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

ZHAO-MIN CHEN[1,2], (Student Member, IEEE), YANHUI LIU[3], XINHUA LIANG[4], (Student Member, IEEE), JUN WANG[6], YUAN LI[2], (Student Member, IEEE), JIAHAO ZHU[2], (Student Member, IEEE), WEN JIANG[2], (Student Member, IEEE), XIAOPENG SHEN[5], (Member, IEEE), LEI ZHAO[1,2], (Senior Member, IEEE), AND TIE JUN CUI[6], (Fellow, IEEE)

[1]School of Information and Control Engineering, China University of Mining and Technology, Xuzhou 221116, China
[2]Jiangsu Key Laboratory of Education Big Data Science and Engineering, School of Mathematics and Statistics, Jiangsu Normal University, Xuzhou 221116, China
[3]AVIC Beijing Changcheng Aeronautical Measurement and Control Technology Research Institute, Beijing 101111, China
[4]Department of Physics and Electronic Engineering, Jiangsu Normal University, Xuzhou 221116, China
[5]Department of Physics, China University of Mining and Technology, Xuzhou 221116, China
[6]State Key Laboratory of Millimeter-Waves, School of Information Science and Engineering, Southeast University, Nanjing 211189, China

Corresponding authors: Lei Zhao (leizhao@cumt.edu.cn) and Tie Jun Cui (tjcui@seu.edu.cn)

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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

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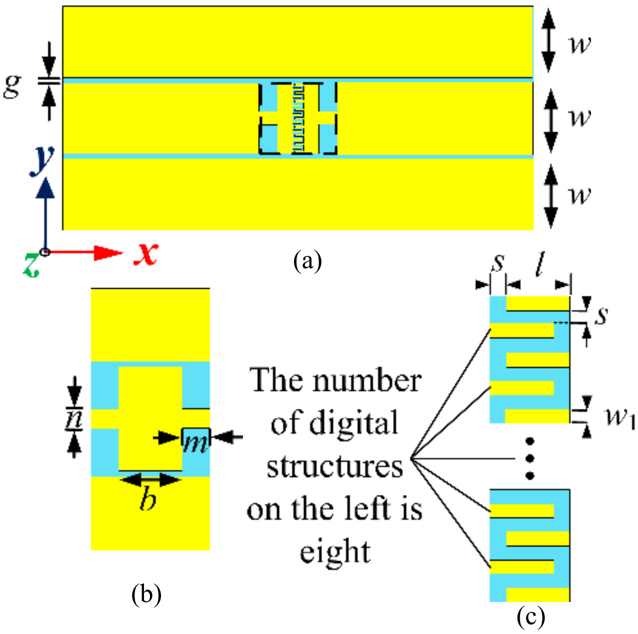

FIGURE 1. (a) Geometry of the proposed band-pass filter. The yellow and blue parts represent metal and substrate, respectively. (b) One cross-shaped element etched on the middle line of CPW. (c) Interdigital structure.

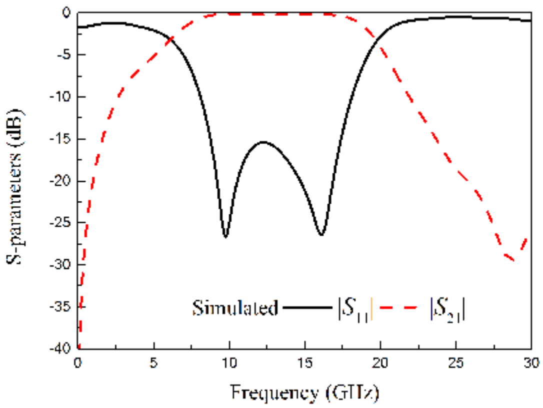

FIGURE 2. Simulated S-parameters of the proposed band-pass filter when $g = 0.1$ mm, $w = 3.3$ mm, $m = 0.55$ mm, $n = 0.3$ mm, $b = 1.5$ mm, $s = 0.1$ mm, $w_1 = 0.1$ mm, $l = 0.4$ mm.

