Optics Communications 332 (2014) 132–135

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Dynamic trapping of terahertz waves by silicon-filled metallic grating structure

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ARTICLE INFO

Article history:
Received 12 December 2010
Received in revised form
26 June 2014
Accepted 1 July 2014
Available online 14 July 2014

Keywords:
Plasmons
Surface waves
Terahertz waves

ABSTRACT

We investigate the feasibility of dynamic trapping of terahertz waves using a silicon-filled metallic grating structure. Using the dispersion relation analysis and the two-dimensional finite element method simulations, we reveal that, if a graded refractive index distribution in the grooves is optical induced, the device has the ability to dynamic trap terahertz waves of different frequencies at different positions (so-called trapping rainbow). Moreover, we demonstrate that the trapped position of a certain frequency of the terahertz waves can be moved continuously along the grooves in subwavelength scale by ingenious control of the distributions of the refractive indices of silicon filled in the grooves. Our design has the potential for the construction of active plasmonic terahertz devices, such as optical controlled terahertz filter, router and demultiplexer in a broadband terahertz communication system.

1. Introduction

In recent years there has been an increasing interest in plasmonic devices, one of the major driving forces is its ability to spatially confine electromagnetic (EM) energy over distances significantly smaller than the wavelengths when the frequencies of the waves are close to the plasma frequency of a conductor [1]. For most metals, this corresponds to radiation at optical frequencies. At terahertz frequencies, on the other hand, metals resemble a perfect electric conductor (PEC), and the negligible penetration of the EM fields leads to weak spatial confinement. However, this problem can be overcome by tailoring the surface topography of a PEC to allow the existence of spoof surface plasmon polaritons (SPPs) over a wide spectral range. The spoof SPPs is so called because the effective permittivity of the surface-tailored PEC in the terahertz frequencies has the same plasma form as that of the metals such as silver in the optical frequencies and the propagation characteristics of the surface mode of the spoof SPPs is very similar to that of real SPPs. Moreover, the characteristics of the spoof SPPs can be arbitrary controlled by varying the geometrics of the surface structures [2]. Taking advantage of such properties, several novel plasmonic devices have been proposed in the terahertz frequencies [3–7].

Among these plasmonic devices, the graded metallic surface grating design [6,7], where the depth of the grating increases uniformly along the propagation direction, has attracted considerable attention recently. This is because such structures are capable of slowing down or even stopping EM waves within an ultrawide spectral band at different locations (so-called trapping rainbow). Such a feature opens a door to the control of the EM wave on-a-chip or even realizes novel applications such as a spectrometer and signal processing applications. Soon after, other gradual structures were devised to realize the “trapping rainbow” effect, such as circular metallic waveguide with a linearly tapered GaAs core [8], metallic film covered by a dielectric grating of graded thickness [9]. However, such gradual structures are challenging to fabricate. To our knowledge, only two studies reported the experimental observation of the “trapping rainbow” effect in the visible frequency range [10,11]. In addition, once the structures are formed, the trap positions of the certain frequencies of the EM waves are fixed. That is, the trapping manner cannot be dynamically controlled. Although a temperature tuning method has been proposed [12], thermal effects are intrinsically slow and may not suitable for applications that require high speed modulation.

In this paper, we propose to use a silicon-filled metallic grating to realize dynamic trapping of terahertz waves along the grating surface. Theory and simulation results show that if a graded refractive index distribution in the grooves is optical induced, the structure has the ability to dynamic trap terahertz waves of different frequencies at different locations along the metallic grating

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http://dx.doi.org/10.1016/j.optcom.2014.07.007
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surface. Besides, the trapped position of a certain frequency can be moved continuously along the grooves in subwavelength scale by ingenious control of the distributions of the refractive indices of silicon filled in the grooves. Compared with these gradual structures described above, our design is easier to fabricate. More importantly, such trapping effects can be optically controlled.

2. Structural design and theoretical analysis

The proposed schematic structure is shown in Fig. 1. It consists of a one dimensional (1D) groove array engraved in the metal plane with depth h, width d and lattice constant p. The grooves are filled with high-resistivity silicon, whose refractive index in the terahertz frequency range can be modulated by laser pumping from the top of the grooves [13].

The dispersive relation of EM waves propagating along the z-axis direction on the surface of the structure can be expressed as [14]:

$$\frac{d}{p}\sum_{n=-\infty}^{\infty}\frac{1}{\tau_n h}\left(\mathrm{sinc}\frac{\beta_n d}{2}\right)^2=\frac{n_f}{kh}\cot k n_f h, \qquad (1)$$

where $\beta_n=\beta_0+2\pi n/p$, β_0 is the propagation constant, τ_n is the exponential decay factor along the x-axis,$\beta_n^2-\tau_n^2=k^2=\omega^2\mu_0\varepsilon_0$. μ_0 and ε_0 are the permeability and permittivity in vacuum, respectively. n_f is the reflective index of the silicon filled in the grooves.

Using the dispersion relation (1), by properly adjusting the structure parameters such as d, h and p, the metal grating structure shown in Fig. 1 can support the surface modes in the terahertz region. That is, the terahertz waves can be spatially confined and guided along the metallic surface. The confinement is increasing with the frequency. When the terahertz wave frequency is close to the cutoff frequency, the confinement is strongest. In such particular case, the group velocity approaches zero, the terahertz wave is trapped along the metallic grating surface. Although this phenomenon has been already confirmed theoretically [7] and experimentally [15], this paper is concerned with the influence of the refractive index of the silicon filled in the grooves on the terahertz surface modes.

