A High Efficiency Band-Pass Filter Based on CPW and Quasi-Spoof Surface Plasmon Polaritons

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ABSTRACT A high efficiency and compact band-pass filter based on coplanar waveguide (CPW) is investigated in this paper, which lower and upper cut-off frequencies of the proposed filter can be tuned independently. In the proposed design, interdigital structure is used to filter the low frequency wave and a quasi-spoof surface plasmon polaritons (Q-SSPPs) structure is designed for tuning the higher cut-off frequency. The proposed Q-SSPPs structure contains only one cross-shaped element and keeps the similar properties of periodic SSPPs structure. The operating principle of the proposed design is explained by field distribution, dispersion curves, and equivalent circuits. The studies of vital parametric are carried out for better understanding the influences of the concerning parameters on the tunability. The simulated results indicate that the proposed design can obtain a wide bandwidth from 8.8 GHz to 17 GHz (about 63.6%) with high transmission efficiency ($|S_{11}| < -15$ dB and $|S_{21}| > -0.2$ dB). A prototype of the proposed design is fabricated and the measured results show good agreement with the simulated ones.

INDEX TERMS Band-pass filter, coplanar waveguide, quasi-spoof surface plasmon polaritons.

I. INTRODUCTION

As the band-pass filters play a vital role in communication systems, many works based on the microstrip line have been reported [1]–[6]. Most of these designs implemented by open-loop resonators [1], coupled-line [2] and slotline structure or hybrid microstrip/CPW [3]–[6] had a limited controllability in operating frequency and bandwidth. To tune the operating frequency or bandwidth, lumped elements were added to these designs for realizing independent controllability of frequencies [7]. However, the design is non-planar, complex structure, and the cost of fabrication is high. Therefore, it is technically very challenging in carrying out an independent tunable band-pass filter with a low cost and compact planar structure.

Spoof surface plasmon polaritons (SSPPs) have some advantages in microwave or terahertz devices because of its ability to confine the field in subwavelength size and tune the high cut-off frequency by optimizing the geometrical parameters [8]–[14]. However, most of reported SSPP structures use gradient corrugation grooves and specific flaring grounds for field transmission and mode conversion [15]–[19], which largely limits the miniaturization. In order to obtain the compact size of SSPP-based devices, the half mode substrate integrated waveguide (HMSIW)-based structure with corrugation grooves etched on the upper metal layer [20] and CPW-based structures with period holes etched on the metal line of the CPW were proposed [21]–[24]. In [23], an independently
tunable band-pass filter was implemented using the SSPP and CPW-based coupling structure, which had a good transmission efficiency with $|S_{11}| < -10$ dB and $|S_{21}| > -1.6$ dB from 7.31 GHz to 10.51 GHz (about 35.9%), but the proposed structure was still non-planar. Moreover, all the designs use the periodic holes or grooves to obtain the features of SSPPs, which are also not conduct to size miniaturization.

In this paper, a quasi-spoof surface plasmon polaritons (Q-SSPP) design is proposed, which is based on CPW with only one cross-shaped element etched on the middle metal line. The dispersion properties of the proposed Q-SSPP with one element are similar to the SSPP structure with periodic elements. An interdigital structure is employed for tuning the lower cut-off frequency of the bandpass filter. To better understand the physical mechanisms, the dispersion curves of periodic elements, simplified equivalent circuits...
and field distributions are carefully investigated. The numerical simulations and experimental measurements verify the characteristics of the proposed design. The proposed band-pass filter has the following advantages: 1) the Q-SSPP structure contains only one cross-shaped element, which largely minimizes the dimension of the filter; 2) the design has an independent controllability at low and high cut-off frequencies by modifying concerning parameters, 3) the simplified equivalent circuit model is implemented to better understand the design; 4) the design has a high transmission efficiency in the pass band.

II. THEORY AND METHOD

The geometry of the proposed design is shown in Fig. 1(a), which combines a Q-SSPP and interdigital structure based on CPW to realize a high efficiency transmission in the passband. The Q-SSPP can tune the high cut-off frequency and the tunability of low cut-off frequency is implemented by using interdigital structure.

The proposed design is printed on the F4B substrate (relative permittivity $\varepsilon_r = 2.65$, loss tangent $\tan \delta = 0.0015$) with the 0.5 mm thickness. The Q-SSPP is one cross-shaped element etched on the middle metal line of a 50 $\Omega$ CPW transmission line. The width and gap of the CPW line is $w$ and $g$, respectively. The sizes of the Q-SSPP are denoted by $n$, $m$, and $b$, which presented in Fig. 1(b). To impress the low-frequency band, an interdigital capacitor is added into the element, which is shown in Fig. 1(c). The length, width and gap of the interdigital structure are marked as $l$, $w_1$, and $s$, respectively.

A. THE Q-SSPP AND CPW-BASED BAND-PASS FILTER

The proposed band-pass filter combines a Q-SSPP and an interdigital structure based on CPW. The performance on the simulated S-parameters is presented in Fig. 2, in which $g = 0.1$ mm, $w = 3.3$ mm, $m = 0.55$ mm, $n = 0.3$ mm, $b = 1.5$ mm, $s = 0.1$ mm, $w_1 = 0.1$ mm, and $l = 0.4$ mm.

It is clearly to be seen that the proposed design has good band-pass features.

