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Nonlinear spoof surface plasmon polariton phenomena based on conductor metamaterials

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Abstract

We present nonlinear phenomena produced from spoof surface plasmon polariton (SSPP) modes. Below the THz spectrum, artificially textured conducting metastructures on a subwavelength scale generate surface-bound modes and are called SSPP modes, similar to surface plasmon polariton (SPP) modes in the visible spectrum. Even though nonlinear effects in the THz domain are negligible, subwavelength metallic gap structures are ideal candidates to realize nonlinear behavior in the THz domain because of slow light propagation, strong electromagnetic confinement, and a high quality factor Q. In particular, when SSPP structures are combined with Kerr nonlinear materials, nonlinear-bistable curves can be observed below the THz spectrum.

Keywords: Bistable; Hysteresis; Spoof Surface Plasmon-Polariton (SSPP); Metamaterials; Terahertz (THz); Quality factor (Q)

Spoof surface plasmon polariton (SSPP) modes of signal propagation are efficient ways to control and steer electromagnetic (EM) signals in the THz spectrum through the dielectric embedded in conductor metamaterials. They enhance the localized EM field density by taking advantage of local cavities created by periodic corrugated gap structures [1,2]. Notably, for signal frequencies in the GHz to THz range, SSPP modes are observed in devices having subwavelength constituents: periodic distance, thickness, height, and width less than wavelength λ of the EM signal [3–5].

SSPP building blocks provide an ability to control electromagnetic fields. Their interactions with electro-optic and nonlinear media have profound significance for dynamic devices used in the miniaturization of circuits [1,2]. Furthermore, the proposed idea can be applied to the 300 GHz to 10 THz region of the EM spectrum. Because most semiconductor materials do not respond to THz radiation, basic device elements such as sources, lenses, switches, modulators, and detectors have not yet been well developed. Therefore, dynamic SSPP devices are promising vehicles to control and steer signals in highly compact circuits operating below the THz domain. More importantly, these approaches are promising for applications such as imaging [6,7], sensors [8], and wireless communications [9].

In this study, we demonstrate nonlinear phenomena based on SSPP architectures using Kerr nonlinear materials. In practice, hysteresis curves can be achieved by using nonlinear materials where the modulation refractive index δn is proportional to input signal power. In particular, it is common to describe the refractive index in the case of small dielectric changes as

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$n = n_o + n_2I$, where I is the intensity of the applied field, n_o is the linear refractive index, and n_2 is the Kerr coefficient. Some nonlinear polymers in the visible spectrum provide a large Kerr constant, thus requiring low incident flux for exhibiting optical bistability [10,11]. Since many nonlinear materials have a value of 10^{-17}–10^{-18} m^2/W, photonic crystals based on cavity structures can be used to realize the nonlinear effects [12–14]. However, the nonlinearity of most materials in the THz domain is extremely weak, thus providing a negligible nonlinear effect. Recently, liquid materials such as CS_2, CCl_4, and $CHCl_3$ have been found to be suitable candidates to provide nonlinear phenomena in the THz domain. Nonetheless, these materials provide a low Kerr coefficient, 10^{-18}–10^{-19} m^2/W [15], and hence require extraordinary EM flux density for nonlinear behavior.

Therefore, we believe that subwavelength metallic gap structures are ideal environments to obtain nonlinear EM enhancement in the THz domain. Similar to photonic crystals in the visible spectrum, SSPP building blocks with subwavelength channels boost nonlinearities in the THz system. Furthermore, SSPP architectures could be a promising way to achieve nonlinear behavior in the THz domain for three reasons: (1) slow light propagation provides a small device footprint with low power requirements; (2) strong light localization related to a small effective volume V_{eff} provides a large shift of resonant frequency $\Delta\omega_o$ at a small refractive index $\delta n/n$; and (3) a high quality factor Q reduces operational power to obtain nonlinear behavior in the THz domain.

1. Basic design architecture of a bistable SSPP switch

Our basic nonlinear SSPP device was based on the waveguide–cavity–waveguide comprised of conductor metamaterials already mentioned in Ref. [2]. As shown in Fig. 1, THz waveguides consisting of corrugated metallic gap structures with subwavelength characteristics allow THz signal propagation at a specific frequency ω_a, thus behaving like THz filters. This specific frequency ω_a is determined by the periodic distance d, the height of the periodic structure $h1$, the thickness of the metallic gap structure t, and the groove width a. A subwavelength metallic cavity provides strong EM confinement to enhance nonlinear plasmonic effects at the resonant frequency ω_o. Furthermore, the resonant frequency ω_o can be modulated by the refractive index n. Specifically, we built subwavelength waveguides with $a/d = 0.2$, $h1/d = 0.8$, $t/d = 1/3$, and

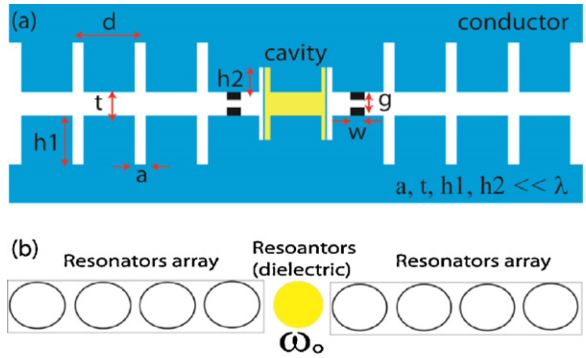

Fig. 1. (a) A SSPP waveguide–cavity–waveguide with 1D periodic metallic structures. Waveguides can be regarded as a large resonator array and cavity can be considered as a small resonator array with different height h, and the refractive index n. The blocking structures have geometrical parameters of width w and gap g. (b) THz waveguide can be regarded as a large resonator array with free space ($n = 1$), and the cavity can be considered as a small resonator array with the different height h and the refractive index n.

$n = 1$, as shown in Fig. 1(a). These subwavelength waveguides can be regarded as equal-spaced coupled resonator arrays, thus providing THz filters as shown in Fig. 1(b). In addition, we implemented a cavity with $a/d = 0.2$, $h2/d = 0.5$, $t/d = 1/3$. To increase quality factor Q of nonlinear SSPP devices, blocking structures with $w/d = 0.2$ and $g/d = 1/6$ were placed inside subwavelength metallic gap structures.

2. Design of cavity using transmission analysis

(1) Transmission analysis: Transmission analysis of the subwavelength cavity was accomplished using finite-difference-time-domain (FDTD) modeling. In contrast with previous methods [1,2], we used transmission analysis to estimate the quality factor Q and resonant frequency ω_o. Note that a transverse magnetic (TM) Gaussian source is located at the end of one cavity as shown in the inset of Fig. 2. Then, we calculated the transmitted power flow at the end of the other cavity corresponding to different frequencies. The transmission responses for the cavity without blockings and the cavity with blockings were calculated and are presented in Fig. 2.

(2) Blocking structures: The quality factor Q can be evaluated by using fractional bandwidth (BW) calculations because $Q \sim 1/\text{BW}$. Thus, at $g/d = 1/6$ and $w/d = 0.2$ (blocking structure), $Q \sim 445$; at $g/d = 1/3$ (no blocking structure), $Q \sim 274$. Furthermore, a resonant frequency of approximately $0.3510(2\pi c)/d$ at $n = 1.5326$ was achieved, and thus