Optics Communications 424 (2018) 103–106

Contents lists available at ScienceDirect

Optics Communications

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

Light controlled surface plasmon polaritons switch based on a gradient metal grating

Lidan Cao, Yan Zhang *

Department of Physics, Capital Normal University, Beijing Key Lab for Metamaterials and Devices, Key Lab of Terahertz Optoelectronics, Ministry of Education, and Beijing Advanced Innovation Center for Imaging Technology, Beijing 100048, China

ARTICLE INFO

Keywords:
Surface plasmon polaritons
Terahertz
Silicon
Gradient metal grating

ABSTRACT

A surface plasmon polaritons (SPPs) switch controlled by a pump light in the terahertz (THz) regime is designed. The switch is based on the surface slow-light technology. A gradient metal grating on a silicon (Si) layer is adopted to slow the SPP waves. By adjusting the grade of grating depths, the location of stopped waves can be tuned. By changing the intensity of pump light shining on the Si layer, the carrier density of Si layer can be modulated and thus the dielectric constant of Si layer. Then the SPPs can switched between two states: going through the structure or being stopped. The bandwidth of the captured surface wave can be effectively broaden by using this kind of depth gradient grating. This approach may provide a new method to design controllable SPPs devices.

1. Introduction

Surface plasmon polaritons (SPPs) is an electromagnetic (EM) model that exists at the interface of metal and dielectric. It has special features of subwavelength scales and local field enhancement. The wavelength of the SPP is shorter than that of the light in the adjacent medium [1], therefore the SPP is favored by researchers as an excellent photon manipulator and integrated carrier. Due to the importance of SPP in photon integration, high resolution imaging and high sensitivity detection, it is quite necessary to carry out efficient SPP propagation and field distribution regulation on the micro-nano scale and plane dimension. The plasmonic structure has potential for spatial confinement of electromagnetic energy within subwavelength dimension over a wide spectral range [2–4]. It has been reported that the plasmonic structures and devices operating in the optical domain can offer great advantages for applications of on-chip integration of optical circuits, surface or interface technology and data storage [1,5,6]. In the past decade, many studies have been conducted to trap the light using various approaches, such as the electromagnetically induced transparency [7], photonic crystal [8], tapered left-handed material structure [9], as well as the experiment illustration of broadband “trapped rainbow” based on the tapered nano-waveguide [10].

Recently, a gradient depth grating structure which can offer the advantage of reducing the speed of light over a wide-bandwidth and the ability to work at ambient temperatures is proposed [11]. Such a structure is capable of stopping light of different frequencies at different locations on the chip. However, a three-dimensional groove in the metal is required which brings great difficult for fabrication. Using a grating structure on a ultrathin flexible dielectric surface to replace the three-dimensional groove type grating structure can increase the feasibility of processing [12]. Since the plane grating structure is simple, ultrathin, and flexible, this method provides a great candidate for special slow-light devices. Although one can adjust the geometry of the gradient grating to regulate the propagation of SPPs, the geometric size cannot be changed any more once the structure is fabricated, thus the propagation of SPPs cannot be modulated actively. In some applications, such as ultra-compact optical modulator [13], it is required to adjust the SPPs conveniently.

In this work, a structure which can optically control the propagation of terahertz (THz) SPPs is proposed. The silicon (Si) with a thin film-type metal grating structure is selected as the light-controllable part. When the Si is illuminated by the pump light, the dielectric property of Si will be changed and thus the propagation of SPPs will be controlled. The SPPs can be controlled to go through the structure or stop in the structure. This concept is demonstrated with numerical simulation results. This paper is arranged as follows: Section 2 describes the design concept and presents the parameter values of structure. Section 3 displays the numerical simulation results and corresponding analysis. At last, Section 4 draws conclusions.

* Corresponding author.
E-mail address: yzhang@cnu.edu.cn (Y. Zhang).

https://doi.org/10.1016/j.optcom.2018.04.054
Received 26 December 2017; Received in revised form 16 April 2018; Accepted 23 April 2018

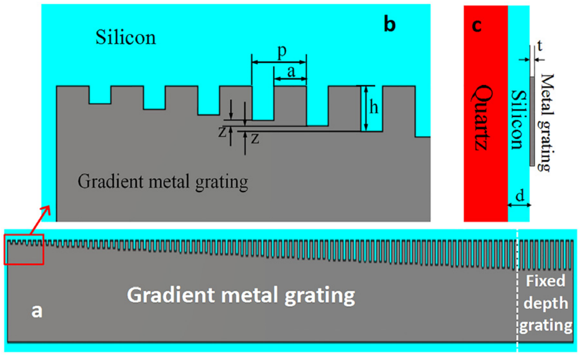

Fig. 1. Schematic of the SPPs switch. (a) Front view. The structure is combined with a gradient grating and a fixed depth grating. (b) Enlargement of red box in (a). Parameters of the gradient metal grating are depth h (initial depth h_0 = 20 μm), width a = 30 μm, lattice constant p = 50 μm and depth increment z = 0.2 μm. The grating is plating on a silicon layer. (c) Side view of (b). The gray region is metal film whose thickness is t = 0.1 μm, the blue region is the Si layer whose thickness is d = 10 μm and the red region is quartz substrate.

