Dynamic control of the terahertz rainbow trapping effect based on a silicon-filled graded grating*

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We theoretically propose a scheme to realize the dynamic control of the properties of the terahertz (THz) rainbow trapping effect (RTE) based on a silicon-filled graded grating (SFGG) in a relatively broad band via optical pumping. Through the theoretical analysis and finite-element method simulations, it is conceptually demonstrated that the band of the RTE can be dynamically tuned in a range of ∼ 0.06 THz. Furthermore, the SFGG can also be optically switched between a device for the RTE and a waveguide for releasing the trapped waves. The results obtained here may imply applications for the tunable THz plasmonic devices, such as on-chip optical buffers, broad band slow-light systems, and integrated optical filters.

Keywords: metamaterials, subwavelength structures, slow light, terahertz

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1. Introduction

By carefully designing the parameters of metamaterials and plasmonic structures, it is possible to stop each frequency component of an electromagnetic (EM) wave packet at different locations of the structures. This kind of slow-light phenomenon is well known as the rainbow trapping effect (RTE),[1] which can find potential applications in nonlinear optics, signal processing, and optical memory. Compared to the conventional schemes of slow light based on atomic vapors[2] and Bose–Einstein condensates,[3] the scheme of the RTE can reduce the speed of light in a broad bandwidth and a wide temperature range, including room temperature. Recent theoretical and experimental investigations on the RTE realized by surface plasmon polaritons (SPPs) or spoof surface plasmons (SSPs) supported by the plasmonic graded metallic grating (GMG) have generated considerable interest, since the structure of the GMG can be easily designed to work in different frequency ranges, such as the terahertz (THz) domain,[4–6] telecommunication domain,[7] and visible domain.[8] Soon after, different kinds of gradual structures were proposed to realize the RTE, including the circular metallic waveguide with a linearly tapered semiconductor core[9] and the metallic film covered by a dielectric graded grating.[10] However, a main shortcoming of the gradual structures mentioned above is that the trapping properties cannot be dynamically controlled due to their fixed parameters.

One method for tuning the surface waves trapped by the gradual structures is to employ materials exhibiting a large thermo-optic effect in the structures and to control their refractive indices by changing the temperature.[7] However, the thermal tuning method can only be used to release the trapped waves, and it is not suitable for applications that require a high speed modulation since the thermal-optic effect is a relatively slow process. Recently, a kind of silicon-filled metallic grating with constant groove depth was proposed to realize a high speed control of the RTE in THz domain.[11] Since the refractive index distribution of the silicon filled in the grooves can be modulated by laser pumping, the dynamic control of the trapping properties can be achieved. However, the controllable bandwidth of this scheme is very narrow (about 0.03 THz) due to the small optical modulation range of the refractive index of the silicon, which is from about 3.15 to 3.4. Can we design a new scheme to realize dynamic control of the RTE properties in a relatively broad bandwidth?

To resolve this problem, we propose a silicon-filled graded grating (SFGG) in which the properties of the THz RTE can be dynamically controlled by optical pumping. This scheme is based on the combination of the conventional GMG structure with the tunability of the refractive index of the silicon. Thus, it has the advantages of both the conventional GMG and the silicon-filled uniform grating. Through the theoretical analysis and finite-element method (FEM) simulations, we conceptually demonstrate that based on our SFGG, the bandwidth of the RTE can be dynamically tuned in a relatively broad range. Most interestingly, we would like to see how we

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can release the trapped waves and guide the electromagnetic (EM) energy on the chip through the SSPs by modulating the refractive index of the silicon. We hope the scheme proposed here can be exploited in the novel designs of the plasmonic devices, such as on-chip optical buffers, broad band slow-light systems, and integrated optical filters, etc.

