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Bandstop Characteristic of Inclined Straight Slot Embedded in Microstrip Line

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Abstract—When a narrow straight slot is etched obliquely in the upper metallic strip of a microstrip line, a bandstop response can be observed from the terminations of the microstrip line. The whole circuit behaves as a single-stage bandstop filter, of which the center operation frequency and the fractional bandwidth can be adjusted by changing the length and the inclined angle of the slot, almost independently. Parametric studies are made to demonstrate the filtering performance, via numerical simulations. An LC equivalent circuit model is given to explain the bandstop behavior, shows its potential use in high order filter design. Samples are designed, fabricated and measured for verification, the experiment results show that the filters have good bandstop performance. It can be used as an alternative or complementary candidate for the traditional spur-line bandstop filter.

1. INTRODUCTION

In the frequency range of microwave, the conventional realizations of bandstop filter (BSF) generally consist of individual resonators and transmission line inverters [1]. One drawback of those designs is the relatively large size in transversal direction, due to the individual resonators. In the past few decades, many techniques have been developed for microstrip BSFs, with the purpose of planarization and miniaturization [2–9]. In [2], the spur-line design was given, which can be built fully in a microstrip line without any width widening. This feature is attractive for both the miniaturization and high integration. However, spur-line is only suitable for wideband BSF, because of the quarter-wavelength open-ended branch in its structure [3]. Defected ground structure (DGS) is a famous technique developed in this century. It offers much more flexible realizations covering many kinds of passive circuits, including BSF [4, 5]. The cutting/etching in the metallic ground cannot be avoided in practice DGS circuits, and increases the crosstalk level between the circuits sharing the same ground. The third technique is the Meta-material. For example, a BSF can be built by integrating a complementary split ring resonators (CSRR) directly into a microstrip line [6]. The CSRR can be fabricated in either the metallic ground (DGS) or the upper strip. In the latter case, the strip will be significantly widened for loading the CSRR [6]. Other new techniques developed for BSFs include dual mode resonator [7] and coupled-line stubs [8], which are suitable for dual-band operations. The last technique introduced here is called the Signal-interference, in which no individual resonator could be found. In [9], the researchers successfully designed a BSF by using a signal interference ring, the BSF has wide tuning fractional bandwidth (FBW) and low loss.

In this study, a new bandstop circuit is proposed. The core structure is a narrow straight slot, etched obliquely in the upper metallic strip of a microstrip line. It has advantages such as compact size, low loss and easy integration. Further studies indicate that the rejection frequency and FBW can be easily controlled by adjusting the slot itself. The detailed discussion is in the following parts.

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2. SINGLE STAGE BANDSTOP FILTER DESIGN

As shown in Fig. 1, the main structure of the proposed circuit is a narrow straight slot etched obliquely in a uniform microstrip line. The slot is placed in the central of the line, with an inclined angle of θ. The circuit is compact in geometry, and can be fully integrated into a transmission line without widening its width. Comparing with the similar spur-line design [2], there is no open-ended stub, which means less end-discontinuity and radiation loss. To demonstrate its performance, several numerical simulations were carried out, by using a commercial full wave package IE3D, on Rogers 5880 substrate ($\varepsilon_r = 2.2$) with thickness of 0.7874 mm. The width of the microstrip line (W) is fixed as 2.4 mm in simulations, with characteristic impedance of 50 Ohm. Therefore, good matching can be guaranteed in the passband.

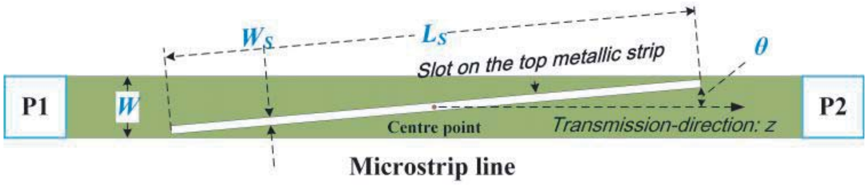


Figure 1. Configuration of proposed bandstop circuit.

