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Spoof Surface Plasmonic Filter with Tunable Pass-Band

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Abstract

This paper presents the design, analysis, and characterization of a spoof surface plasmonic i.e. plasmonic metamaterial, based pass-band tunable filter. A T-shape resonator corrugated with rectangular shape has been used to design the proposed filter. Varactor diodes (*SMV1232-079LF*) are used to introduce tuning in the designed SSPP based T-shape resonator. The operating mechanism of designed filter is explained mathematically through its equivalent even-odd mode analysis. The tuning range of the developed center frequency tunable T-shape bandpass filter prototype is *3.49 GHz - 3.63 GHz* (*~140MHz*). The proposed tunable bandpass filter shows an important role for the development of integrated flexible plasmonic devices and circuits at THz and microwave frequency.

1. Introduction

Tunable filters are the crucial component of RF Front end and hence attracting more attention for research and development. Due to emerging advance wireless communication, demand for electronically controlled RF system increases. Conventional microwave filters that uses microstrip suffers from cross talk and mutual coupling problems. Crosstalk and mutual couplings in between transmission lines results severe losses of signals. In this direction a new technique to design RF systems has been proposed which is plasmonic metamaterial based i.e. spoof surface plasmon polaritons (SSPP) based circuits and systems [1], [2]. Natural SPP's are special surface wave, found at optical frequency, which are highly localized electromagnetic modes at the interface of the two materials with opposite signs of their real part of the dielectric constant. SPP wave decays exponentially in the vertical direction at the vicinity of the metal-dielectric [3]. SPP's offer strong field confinement and enhancement along the interface. Thus, plasmonics, which uses SPP wave, offers the advantage of both the photonic and microelectronics [4]. However, SPP's are not supported by metal-dielectric at lower frequency regimes i.e. Microwave or THz frequencies because at these frequencies metal behaves like perfect conductor. Hence, plasmonic metamaterial, also known as SSPP, has been proposed to explore the characteristics of SPP at these frequencies [5]. Recently, various applications use the property of spoof SPP to design the transmission lines and found its potential application in the designing of static and tunable filters, power divider, and to excite the antenna [6]-[16].

Here, in this paper, we present a pass-band tunable filter using the concept of SSPP. In the Section-II, we discuss the development of the proposed filter along with its equivalent even-odd mode analysis of proposed tunable T-shape resonator. Experimental result has been demonstrated in the Section-III. Section-IV discusses the conclusion.

2. Tunable Filter Design Theory

The design and development of a pass-band tunable filter based on the concept of SSPP have been described in the following subsections.

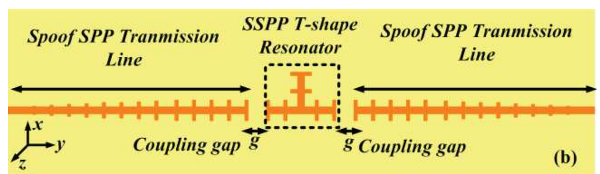

Figure 1. Schematic of the proposed filter using spoof SPP T-shape resonator.

2.1 Design of Feeding Network

Spoof SPP transmission line has been used here to feed the SSPP based T-shape resonator, as shown in Fig. 1, at its input and output port. First, a double-sided corrugated metallic surface having rectangular shape grooves as a unit cell has been designed to determine the dispersion of SSPP using CST MWS as shown in Fig. 2(a). A substrate having a dielectric constant of *3.38* is used for analysis. The loss tangent and height of the used substrate are *0.0016* and *1.524 mm* respectively. The copper metal has been used for the analysis with conductivity of 5.8×10^7 *S/m* and thickness *0.018 mm*. The physical dimension used for designing of unit cell are *w=2, h=2, d=4,* and *a=1 (all in mm)*. The analyzed dispersion curve is shown in Fig. 2(b), where the SSPP wave vector is shown using the pink colored curve and the black colored curve is used to show the freely propagating wave number. The relationship between these two kinds of wave vector is stated by (1) [3].