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

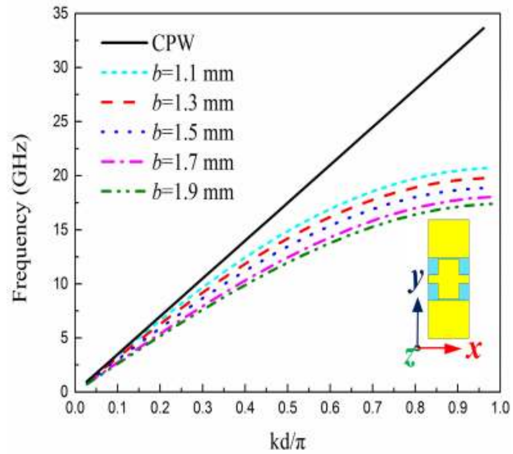

FIGURE 3. Simulated dispersion curves for the fundamental mode of the periodic element with different element length *b*.

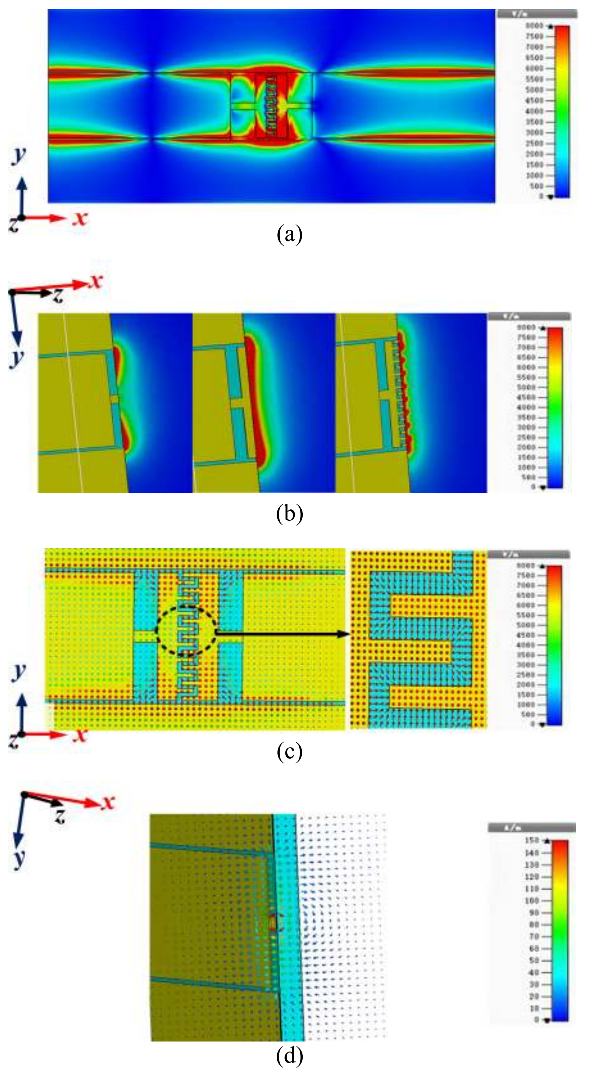

FIGURE 4. (a) The simulated electric field contour distribution on the *x*-*y* plane at 12 GHz when $b = 1.5$ mm. (b) The magnitudes of electric field flow on cross sections of the proposed Q-SSPPs based band-pass filter at three different locations at 12 GHz when $b = 1.5$ mm. (c) The simulated electric field arrows distribution on the *x*-*y* plane at 12 GHz when $b = 1.5$ mm. (d) The simulated magnetic field arrows distribution on the y-z plane at 12 GHz when $b = 1.5$ mm.

