Terahertz Plasmonic Metamaterial Based Multi-band Band-Pass Filter Using Micro-Ring Resonator

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***Abstract*—This paper reports the design and theoretical analysis of the spoof plasmonic metamaterial based multi-band band-pass filter (BPF) using corrugated planar micro-ring resonator at THz frequency. Plasmonic metamaterial i.e. spoof surface plasmon polaritons structures support EM mode at the interface of the metal-dielectric and thus highly confined and localized E-field can be obtained. Due to this sub-wavelength field confinement, spoof SPP structures show low-loss, low crosstalk and low mutual coupling and is being used for developing the compact integrated circuits. Sub-wavelength rectangular grooves are corrugated on the metallic planar ring is fed through the spoof SPP transmission line at its input and output ports to provide a band-pass response. The detailed mathematical analysis is provided for the designed band-pass filter. The Full wave EM simulation is performed to obtain the reflection and transmission coefficient. The designed spoof plasmonic ring resonator will provide a path to design and development of the plasmonic sensors.**

Keywords—Band-Pass Filter (BPF); Plasmonic Metamaterial, Ring Resonator.

I. Introduction

Integrated micro ring resonators have shown a great promise as a basic building block for a variety of applications in microwave and optics e.g amplifiers, sensors, biosensors, filters, measurement of various discontinuities and artificial media. The response of the coupled ring resonator can be designed using different coupling configurations and thus response of the ring resonator filters is designed to have a flattop and steep roll off. However, optical devices suffer from the diffraction limit, which restrict miniaturization of the optical devices. Plasmonics that embody the SPP wave is believed to overcome this problem due to sub-wavelength confinement feature of the SPP. SPP's are the special kind of EM mode that are found at optical and near infrared frequency at the interface of the two materials having opposite signs of their real part of the dielectric constant. Thus, SPP offers a solution to overcoming the diffraction limit and provide the miniaturization of optical devices [1, 2]. However, such exotic property cannot be obtained at THz and microwave frequencies due to the perfect conductor behaviour of metal. Hence, Plasmonic metamaterial has been proposed which supports SPP-like characteristics at these frequencies and its properties are dependent on geometrical parameters. Hence, it is also termed as designer or spoof SPP [3]. Recently researchers have paid their attention to utilize the properties of the SPP and the ring resonator in developing of the filters and plasmonic sensors [4]-[7].

Here, in this paper we report the design and analysis of the multi-band BPF using planar ring resonator at THz frequency. The designed corrugated ring has been excited through a straight plasmonic metamaterial based transmission line with a capacitive coupled gap *g*. The design layout and performance of the proposed multi-band BPF is given in detail.

II. Design and Analysis of BPF

A. Design of the Feeding Network

Here, the corrugated ring is capacitive coupled with the feeding element at its input and output port which is provided by the spoof SPP transmission line. To design the transmission line, a transition between QTEM modes of the microstrip to TM mode of the spoof SPP has been developed at THz frequency. Fig. 1 shows the process of developing the desired transition. Fig.1 (a) and (b) shows the spoof SPP unit cell and its dispersion curve. Numerical simulation of the dispersion is achieved using CST microwave studio using the substrate of dielectric constant *2.2*, height of *20*μm and loss tangent of *0.0009*. Gold with electrical conductivity of $4.561x10^7$ S/m and thickness of *0.35*μm is used for the analysis. In Fig. 1(b) green colored curve is used for the freely propagating wave vector k_0 i.e. light line and pink colored curve is used for spoof SPP unit cell k_y. Since, $k_y>k_0$ as can be noticed from Fig. 1(b), hence to match this momentum, a gradual conversion between these two wave vectors is needed. For that a conversion is designed as shown in Fig. 1(c) by gradual changing the height of the grooves from *5*μm to *40*μm. Further, a back to back transition is developed as shown in Fig. 1(e) and corresponding S parameter characteristics is shown in Fig. 1(f).

B. Design of Corrugated Planar Micro-Ring Resonator

Here, a multi-band BPF configuration is designed using SSPP based planar ring resonator. A ring has been corrugated with rectangular shape grooves and directly fed through the spoof SPP transmission line both at its input and

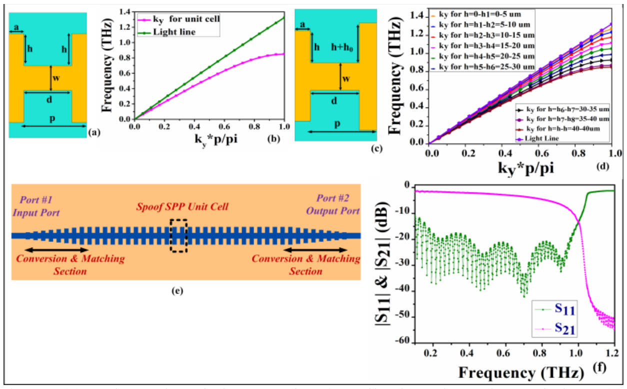

Fig. 1 (a) Schematic of the spoof unit cell, (b) Dispersion relation, (c) Schematic of the convsersion section showing gradual conversion, (d) Dispersion curve related to the gradual conversion, (e) Back-to-back transition, and (f) Magnitude of the reflection $|S_{11}|$ and transmission coefficient $|S_{21}|$ for the designed transition.

