrated THz circuits is considerably easier by this method, and will further promote the research of material identification for THz-sensitive molecules or cells, as well as surface THz metamaterials and quantum dots.

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