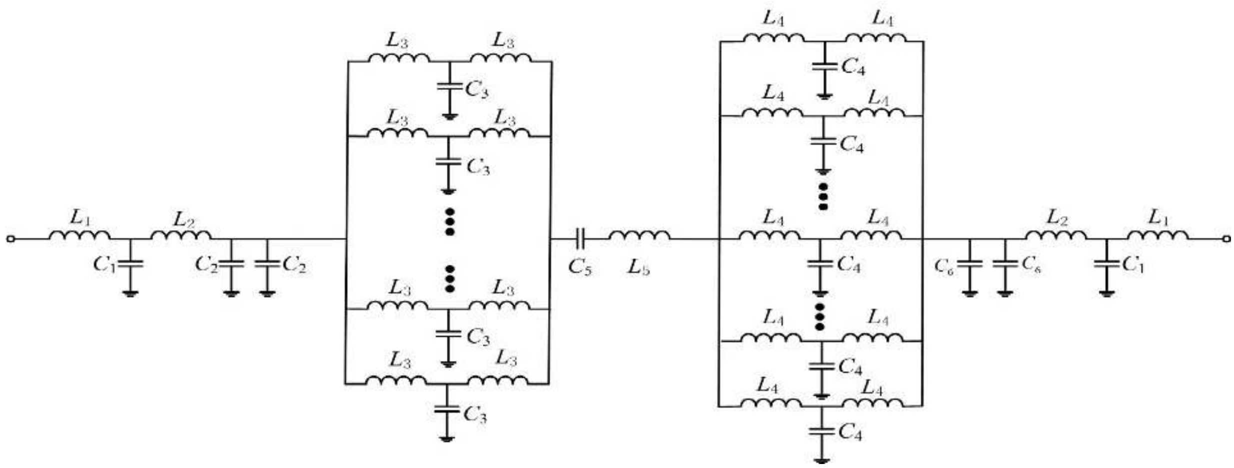

FIGURE 5. Equivalent circuit of the proposed band-pass filter structure.

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 Ω 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.

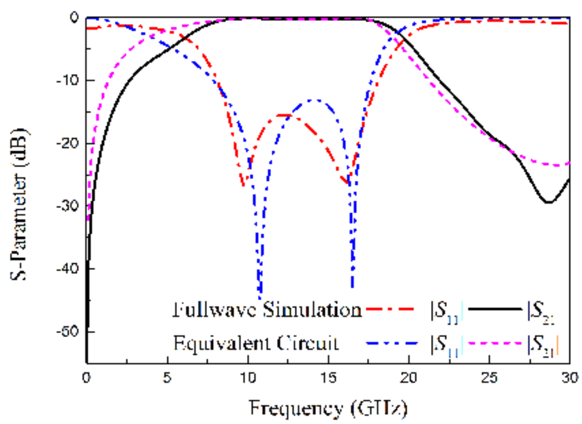

FIGURE 6. Simulated S-parameters of the proposed band-pass filter and equivalent circuit model.

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, 0.3mm, 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.