The dispersion curves of periodic cross-shaped elements with different length $b$ are displayed in the Fig. 3. It is clearly to be observed that the longer the length of element is, the larger deviation from the CPW line the dispersion curves has, when $m$, $n$ is fixed as 0.55 mm, 0.3 mm, respectively. Compared Fig. 3 with Fig. 2, it is seen that the proposed Q-SSPPs band-pass filter has the almost same cut-off frequency at high frequency with the periodic element. Moreover, the simulated electric field contour distribution on the x-y plane and magnitudes of electric field flows on the cross sections at 12GHz when $b$ is fixed as 1.5 mm are demonstrated in Fig. 4 (a) and (b), which show the good propagation property and excellent field confinement of the proposed filter. Figure (c) and (d) show the electric field arrows distribution on the x-y plane and magnetic field distribution on the y-z plane at 12 GHz when $b$ is fixed as 1.5 mm, respectively. It is observed that the proposed Q-SSPPs design converts the quasi-TEM mode to TM mode successfully.
B. SIMPLIFIED EQUIVALENT CIRCUIT MODEL OF Q-SSPPS BAND-PASS FILTER

In order to understand the physical mechanism, the proposed band-pass filter is divided into three parts: 1) CPW feeding part, 2) left conductor, which consists of T-shaped patch and left eight fingers, 3) right conductor, which consists of T-shaped patch and right nine fingers. A LC equivalent circuit structure is shown in Fig. 5, where $L_1$ and $C_1$ are the equivalent parameter of CPW feeding part. $L_2$ is the inductance of the T-shaped patch structure; $C_2$ and $C_6$ are the single grounded capacitance of left and right conductor, respectively. $L_3$ and $C_3$ are the self-inductance and self-capacitance of left digital structure, respectively. Similarly, $L_4$ and $C_4$ are the self-inductance and self-capacitance of right digital structure, respectively. Moreover, $L_5$ is the mutual inductance between digital structures and $C_5$ is the interdigital capacitance. The values of $L_1$ and $C_1$ of CPW can be obtained from [25] and can be presented as:

$$L_1 = \frac{Z_0 \sqrt{\varepsilon_{re}}}{c_0}$$  \hspace{1cm} (1)

$$C_1 = \frac{L_1}{Z_0^2}$$  \hspace{1cm} (2)

where $c_0$ is the velocity of light in frees pace, $\varepsilon_{re}$ is the effective dielectric constant and $Z_0$ is the characteristic impedance of the CPW. And the values of optimized equivalent parameters of the proposed simplified LC circuit model are calculated as: $L_1 = 0.23884 \text{ nH}$, $C_1 = 0.28269 \text{ pF}$, $L_2 = 0.70786 \text{ nH}$, $C_2 = 0.01500 \text{ pF}$, $L_3 = 0.47504 \text{ nH}$, $C_3 = 0.01763 \text{ pF}$, $L_4 = 0.49999 \text{ nH}$, $C_4 = 0.01772 \text{ pF}$, $L_5 = 0.30043 \text{ nH}$, $C_5 = 0.39120 \text{ pF}$, $C_6 = 0.00498 \text{ pF}$ with the aid of Advanced Design System (ADS) commercial software and formulas (1)-(2).

C. FILTER PERFORMANCE AND PARAMETRIC STUDIES

To better analyze the performance of the proposed design, the vital parametric study is now conducted. As shown in Fig. 6, the equivalent circuit model by ADS are well agreement with the CST full-wave simulation results, which verify the proposed concept. The simulated S-parameters of the proposed design and $l$ varies from 0.0 mm to 0.8 mm with the step 0.2 mm is shown in Fig. 7. It is clearly to be seen that the low cut-off frequency can be tuned by the parameter $l$, and the larger $l$ is, the lower the low cut-off frequency is. Similarly, the influences of the length of element $(b)$ on...
In this paper, a compact and high efficiency band-pass filter is proposed, which is based on the Q-SSPPs structure. The operating principle of the proposed filter is explained by the dispersion curves, field distributions, and equivalent circuits.

The low and high cut-off frequencies can be controlled by tuning the related vital parameters independently. A prototype of the proposed design was fabricated, and the measured results agree well with the simulated ones, which verifies the proposed concept. Moreover, the proposed Q-SSPPs band-pass filter contains only one cross-shaped element, which extremely minimize the dimensions of the designs.

III. EXPERIMENTAL VERIFICATION

A prototype based on F4B substrate is fabricated to validate the performance of the proposed Q-SSPPs band-pass filter, which displayed in Fig. 9. The F4B substrate has a thickness of 0.5 mm with εr = 2.65, loss tangent (δ) = 0.0015. The thickness of metallic strips is 0.018 mm. The dimensions of fabricated Q-SSPPs band-pass filter are: g = 0.1 mm, w = 3.3 mm, m = 0.55 mm, n = 0.3 mm, b = 1.5 mm, s = 0.1 mm, w1 = 0.1 mm, l = 0.4 mm. The simulated and measured results of the proposed design is presented in Fig. 10, which shows the measured results agree well with the simulated ones. The bandwidth of the proposed filter is from 8.8 GHz to 17 GHz (for |S11| < −15 dB and |S21| > −0.2 dB), about 63.6%, which is useful in microwave integrated applications.

IV. CONCLUSION

In this paper, a compact and high efficiency band-pass filter is proposed, which is based on the Q-SSPPs structure. The operating principle of the proposed filter is explained by the dispersion curves, field distributions, and equivalent circuits.

The low and high cut-off frequencies can be controlled by tuning the related vital parameters independently. A prototype of the proposed design was fabricated, and the measured results agree well with the simulated ones, which verifies the proposed concept. Moreover, the proposed Q-SSPPs band-pass filter contains only one cross-shaped element, which extremely minimize the dimensions of the designs.

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