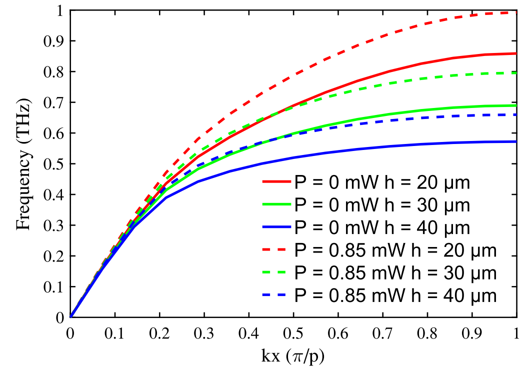

Fig. 2. Dispersion curves of a fixed-depth grating. From top to bottom, for the case of h = 20 μm at 0.85 mW pump light (red dashed line), h = 20 μm at 0 mW pump light (red solid line), h = 30 μm at 0.85 mW pump light (green dashed line), h = 30 μm without pump light (green solid line), h = 40 μm at 0.85 mW pump light (blue dashed line) and h = 40 μm without pump light (blue solid line).

2. Basic design

The SPPs switch, which is based on the surface slow-light technology, is designed in the THz regime because that the dielectric property of semiconductor can be easily controlled by the extra optical pumping. This device is a gradient metal grating followed by a fixed metal grating fabricated on the Si layer, as shown in Fig. 1(a). The gradient metal grating is used for slowing the SPPs and controlling the SPPs' propagation on the Si surface. The parameters of metal grating are: Width a = 30 μm, lattice constant p = 50 μm and depth increment z = 0.2 μm, the initial depth of grating is h_0 = 20 μm, as shown in Fig. 1(b). The period of fixed metal grating is p = 50 μm, width a = 30 μm and the depth is fixed as h = 40 μm. The side view of Fig. 1(b) is shown in Fig. 1(c), the thickness of metal film is t = 0.1 μm and the thickness of Si layer is d = 10 μm. The whole structure is placed on a quartz substrate for easy fabrication. Numerical simulations are carried out using a commercial finite-difference-time-domain simulation software, CST STUDIO SUITE. The metal is considered as a perfect electrical conductor due to its high electric conductivity in the THz regime. The source is incident from the left side of structure and the background material is vacuum.

3. Numerical simulation results and discussions

3.1. Slowing light with gradient grating

The gradient metal grating is chosen to design a THz SPPs switch because it can not only perform the conversion of THz radiation from propagation mode into SPPs mode but also can slow and even bound the SPPs on the chip in a wide frequency regime. Furthermore, the center frequency and working band can be tuned by adjusting the geometric parameters of the grating. In addition, it is also facilitated the observation of propagation position clearly through the gradient design [11].

Firstly, the dispersion behavior and slow light characteristics of a grating with fixed depth is analyzed [11,14,15]. The dispersion curves of metallic grating with a constant depth on the Si surface is simulated. Parameters of the grating are: Width a = 30 μm, lattice constant p = 50 μm and depth h = 20, 30, 40 μm, respectively. The relative permittivity of Si layer is set as ε_r = 11.07. As shown in Fig. 2, the parallel momentum k_x will approach to infinity at a specific frequency, that means the SPPs with that frequency is stopped. The cut-off frequency is defined as $\sqrt{2}/2$ of the frequency with a near infinite k_x. It can also be drawn that the grating depth will effect the cut-off frequency while other geometric parameters remain unchanged. For h = 20 μm, the cut-off frequency of dispersion curve is close to 0.80 THz. The SPPs could be coupled into the grating structure and will be confined at the surface within a narrow range around 0.80 THz. While the h is increased to 30 μm and 40 μm, the cut-off frequency is reduced to 0.65 THz and 0.55 THz, respectively.

It is worth to note that the different depths can be transmitted to the horizontal propagation distance. By adjusting the metal grating depth brick by brick, the group velocity of SPPs is slowed down gradually and the cut-off frequency is different for different depth. A fixed-depth grating whose depth is as the same as the final period of the gradient grating is designed as a critical switch to distinguish the SPPs' passing through or stopping on the gradient grating, as shown in the right part of Fig. 1(a).

Numerical simulations are carried out to verify that the structure can make the SPPs with different frequencies to be stopped at different horizontal positions x. Fig. 3 presents the distribution of E_z component of electric-field for the SPPs switch. The frequency is changed from 0.60 to 0.80 THz with a step of 0.04 THz. It can be found that from the low frequency (0.60 THz) to high frequency (0.80 THz), the propagation distance are decreasing from 3682.8 μm to near 0 μm. The SPP waves with different frequencies can be stopped at different horizontal positions on the gradient grating.

3.2. Basic principle for light control

The Si is a kind of semiconductor material whose carrier concentration increases when it is irradiated by the pump light. The real part of its permittivity decreases and the imaginary part increases while the intensity of pump light rising [16]. The complex relative permittivity ε_r of Si can be described by the Drude theory [17] and the conductivity σ (optical conductivity) of Si is

$$\sigma(\omega) = \frac{\sigma_0}{1 - i\omega\tau}, \tag{1}$$

where σ_0 is the Drude DC conductivity, τ is the relaxation time of electrons. The denominator of Eq. (1) is rationalized and the conductivity can be expressed as

$$\sigma(\omega) = \frac{\sigma_0(1 + i\omega\tau)}{1 + (\omega\tau)^2} = \frac{\sigma_0}{1 + (\omega\tau)^2} + i\frac{\sigma_0\omega\tau}{1 + (\omega\tau)^2}. \tag{2}$$

Thus the relative permittivity $\varepsilon_r(\omega)$ can be got as:

$$\varepsilon_r(\omega) = 1 + \frac{i\sigma(\omega)}{\varepsilon_0\omega} = 1 + \frac{i}{\varepsilon_0\omega}\left[\frac{\sigma_0}{1 + (\omega\tau)^2} + i\frac{\sigma_0\omega\tau}{1 + (\omega\tau)^2}\right]. \tag{3}$$