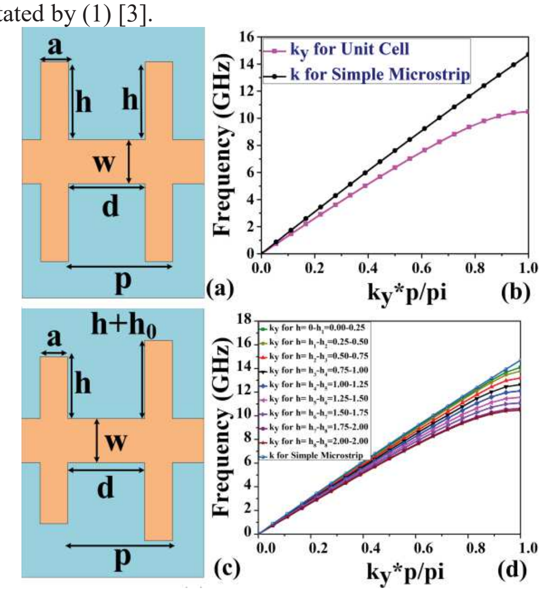

Figure 2. (a) Schematic of SSPP unit cell, (b) Dispersion curve, (c) Schematic of conversion section, (d) dispersion curve for conversion.

$$k_y^2 = k_0^2 + k_0^2 \frac{d^2}{p^2} tan^2(k_0 h) \qquad (1)$$

Where k_0 is the propagating wave number in free space and k_y is the SSPP wave number propagating in the y-direction. k_y mainly depends on the physical dimensions. Since k_y have larger as compared to k_0, as can be seen from Fig 2(d), hence to excite the spoof SPP modes through the guided (QTEM) modes of the microstrip, an transition structure is needed which converts quasi TEM mode of microstrip into spoof SPP mode. The designed converter and related dispersion curve have been shown in Fig. 2(c) and Fig. 2(d) respectively. The conversion is achieved gradually by using gradient corrugation whose height is varied from h_1-h_8 i.e. *0.25 mm* to *2 mm*, with the equal step of 0.25 mm.

2.2 Design of T-shape Resonator and Analysis of Even and Odd Mode Equivalents

Fig. 4 illustrates the geometry of the proposed T-shape spoof SPP resonator. It comprises of three SSPP transmission line sections connected to each other in T shape. Electrical length (in degree) and admittance (1/Ohm) of two of line sections are ($\psi_1/2$, Y_1) while another one has (ψ_k, Y_1). Each transmission line is corrugated with a metallic section on it with electrical length and admittance of $\Delta\psi'$, $\Delta Y'$ respectively. Due to the symmetry of the resonating structure, its operating mechanism can be mathematically explained through its equivalent even-odd mode analysis. Fig. 4 depicts the equivalent even and odd mode circuit configuration. Resonance condition for the proposed spoof SPP T-shape resonator can be obtained and expressed as

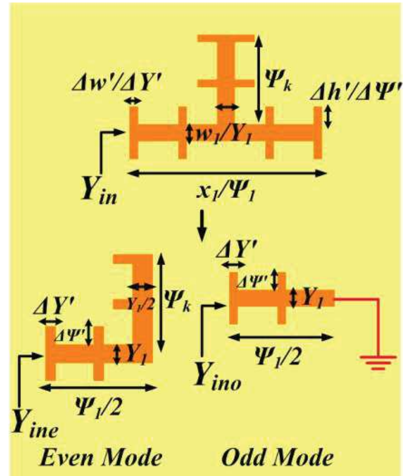

Figure 4. Equivalent even-odd mode circuits for designed T-shape resonator

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

Where Y_{ine} is the admittance of its even-mode and it is determined as

$$Y_{ine} = Y_1 \left[\frac{Y_M + jY_1 \tan\left(\psi_1/_2\right)}{Y_1 + jY_M \tan\left(\psi_1/_2\right)}\right] + n * (j\Delta Y' tan\Delta\psi') \quad n = 4$$

$$\text{With } Y_M = j\frac{Y_1}{2} tan\psi_k + m * (j\Delta Y' tan\Delta\psi') \qquad m = 2$$

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

Where Y_{ino} is the admittance of its odd-mode and it is determined as

$$Y_{ino} = (-jY_1 \cot\left(\psi_1/_2\right) + n * ((j\Delta Y' tan\Delta\psi') \qquad n = 4$$

From (2) and (3), it is clear that ψ_1 affects both the even and odd modes while ψ_k influences even mode only. Hence, by tailoring the physical length of the transmission line sections, the equivalent electrical path for different even and odd mode frequencies can be controlled. Fig.5 shows the simulated scattering parameter response for the proposed filter in the absence of tuning elements. It can be verified from the S-parameter response that resonator has a dual-mode response at frequencies *3.138* and *3.316* GHz respectively. Fig.6 illustrates the corresponding electric and magnetic field distribution at even and odd mode frequencies.

