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Spatial accumulation of phase difference in spoof plasmon based Mach–Zehnder Interferometer

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ABSTRACT

An active beam steering structure comprising the spoof surface plasmon polariton (SSPP) waveguide is presented. The proposed structure consists of two stages: the two arms structure as a Mach–Zehnder interferometer (MZI), and free space propagation stage. The SSPP waveguide includes periodic grooves, which are filled with a thin layer of doped semiconductor like GaAs. By applying electric voltage at the electrodes on top of the waveguide, the depletion layer thickness and the effective refractive index of the dielectric inside the grooves can be changed. The effective refractive index of the dielectric inside the groove is derived analytically and the phase change of the propagation wave along the single sided SSPP waveguide is calculated as a function of input voltage. The relation between the input signal and the angle of maximum radiation of output beam is investigated and the linearity is improved. We have shown that the MZI beam steering section has the capability to bend the electromagnetic beam about 42 degrees. At the end, we presented an application of the proposed beam steering device as a spatially accumulated phase difference structure that can be utilized in devices such as digital-to-analog converter (DAC).

1. Introduction

The components and devices working in the THz region, which lies between the microwave and optical spectrum, (0.1–10 THz) have gained a lot of interest in recent decades [1,2]. The nonionizing character of interaction of the THz radiation with matter and unique material spectral foot print in this region found multiple applications in various fields: from medical imaging [3–6] to detecting hazardous materials and bio-sensing [7–10]. Besides these applications, the emergence of high bandwidth communications, results in exploring the THz spectrum which is capable of high-speed communication [11,12]. Despite those applications in the lab scale, the real implementations of THz devices have encountered challenges and the THz band has remained under-developed and underexplored [13]. There are several major problems standing in the way of developing THz based circuits: the scarcity of low loss structures and materials in the THz frequency range, high speed detectors, and high power sources working at room temperature. Resonant tunneling diodes (RTD) have been explored in literature as one of the candidates that can deliver THz power at room temperature [14,15]. In the field of THz detector, different structures have been proposed that can detect THz signals at a decent speed [16,17]. In the area of guiding THz waves, there have been some efforts to exploit the conventional EM waveguides in the THz spectrum [18] utilizing subwavelength metal wires, conventional hollow metallic tube, and dielectric lab waveguides such as Si [19–23]. There are still some obstacles such as, high metal loss, high bending loss, coupling difficulty, group velocity dispersion, and fabrication difficulty [22–25].

In order to overcome the aforementioned problems, there have been efforts to use optical approach to overcome THz waveguiding, such as utilizing plasmonic waveguide. Oscillation of plasmas along the interface of the metal and the dielectric below the plasma frequency result in surface plasmons, but it is barely capable of guiding THz signal because of highly damped nature of surface plasmon polaritons (SPP) at this frequency range [24]. In [25], however, Pendry with coauthors showed that a periodically modulated metallic surface can support bounded states of the electromagnetic field mimicking the SPP behavior. It has been shown that these spoofed surface plasmon polariton (SSPP) modes exhibit features such as field enhancement and localization at the grooves [26–28]. The confinement and concentration of the electromagnetic field in a very small volume can be used in subwavelength transmission of electromagnetic waves and enhance the signal–matter interaction [10,26]. Using the SSPP waveguides, different components such as biosensor [10], THz switches, Boolean gates, couplers, etc. [26,28–34] have been proposed and designed in recent works. The high field concentration and slow wave nature of the SSPP modes

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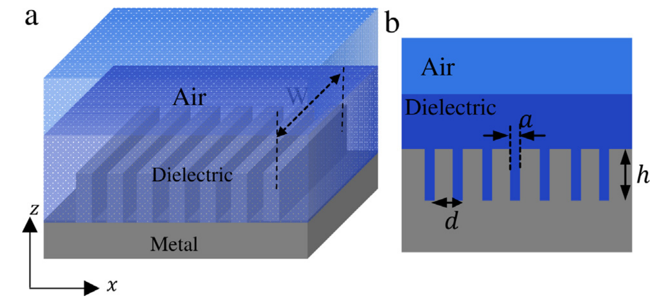

Fig. 1. (a) The schematic view of the SS-SSPP waveguide. (b) The cross section of the waveguide.

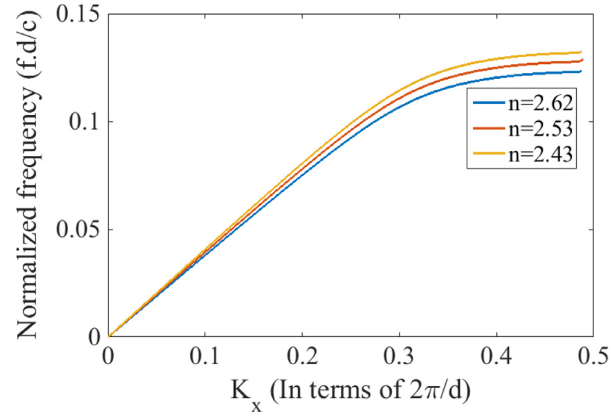

Fig. 2. The fundamental branch of SSPP in a SS SSPP waveguide with d = 50 μm, h = 40 μm, a = 5 μm for different values of the refractive index.