2. Theoretical model

Figure 1 illustrates the proposed SFGG, which consists of a one-dimensional (1D) sub-wavelength metallic groove array with groove width d, period p, and graded depth $h(x)$. The grooves are filled with high-resistivity silicon, whose refractive index $n_{\rm f}(x)$ in the THz range can be altered by laser pumping.[11,12] One would expect to dynamically control the distribution of $n_{\rm f}(x)$ along the x-direction by modulating the power distribution of the pump laser. It should be noted that the graded index distribution of Si along the z-direction under pumping has been neglected to simplify the theoretical discussion and make our concept clear. In most of the studies for the metallic structures based on SSPs in THz domain, as an approximation, the metals could be treated as perfect electrical conductors (PEC).[13,14] Thus we also assume a PEC here. Then, based on the previous work,[5,11] the dispersion relation for TM-polarized surface waves propagating in the x-direction can be obtained. Furthermore, by considering the long wavelength limit ($\lambda \gg p > d$) and the location-dependent parameters of the SFGG, the dispersion relation at the first-order approximation can be obtained, which is also the propagation constant of the SSPs supported by our SFGG:

$$\beta = \frac{\omega}{c}\sqrt{\frac{d^2}{p^2}n_{\rm f}^2(x)\tan^2\left[\frac{\omega}{c}n_{\rm f}(x)h(x)\right]+1}, \tag{1}$$

where ω is the angular frequency and c is the light velocity in a vacuum. The dispersion relation for the SFGG with various parameters (d, p, $h(x)$, $n_{\rm f}(x)$) can be obtained by solving Eq. (1). Then, the group velocity $v_{\rm g}$ for the SSPs may be derived from $v_{\rm g} = {\rm d}\omega/{\rm d}\beta$ and written as

$$v_{\rm g} = \frac{c}{Y + \dfrac{2d^2 n_{\rm f}^2(x)h(x)\omega}{p^2 cY}\tan\left[\dfrac{\omega}{c}n_{\rm f}(x)h(x)\right]\sec^2\left[\dfrac{\omega}{c}n_{\rm f}(x)h(x)\right]}, \tag{2}$$

where $Y = \sqrt{(d^2/p^2)n_{\rm f}^2(x)\tan^2[n_{\rm f}(x)h(x)\omega/c]+1}$. If the changes of $h(x)$ and $n_{\rm f}(x)$ along the x-direction are sufficiently small, the cut-off frequencies $\omega_{\rm c}$ will be dependent on the locations, i.e., $\omega_{\rm c}(x) \approx \pi c/[2n_{\rm f}(x)h(x)]$. This implies that the SSP modes are completely trapped at different locations along the SFGG surface ($v_{\rm g} \to 0$) when the frequencies of the incident THz waves are slightly below the cut-off frequencies ($\omega \to \omega_{\rm c}^{-}(x)$). This phenomenon is the so called THz RTE. For the device proposed here, the RTE bandwidth can be estimated by $\Delta\omega \approx \omega_{\rm c}^{\rm MAX} - \omega_{\rm c}^{\rm MIN}$, in which $\omega_{\rm c}^{\rm MAX}$ and $\omega_{\rm c}^{\rm MIN}$ are the maximum and the minimum of the cut-off frequencies, respectively.

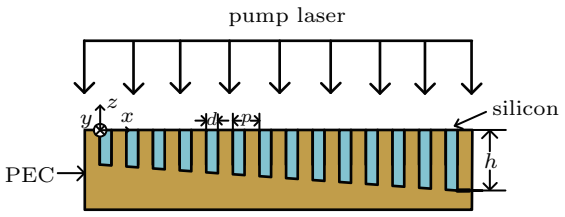


Fig. 1. (color online) Schematic illustration of the silicon-filled graded grating (SFGG). The geometric parameters are chosen as $h(x) = 52.94 + 2.1x$ μm, $d = 20$ μm, and $p = 40$ μm in our discussion. Note that x is in units of mm, and x changes from 0 to 2. Thus the variation of $h(x)$ is from 52.94 μm to 57.14 μm.

3. Discussion

Since we can alter the distribution of $n_{\rm f}(x)$ by modulating the laser pumping along the x-direction, the band of the THz RTE can be tuned dynamically. As illustrated in Fig. 2, based on Eqs. (1) and (2), we calculate the SSP dispersions and the $c/v_{\rm g}$–h relations for $n_{\rm f}(x) = 3.15$, 3.4, and $n_{\rm f}(x) = 3.15 + 0.125x$, respectively. One can see from the figures that the band of the RTE can be tuned from 0.419–0.448 THz to 0.388–0.415 THz when the distribution of $n_{\rm f}(x)$ is altered from 3.15 to 3.4. It means that for a uniform distribution of $n_{\rm f}(x)$, the RTE bandwidth $\Delta\omega/2\pi$ is below 0.03 THz. Interestingly, if we modulate the laser pumping to induce a graded distribution of $n_{\rm f}(x)$, such as $3.15 + 0.125x$, the RTE can be achieved from about 0.388 THz to 0.448 THz. The bandwidth is broadened to $\Delta\omega/2\pi \approx 0.06$ THz, which is about 2 times of that of the silicon-filled uniform grating proposed in Ref. [11].