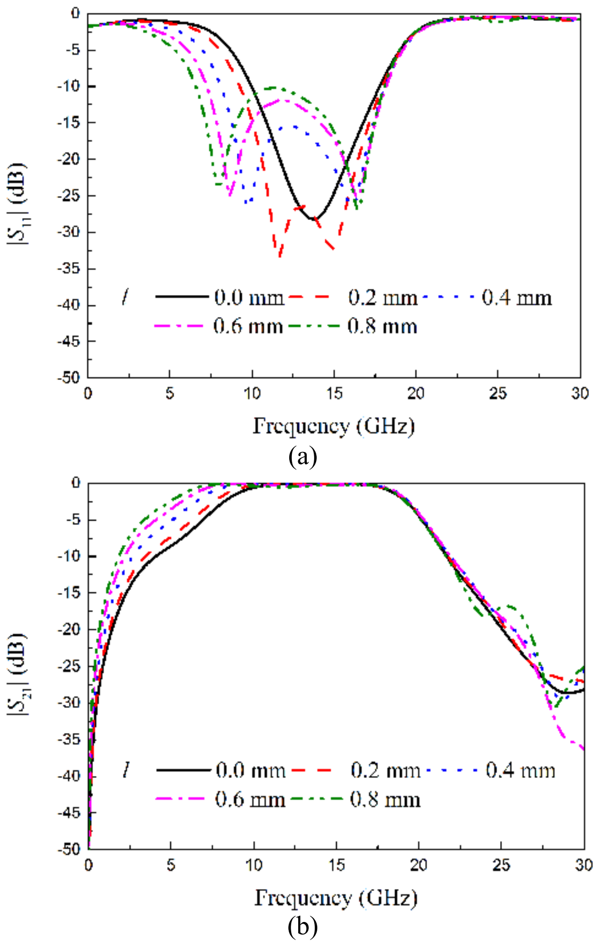

FIGURE 7. Simulated $|S_{11}|$ (a) and $|S_{21}|$ (b) of the proposed band-pass filter and *l* changes from 0.0 mm to 0.8 mm with the step 0.2 mm.

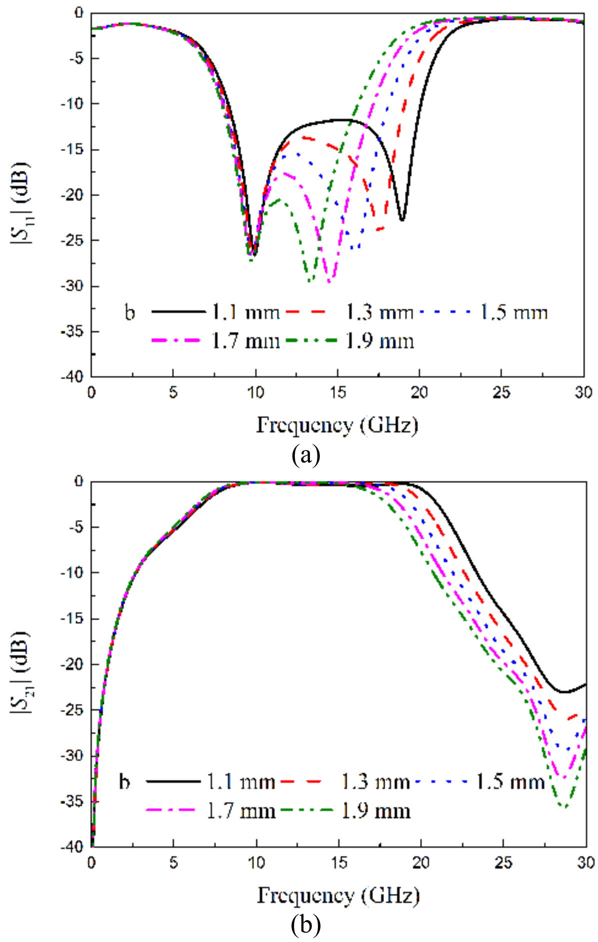

FIGURE 8. Simulated $|S_{11}|$ (a) and $|S_{21}|$ (b) of the proposed band-pass filter and *b* changes from 1.1 mm to 1.9 mm with the step 0.2 mm.

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:

$$L_1 = Z_0 \frac{\sqrt{\varepsilon_{re}}}{c_0} \tag{1}$$

$$C_1 = \frac{L_1}{Z_0^2} \tag{2}$$

where c_0 is the velocity of light in frees pace, ε_{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: $L_1 = 0.23884$ nH, $C_1 = 0.28269$ pF, $L_2 = 0.70786$ nH, $C_2 = 0.01500$ pF, $L_3 = 0.47504$ nH, $C_3 = 0.01763$ pF, $L_4 = 0.49999$ nH, $C_4 = 0.01772$ pF, $L_5 = 0.30043$ nH, $C_5 = 0.39120$ pF, $C_6 = 0.00498$ 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

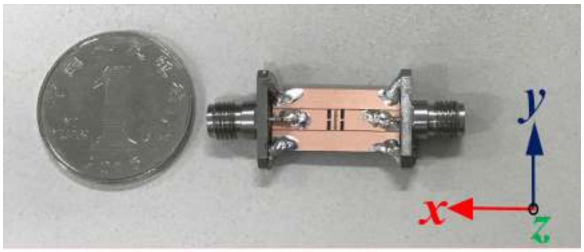

FIGURE 9. Photograph of the fabricated band-pass filter.