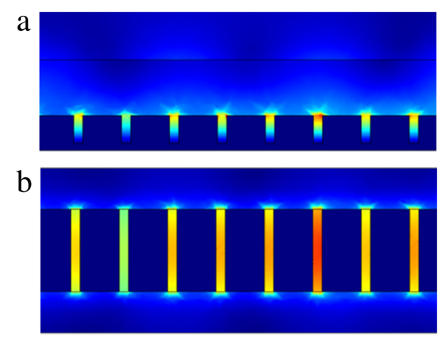

Fig. 3. E-field distribution along the structure at frequency 10.50 THz. (a) Cross view. (b) Top view.

can open the road for further application that rely on the interaction of the EM wave and propagating medium, such as controlling the phase of THz signal through SSPP waveguide in small length of the waveguide. These properties are critical for localized modulation of the THz signals with enhanced efficiency. In this paper, we have combined the idea of having accurate control on phase and Mach–Zehnder interferometer structure to offer an active beam steering device. We have shown that the phase constant of the single-sided SSPP (SS-SSPP) is sensitive enough to the refractive index of the material inside the grooves. Then using the plasmonic behavior of the SS-SSPP dispersion diagram and its sensitivity to the refractive index inside the grooves, we have demonstrated that one can reach beam steering around 42 degrees in a short waveguide length. The proposed structure offers high spatial resolution over small range of input applied voltage as a controlling stimulus.

This paper is organized as follows: in Section 2, a general analysis of the SSPP waveguide is performed. We show that varying the dielectric function of the material inside the grooves, the phase of propagating SSPP can be changed. Also, an implementation of the MZI based on open SSPP waveguide is proposed. In Sections 3 and 4, a mathematical modeling is presented to analyze the output beam, also the effective refractive index of the doped semiconductor inside the grooves when its operating at spoof surface plasmons mode is calculated. To control the angle of radiation, doped semiconductor in its depletion mode has been used. It is demonstrated that by applying voltage to the electrodes and depleting the doped region, it is possible to tailor the angle of radiation. In Section 4, we utilize the proposed MZI beam steering structure as a spatial phase accumulator device to demonstrate digital to analog conversion.

2. Modeling

Fig. 1 shows the schematic view of a structure supporting spoof plasmons. It consists of three layers: the metallic corrugated layer, the dielectric layer, and the air. The dielectric layer acts as a slab waveguide to confine the wave inside the dielectric, the corrugated metal acts as a reactance layer and results in SSPP mode propagating along the structure.

The dispersion relation of the SS-SSPP waveguide is obtained by, first, noticing that in the low frequency range only the TM mode exists, and their dispersion equation can be written as [35]

$$jk_0 X(k_0,\beta)\tan\left(k_0 h\right) = 1, \tag{1}$$

where we have introduced $X\left(k_0,\beta\right) = \sum_{m=-\infty}^{\infty} S_m^2/k_z^{(m)}$ and $S_m = \sqrt{a/d}\,\mathrm{sinc}\left(k_x^{(m)} a/2\right)$, $k_x^{(m)} = \beta + 2\pi m/d$, $k_0 = n\omega/c$, $k_z^{(m)} = \sqrt{k_0^2 - \left(k_x^{(m)}\right)^2}$, and β is the Bloch wavenumber. The important feature of Eq. (1) is that being understood as an equation relating k_0 and β, it does not depend on the refractive index, which enters the dispersion equation only through k_0. Thus, the dependence of frequency on β and on the refractive index is given by $\omega = k_0(\beta)\,c/n$, where $k_0(\beta)$ is a solution of Eq. (1). As a result, the variation of the dispersion diagram with the refractive index reduces to simple rescaling along the frequency axis as illustrated by Fig. 2 showing solutions of Eq. (1) for different values of n.

The dispersion diagram shows the existence of two well defined regimes: near zero frequency (or near the cut-off frequency for structures bounded in the y-direction by conducting planes [10]), where the dispersion curve is close to the light-line, and near the spoof plasma frequency ω_S defined by $k_0\left(\omega_S\right)h = \pi/2$, where the dispersion curve demonstrates saturation and deviates significantly from the light-line. The crossover between these regimes occurs at intersection of the light-line and the spoof plasma frequency, $k_S = \pi/2h$. Within the first regime, $\beta < k_S$, retaining only $m = 0$ term in the expansion for $X\left(k_0,\beta\right)$, we obtain

$$k_0 = \beta\left(1 - \frac{1}{2}S_0^4 h^2 \beta^2\right). \tag{2}$$

In the opposite case, $\beta > k_S$, if it is reachable in the structure with given period, the distribution of the electric field along the structure is highly inhomogeneous (see Fig. 3) and $m = 0$ approximation for $X\left(k_0,\beta\right)$ should be applied with caution [35]. It is, however, sufficient for our purposes here. Taking into account that for $\beta > k_S$ the frequency is close to ω_S, we find

$$k_0 = k_S\left(1 - \frac{S^2}{\sqrt{\beta^2 h^2 - (\pi/2)^2}}\right). \tag{3}$$

Altering the refractive index of the dielectric while keeping the frequency fixed changes the SSPP propagation constant

$$\Delta\beta \approx \frac{\omega \Delta n}{(\partial k_0/\partial\beta)c}, \tag{4}$$