The concept described above can be validated by the FEM in the two-dimensional (2D) space. In the simulation, the dimension of the calculation region is 2 mm × 1 mm, and it is surrounded by a perfectly matched layer absorber. The TM-polarized THz wave is incident from the left boundary. Figure 3 shows the 2D distributions of the electric field intensities ($|\boldsymbol{E}|^2$) under the three kinds of modulations of $n_{\rm f}(x)$ corresponding to Fig. 2. It is clear that the THz waves of different frequencies can be completely trapped at different locations on the SFGG surface. The theoretical prediction of the effects of $n_{\rm f}(x)$ on the RTE band is in accordance with the simulated results. One can also see that the bandwidth obtained by our theory is slightly larger than the simulated one. This is because equations (1) and (2) come from the first-order approximation. If higher-order scattering components are incorporated into our model, the accuracy of prediction can be improved, but a complicated formulation will be encountered. Therefore, it is convenient to use the approximate model to illustrate the principle of our design for the dynamic control of the THz RTE.

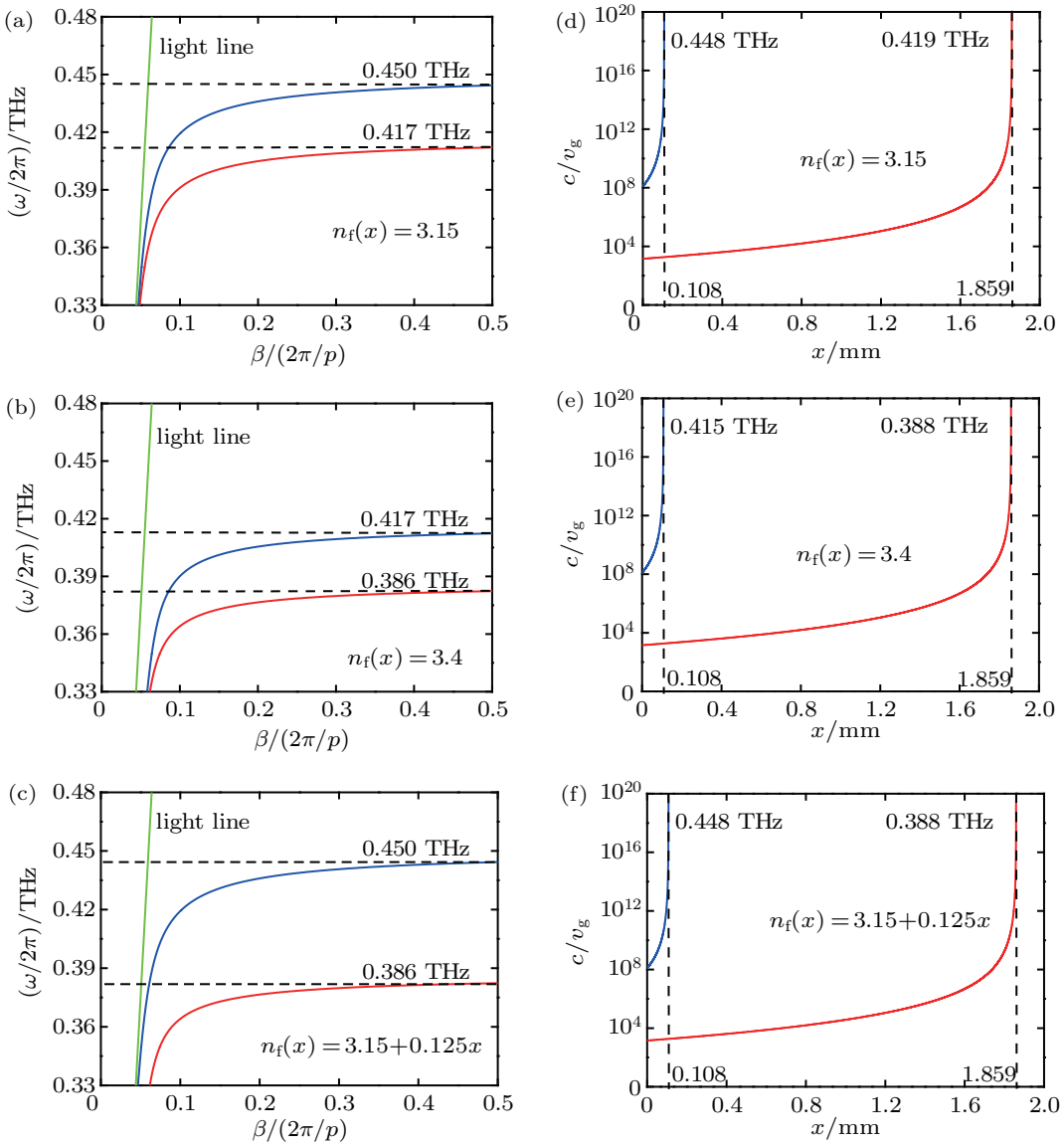


Fig. 2. (color online) The dispersion relations of the SSPs supported by the SFGG for (a) $n_f(x) = 3.15$, (b) $n_f(x) = 3.4$, and (c) $n_f(x) = 3.15 + 0.125x$. Reciprocal of v_g of the SSPs corresponding to (d) $n_f(x) = 3.15$, (e) $n_f(x) = 3.4$, and (f) $n_f(x) = 3.15 + 0.125x$ are calculated according to the dispersion curves.