output port with a coupling gap *g*. Coupling gap *g* and ring radius are the important geometrical parameters which are responsible for the resonance of the ring resonator. The relationship between ring radius with the wavelength is given as [4].

$$n_{eff}*(2\pi r)= n*\lambda_g,\ n=0,\ 1,\ 2\ldots \qquad (1)$$

Where n_{eff} is modal effective index and can be calculated through dispersion curve, r is the mean radius, and λ_g is the resonating guided wavelength. Whenever circumference of the corrugated ring becomes integral multiples of λ_g, standing waves are setup in the ring and resonance condition is achieved. Fig. 2 (a) and (b) shows the schematic of the proposed ring resonator along with its equivalent even and odd mode analysis respectively. Here, it is assumed that this ring resonator is made up of two parallel SSPP transmission line sections connected at the middle of the ring. Each section has electrical length of $\Psi_1/2$ with physical length of $l_1/2$ and characteristics admittance Y_1 (physical width of W_1) with corrugated stubs on them. Each loaded stub has fixed characteristics admittances ΔY_s with corresponding width ΔW_s. There are *20* stubs in the ring resonator structure and out of these *20* stubs, the top and bottom stubs are numbered as $m=0$ and others stubs are labeled as $m=1$ *to* $m=9$. Since ring is symmetrical, hence resonance conditions can be derived in terms of even-odd mode techniques;

$$Img[Y_{ine}] = 0 \qquad (2)$$

$$\text{and}\quad Img[Y_{ino}] = 0 \qquad (3)$$

where, $Y_{ine} = j2Y_1 tan\frac{\psi_1}{4} + j9\Delta Y_s tan\Delta\psi_s + 2j\frac{\Delta Y_s}{2}tan\Delta\psi_s$ and

$$Y_{ino} = -j2Y_1 cot\frac{\psi_1}{4} + 9j\Delta Y_s tan\Delta\psi_s$$

Where Y_{ine} and Y_{ino} are the even and odd mode input admittances respectively. The resonant frequencies obtained at *0.21*, *0.42*, *0.61* and *0.77*THz respectively as shown in Fig. 2(c). The reflection and transmission coefficients are better than *10*dB and *6*dB respectively. Fig. 3 shows the simulated electric field distribution for the designed multi-band BPF using ring resonator. It is noticed that for mode no. $n=1$, two field maxima are obtained at feeding position with 180^0 phase shift. Similarly, for $n=2$, *3 and 4*, four field maxima with 90^0 shift, six maxima with 45^0 and eight maxima with 22.5^0 phase difference respectively are observed.

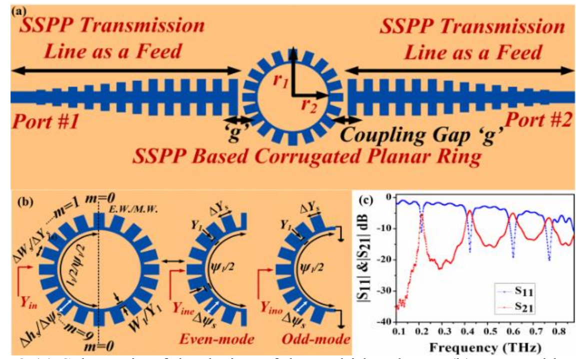

Fig. 2 (a) Schematic of the design of the multi-band BPF (b) Even-odd mode equivalent, and (c) S parameter response.

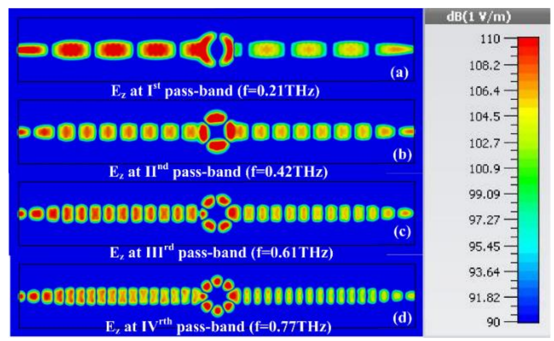

Fig. 3 Simulated E-field distribution for mode $n=1,2,3$, and *4*.

III. Conclusions

In this paper, a multi-band band-pass filter is proposed using spoof plasmonic metamaterial based planar ring resonator at THz frequency. The ring is corrugated with sub-wavelength rectangular grooves which supports TM wave and thus highly confined E-field can be achieved. Due to its symmetrical nature, the phenomenon is derived using even-odd mode analysis. The reflection and transmission coefficient are below 10 dB and 5dB within the pass-band range. Since ring resonator has high Q factor, hence this designed structure can be used for many applications including sensors, discontinuity analysis etc.

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