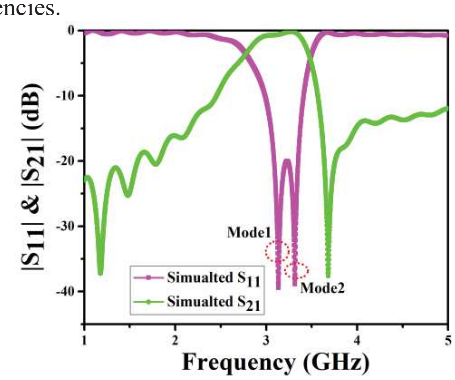

Figure 5. Simulated S-parameter results for the designed SSPP based T-shape filter as shown in Fig. 1 with coupling gap *g=0.12*mm.

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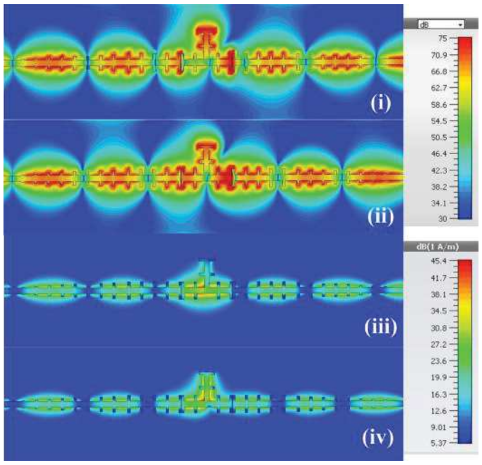

Figure 6. Simulated (i-ii) electric field distribution, (iii-iv) magnetic field distribution at frequencies *3.138 GHz and 3.316 GHz* respectively.

2.3 Design of the Proposed Reconfigurable T-shape Resonator

Fig. 7 shows the schematic for the tunable T-shape resonator and its corresponding even-odd mode equivalent circuit configurations. Here, two variable capacitors i.e. varactors (C) are symmetrically placed in the T-shaped resonator horizontally across the plane of symmetry in the X direction of XY plane. Resonance condition for this proposed configuration can be obtained and derived as

$$\mathrm{Img}[Y_{ine}] = 0 \quad (4) \quad \text{and}$$

$$\mathrm{Img}[Y_{ino}] = 0 \quad (5)$$

Where Y_{ine} and Y_{ino} are the even and odd mode admittance and expressed as

$$Y_{in} = Y_1\left[\frac{Y'_M + jY_1\tan(\psi_A)}{Y_1 + j\,Y'_M\tan(\psi_A)}\right] + n * (j\Delta Y' tan\Delta\psi')$$

$$Y_{ine} = Y_{in} \qquad \text{when } Y'_M = \frac{Y_M * j\omega C}{Y_M + j\omega C}$$

$$\text{with } Y_M = (j\frac{Y_1}{2}\tan(\psi_k) + m * (j\Delta Y' tan\Delta\psi')$$

$$\text{and} \qquad Y_{ino} = Y_{in} \qquad \text{when} \quad Y'_M = j\omega C$$

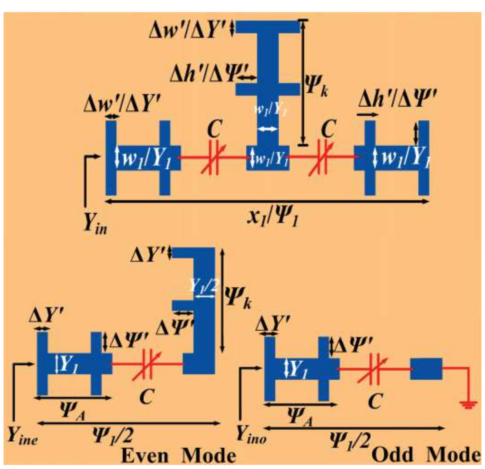

Figure 7. Schematic of varactor loaded T-shape resonator and its equivalent even and odd mode circuit.