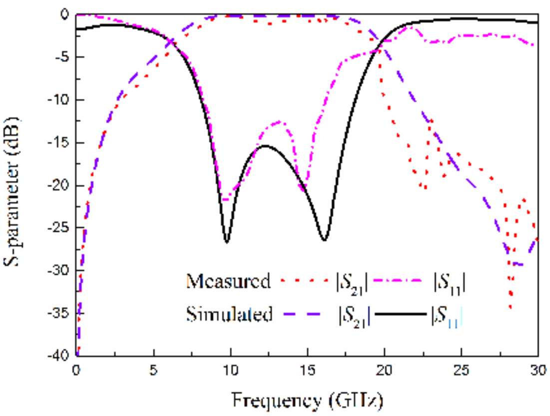

FIGURE 10. Measured and simulated S-parameters of the.

resistance to the high frequency is displayed in Fig. 8. It is obvious that the larger b is, the lower the high cut-off frequencies are. Moreover, comparing the Fig. 3 with Fig. 8, we can obtain that the high cut-off frequency agrees well with the simulated periodic dispersion curves. Therefore, the proposed design can independently control the low and high cut-off frequencies by changing parameters l and b according to the studies above.

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 $\varepsilon_r = 2.65$, loss tangent tan $(\delta) = 0.0015$. 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, $w_1 = 0.1$ 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 $|S_{11}| < -15$ dB and $|S_{21}| > -0.2$ 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 control by tuning the releated 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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ZHAO-MIN CHEN was born in Jiangsu, China. She received the B.S. degree form Jiangsu Normal University, Xuzhou, China, in 2016, where she is currently pursuing the M.S. degree. Her research interest includes design of RF/ microwave antennas and filters.

YANHUI LIU was born in Hebei, China. She received the M.S. degree in the application of information systems from the China University of Geosciences, Beijing, in 2014. Since 2014, she has been with the AVIC Beijing Changcheng Aeronautical Measurement & Control Technology Research Institute. Her current research interests include automated test systems and related standards.

XINHUA LIANG was born in Jiangsu, China. He received the B.S. degree from the Changchun University of Science and Technology, Changchun, China, in 2017. He is currently pursuing the M.S. degree with Jiangsu Normal University, Xuzhou, China. His research interest includes the design of RF/microwaves filters and metasurface.

JUN WANG was born in Jiangsu, China. He received the B.S. and M.S. degrees from Jiangsu Normal University, Xuzhou, China, in 2013 and 2017, respectively. He is currently pursuing the Ph.D. degree with Southeast University, Nanjing, China. His research interest includes the design of RF/microwave antennas and components.

YUAN LI was born in Jiangsu, China. She received the B.S. degree from Jiangsu Normal University, Xuzhou, China, in 2017, where she is currently pursuing the M.S. degree. Her research interest includes design of RF/microwaves filters.

JIAHAO ZHU was born in Jiangsu, China. He received the B.S. degree from Jiangsu Normal University, Xuzhou, China, in 2018, where he is currently pursuing the M.S. degree. His research interest includes the method of DGTD.

WEN JIANG was born in Jiangsu, China. She received the B.S. degree from Jiangsu Normal University, Xuzhou, China, in 2018, where she is currently pursuing the M.S. degree. Her research interest includes the design of RF/microwaves filters.

XIAOPENG SHEN (M'18) received the B.Sc. degree in physical education from Qufu Normal University, in 1997, and the second B.Sc. degree in internal trade and the M.Sc. degree in theory physics from the China University of Mining and Technology, in 1997 and 2006, respectively. In August 1999, he joined the School of Physical Science and Technology, China University of Mining and Technology, Xuzhou, China as a Lecturer, and became an Associate Professor in 2008. His current research interests include photonic crystals, plasmonics, and metamaterials. He received the Second Prize of National Natural Science Award of China, in 2018.