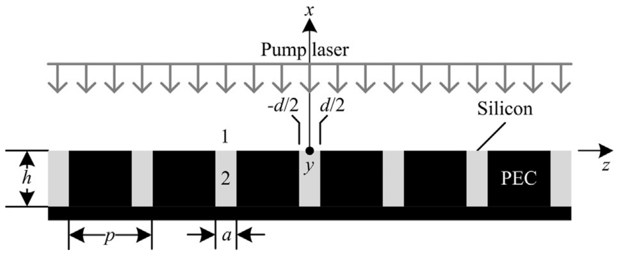

Fig. 1. Structure diagram of a 1D metallic grating. The grooves are filled with high-resistivity silicon.

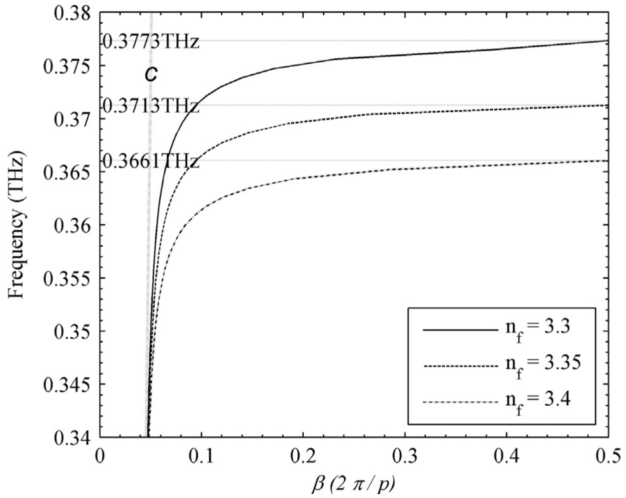

Fig. 2. Dispersion curves calculated for $d=20\,\mu$m, $h=60\,\mu$m and $p=40\,\mu$m with different n_f. Corresponding cutoff frequencies (horizontal lines). Gray line labeled by c (light line).

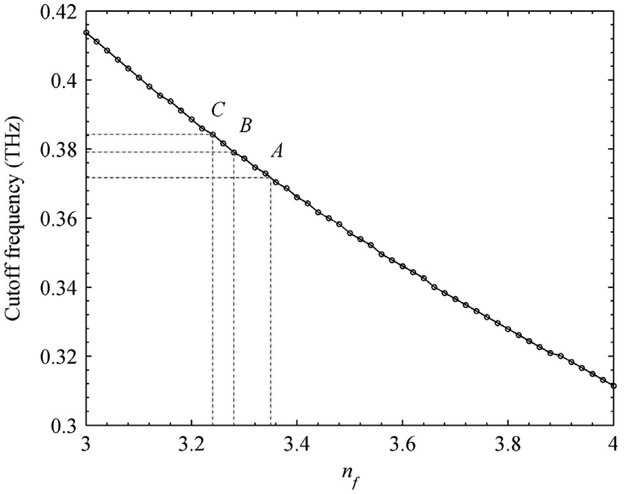

Fig. 3. Cutoff frequency of the dispersion curve versus n_f within the range of 3–4.

Fig. 2 shows the dispersion curves calculated for $d=20$ μm, $h=60$ μm and $p=40$ μm with different reflective indices of silicon. One can see that the cutoff frequency of the dispersion curve is sensitively dependent on the reflective index of the silicon filled in the grooves. In Fig. 3 we plot the cutoff frequency versus the refractive index of the silicon within the range of 3–4. The cutoff frequency continuously decreased with the increase of the refractive index. Once the cutoff frequency of the dispersion curve is changed by the modifying of the n_f, the propagating characteristics of the terahertz surface mode will be altered. Since the value of n_f can be modulated by laser pumping, one would expect to achieve the dynamic control of the terahertz surface modes propagating along the metallic surface. That is the main starting point of this paper.

3. Simulation results and discussion

In order to directly observe the influence of changing of the cut-off frequency on the terahertz surface modes propagating along the surface of the metallic grating structure shown in Fig. 1, we conducted COMSOL simulation based on the finite-element method (FEM) in the two dimensional (2D) space. In the simulation, the metal is treated as a PEC, and the number of the grooves along the z-axis is set to 30. The dimensions of the simulation region are 1.4 mm × 0.6 mm, and it is surrounded by a perfectly matched layer absorber. The TM-polarized terahertz wave is incident from the left boundary in region 1 along the z-axis direction. The period, width, and depth of the periodic grating are set to 40, 20, and 60 μm.

Fig. 4 shows the 2D distributions of the field intensities ($|E|^2$) under three different indices of the silicon. From Fig. 3 one can see that the cutoff frequency of the dispersion curves for n_f=3.3, 3.35 and 3.4 are 0.3773, 0.3713 and 0.3661 THz, respectively. The incident frequency is chosen as 0.3662 THz. The terahertz waves are confined along the metallic grating surface, as shown both in Fig. 4(a) and (b). However, the confinement in Fig. 4(b) is stronger than that in Fig. 4(a). This is because that the incident frequency is closer to the cutoff frequency for n_f=3.35. In Fig. 4(c), there is no terahertz surface wave propagating along the surface, since the frequency is already beyond the cutoff frequency for n_f=3.4. These