From (4) and (5), one can observe that *C* changes both the even and odd mode by changing the electrical path lengths. Hence, as the reactance of variable capacitor C changes, the electric path length associated with both the even and odd mode frequency changes and it can control the overall center frequency accordingly.

3. Experimental Validation

For the validation of the proposed design, the spoof SPP based center frequency tunable filter is implemented. Fig. 8 shows the schematic and fabricated prototype of the designed filter. *SMV1232* in *SC 79* package has been used here as a variable capacitor device *C*. To bias, these variable capacitors, three *33* nH RF choke inductors (*0603HP27N*) has been used. Fig. 9 shows the pass-band tunability of the proposed T-shape resonator. It is clearly observe in Fig. 9 that as the bias (V_C) changes from *0.29*V to *1.49* V, due to change in electrical path length of both the even and odd mode as discussed above, the overall center frequency is shifted from *3.49 GHz* to *3.63 GHz (~140 MHz).* An insertion loss of *6.3-8.3 dB* and return loss better than *10 dB* is observed in the tuning range of the proposed pass-band tunable filter. A state of art comparison table is presented in Table I.

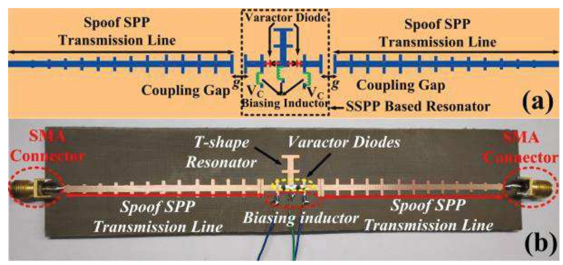

Figure 8. (a) Schematic, and (b) Fabricated prototype of varactor loaded T-shape SSPP resonator based center frequency tunable bandpass filter.

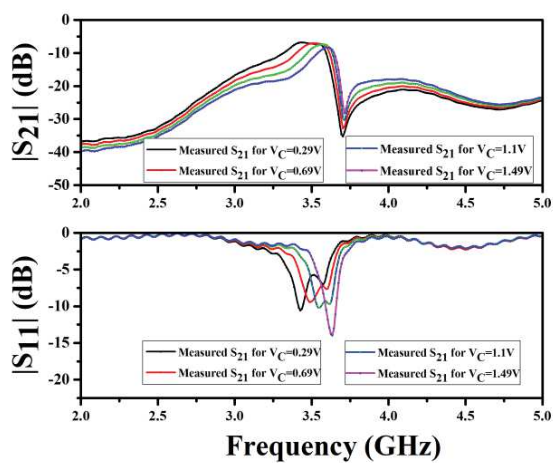

Figure 9. Measured S-parameter response of varactor loaded T-shape SSPP resonator based center frequency tunable bandpass filter.

TABLE I. COMPARISON OF RELATED WORKS

Ref.	Work Done	Tuning method/ Tuning parameter
14	Rectangular and T-shape defects used as bandwidth tunable BSF	Static tuning using physical dimensions of defects (Different prototypes are needed)
15	Lumped capacitors loaded with spoof SSP transmission line for dispersion and cutoff frequency tuning	Static tuning with different fixed value of capacitor (Different prototypes are needed)
16	Band-pass tunable characteristics of spoof SPP Unit cell	Dynamic tuning with variable capacitance elements (nearly 24 variable elements are used in the simulation, No measured results
This work	Tunable pass-band filter using SSPP fed T-shape Resonator	Dynamic tuning with Varactors, incorporated in T-shape resonating structure to control the even and odd mode frequencies. Fabricated prototype along with measured result are provided

4. Conclusion

In this paper, a spoof surface plasmonic based tunable bandpass filter has been reported. A T-shape spoof SPP based resonator is used with its operating controlling mechanism through its equivalent even-odd mode analysis using tuning element has been discussed. A slightly higher insertion loss has been observed due to the inherent real resistance of varactors and SMA losses and fabrication tolerance. As the proposed filter can tune the center frequency dynamically it has great potential and scope in the development of flexible plasmonics based devices and circuits.

5. References

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