LEI ZHAO (M'09–SM'18) received the B.S. degree in mathematics from Jiangsu Normal University, China, 1997, and the M.S. degree in computational mathematics and the Ph.D. degree in electromagnetic fields and microwave technology from Southeast University, Nanjing, China, in 2004 and 2007, respectively.

From September 2009 to December 2018, he worked in Jiangsu Normal University, Xuzhou, China. From August 2007 to August 2009, he worked in the Department of Electronic Engineering, The Chinese University of Hong Kong, as a Research Associate. From February 2011 to April 2011, he worked in the Department of Electrical and Computer Engineering, National University of Singapore, as a Research Fellow. From September 2016 to September 2017, he worked in the Department of Electrical and Computer Engineering, University of Illinois at Urbana–Champaign, USA, as a Visiting Scholar. He joined the China University of Mining and Technology, Xuzhou, China, in 2019, where he is currently the Full Professor. He has authored and coauthored more than 60 refereed journal and conference papers. His current research interests include spoof surface plasmon polaritons theory and its applications, antennas design and its applications, computational electromagnetics, and electromagnetic radiation to human's body.

Dr. Zhao serves as an Associate Editor for IEEE ACCESS, an Associate Editor-in-Chief for ACES Journal and a reviewer for multiple journals and conferences including the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, IEEE ACCESS, IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, *ACES Journal*, and other primary electromagnetics and microwave related journals.

TIE JUN CUI (M'98–SM'00–F'15) received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from Xidian University, Xi'an, China, in 1987, 1990, and 1993, respectively. In March 1993, he joined the Department of Electromagnetic Engineering, Xidian University, and was promoted to an Associate Professor in November 1993. From 1995 to 1997, he was a Research Fellow with the Institute fur Hochstfrequenztechnik und Elektronik (IHE), University of Karlsruhe, Germany. In July 1997, he joined the Center for Computational Electromagnetics, Department of Electrical and Computer Engineering, University of Illinois at Urbana–Champaign, first as a Postdoctoral Research Associate and then a Research Scientist. In September 2001, he was a Cheung-Kong Professor with the Department of Radio Engineering, Southeast University, Nanjing, China, where he became a Chief Professor in January 2018. He first authored the books *Metamaterials—Theory, Design, and Applications* (Springer, November 2009) and *Metamaterials: Beyond Crystals, Noncrystals, and Quasicrystals* (CRC Press, March 2016). He has published more than 500 peer-review journal articles, which have been cited by more than 25000 times (H-Factor 79; from Google Scholar), and licensed over 60 patents.

Dr. Cui was awarded a Research Fellowship from the Alexander von Humboldt Foundation, Bonn, Germany, in 1995, received a Young Scientist Award from the International Union of Radio Science in 1999, was awarded a Cheung Kong Professor under the Cheung Kong Scholar Program by the Ministry of Education, China, in 2001, and received the National Science Foundation of China for Distinguished Young Scholars in 2002. He received the Natural Science Award (first class) from the Ministry of Education, China, in 2011, and the National Natural Science Awards of China (second class), in 2014 and 2018, respectively. His researches have been selected as one of the most exciting peer-reviewed optics research Optics in 2016 by Optics and Photonics News Magazine (OSA), 10 Breakthroughs of China Science in 2010, Best of 2010 in *New Journal of Physics*, and Research Highlights in a series of journals. His work has been widely reported by *Nature* News, *MIT Technology Review*, *Scientific American*, *Discover*, and *New Scientists*. He served as a General Co-Chair for the International Workshops on Metamaterials (META'2008, META'2012), a TPC Co-Chair for Asian Pacific Microwave Conference (APMC'2005) and for Progress in Electromagnetic Research Symposium (PIERS'2004), and a TPC Member for the International Congress on Advanced Electromagnetic Materials in Microwaves and Optics (Metamaterials'2014, 2016, 2018, 2019). He presented more than 30 Keynote and Plenary Talks in Academic Conferences, Symposiums, or Workshops. He was an Associate Editor in the IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, a Guest Editor in *Science China—Information Sciences*, *Science Bulletin*, and Guest Editor in Research.