The next question that arises after trapping the THz rainbow at different locations along the SFGG in a relatively broad band is how to release the trapped SSP modes dynamically. Based on the discussion above, it is obvious that the properties of the trapped SSPs, including β, v_g, and ω_c, are sensitive to the effective depth of the grooves, which can be defined as $h_{eff} = n_f(x)h(x)$. In the scheme to realize dynamic control of the band of the RTE, the effective depth h_{eff} is graded from the left-hand side to the right-hand side of the SFGG, and the graded distribution of h_{eff} is tunable. Moreover, the distribution of h_{eff} can also be switched between graded state and uniform state (h_{eff} = constant) by modulating the laser pumping. The SFGG with a graded distribution of h_{eff} can realize the RTE, while that with a uniform distribution can release the trapped waves by providing a waveguide to support propagating SSP modes. Figure 4 shows the concept of how the SFGG can be switched between a device for the RTE and a waveguide for releasing. As illustrated in the figures, when the silicon refractive index is tuned to $n_f(x) = 3.4$, the EM wave at 0.414 THz could be coupled into the SFGG and trapped near $x = 0.2$ mm. Once we modulate $n_f(x)$ to $180/h(x)$, corresponding to $h_{eff} = 180$ μm, the cut-off frequencies for the region of $x > 0.2$ mm become ω_c $(x > 0.2 \text{ mm})/2\pi = 0.417$ THz. Thus the trapped SSPs at the frequencies below 0.417 THz will turn into the propagating SSP modes supported by the SFGG. In this way, the trapped waves can be released on chip one by one through tuning the distribution of $n_f(x)$ by the pump laser, representing a possible way to realize the controllable optical buffers for future on-a-chip THz applications.

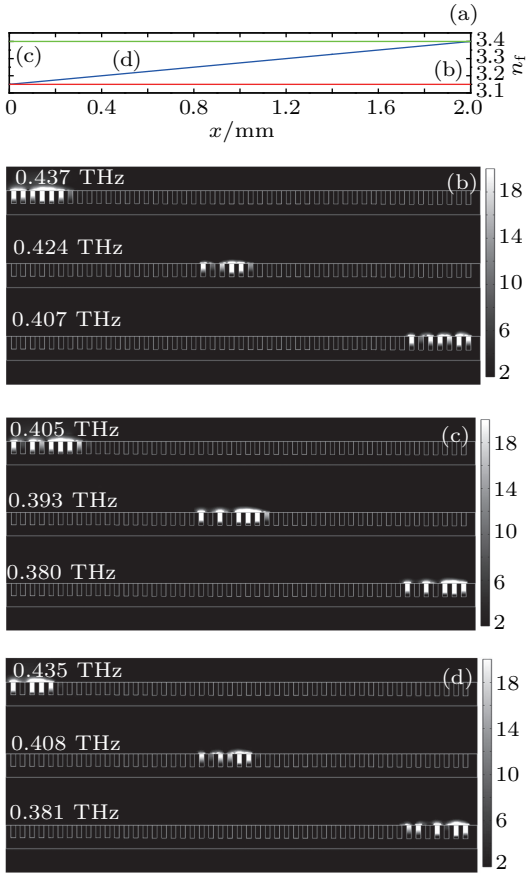


Fig. 3. (color online) (a) Three kinds of distributions of $n_f(x)$ along the x-direction, i.e., $n_f(x) = 3.15$, 3.4, and $n_f(x) = 3.15 + 0.125x$, respectively. The 2D distributions of the electric field intensities for (b) $n_f(x) = 3.15$, (c)$n_f(x) = 3.4$, and (d) $n_f(x) = 3.15 + 0.125x$.

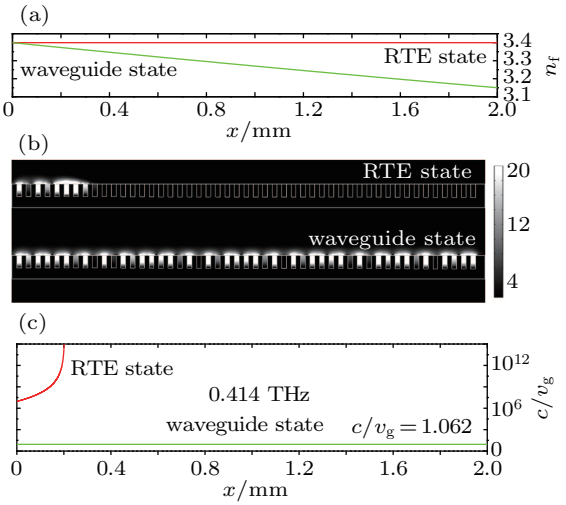


Fig. 4. (color online) (a) The distributions of $n_f(x)$ corresponding to the RTE state and the waveguide state of the SFGG. (b) The 2D distributions of the electric field intensities and (c) the reciprocal of v_g for the two kinds of working states.

Obviously, the direct coupling between the trapped SSPs and the free-propagating photons is inefficient due to the momentum mismatch. Therefore, several coupling approaches proposed previously can be applied to enhance the coupling efficiency, including coupling via evanescent waves,[15] scattering edges,[16] and gratings.[14,17,18] Next, the pumping-modulation issue is an important problem in practical application. In the THz range, it has been experimentally demonstrated that the refractive index of Si could be tuned from about 3.15 to 3.4 by increasing the power of a CW pump laser at 980 nm.[12] To control the distribution of the laser pumping, we could utilize carefully designed attenuating plates or multiple pump lasers with tunable power. Moreover, the modulation speed of the SFGG is limited by the relatively long lifetime of carriers in Si. Here Si is chosen for its low dark conductivity and near zero dispersion over the THz bandwidth investigated in this paper. If we want to obtain a faster modulation speed, GaAs is a possible choice. From the point of view of practice, the photoexcitation of Si/GaAs usually generates a graded index distribution instead of a uniform one along the z-direction in each groove, but it does not change the essence of our scheme. Finally, to fabricate the proposed SFGG, the copper plating of the lithographically patterned silicon layer on a dielectric substrate could be applied.[16,19] We can first employ a photoresist to coat the silicon layer and form the photoresist grating by using contact optical lithography. The photoresist grating is used as a mask here. The patterned silicon layer can be etched by fast atom beam etching and lifting off the photoresist. Then, copper can be deposited on the surfaces of the patterned silicon layer by catalytic plating. Note that the existence of the dielectric layer may induce a shift of the SSP band but not change the physical essence discussed above.

4. Conclusion

We have proposed a scheme to dynamically modulate the THz RTE based on a silicon-filled graded grating. One could control the properties of the RTE by tuning $n_f(x)$ via modulating the power distribution of the pump laser. The theoretical model and FEM simulations conceptually demonstrate that we can tune the band of the RTE in a range of ~ 0.06 THz. Furthermore, we also show that the SFGG can be optically switched between a device for the RTE and a waveguide for SSP releasing. The results obtained and discussed here can imply important applications for the tunable THz plasmonic devices, such as on-chip optical buffers, broad band slow-light systems, and integrated optical filters.

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