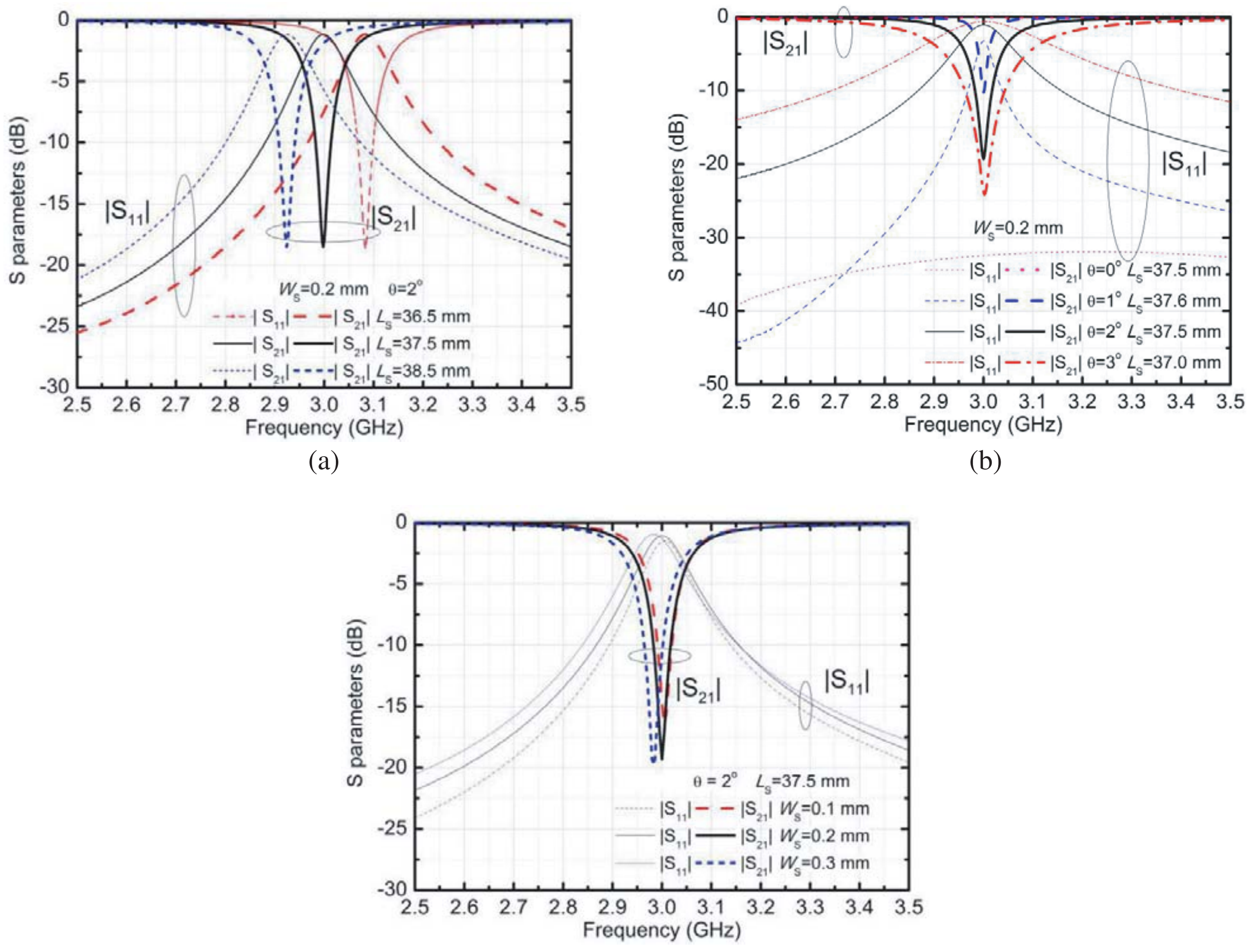
First, the impact of the slot length (L_S) on the center operation frequency (f_c) is investigated. Fig. 2(a) shows the simulated S parameters ($|S_{11}|$ & $|S_{21}|$) of models with different L_S, fixed inclined angle (θ) of 2° and slot width (W_S) of 0.2 mm. It can be observed that f_c increases from 2.925 to 3.080 GHz as L_S decreases from 38.5 to 36.5 mm. The post calculations prove that L_S is about a half (guided) wavelength at the corresponding f_c, that means the slot is resonating at the rejection frequency. Besides, the $|S_{21}|$ at f_c are all below -18 dB and the 3-dB FBWs are about 3.3% in the three cases. Therefore, the slot length dominates the BSF's operation frequency without the changing of FBW.

Second, let's tune the FBW at a fixed f_c of 3.0 GHz. Fig. 2(b) shows the simulated S parameters with different θ, slightly changed L_S around 37.3 mm and fixed W_S of 0.2 mm. The 3-dB FBW changes from 0%, 1.1%, 3.7% to 8.2%, as θ varies from 0, 1, 2 to 3°, respectively. In simulation, the slight modification of L_S is in the range of $\pm 1\%$ ($37.0 \sim 37.6$ mm). It is obvious that FBW can be widened/narrowed mainly by increasing/decreasing θ. Particularly, the minimum/zero θ makes the filter retrograde into a parallel coupled line pair in common mode, which behaves as a uniform allpass transmission network. Meanwhile, the upper bound of θ ($\arcsin(W/L_s)$) and the maximum FBW depend directly on L_S and W, as shown in Fig. 1. For a given θ, an over-length slot will cut the microstrip line off, leading to full reflection at all frequencies. Therefore, the proposed BSF is much more suitable for narrow band applications, and can be used as a complementary candidate for the spur-line filters [2], which used usually for wideband applications.

Finally, the impact of W_S is investigated. As shown in Fig. 2(c), the widening of W_S slightly broadens the FBW and decreases f_c, while keeping L_S and θ unchanged. One may find that W_S has much less contributions than L_S and θ. In practice, narrower slot may be preferred for less coupling loss. The minimum slot width depends on manufacture capability. After the parametric studies, we can conclude that the FBW and f_c of the single-stage BSF can be controlled almost independently by θ and L_S, respectively. In the following part, the bandstop behavior will be explained by using an equivalent circuit model to reveal its physical nature.

3. EQUIVALENT CIRCUIT AND DISCUSSION

It has been discussed that an obliquely embedded slot in a microstrip line will generate bandstop response, of which the rejection bandwidth is dominated by the inclined angle. Particularly, the bandstop response disappears when the slot is arranged parallel to the microstrip line, as shown in Fig. 2(b). According to the phenomenon, an equivalent circuit is proposed to demonstrate this BSF. As shown in Fig. 3, the slot is modeled as a series LC resonators hunting at the central point of the microstrip line. The resonant frequency f_c depends only on the slot length, as has been discussed in



(a) (b)

(c)

Figure 2. Simulated frequency responses of proposed BSF (Microstrip Width: $W = 2.4\,\mathrm{mm}$). (a) Varied slot length L_S with fixed $\theta = 2°$ and $W_S = 0.2\,\mathrm{mm}$. (b) Varied inclined angle θ with $L_S \approx 37.3\,\mathrm{mm}$ and $W_S = 0.2\,\mathrm{mm}$. (c) Varied slot width W_S with $L_S = 37.5\,\mathrm{mm}$ and $\theta = 2°$.

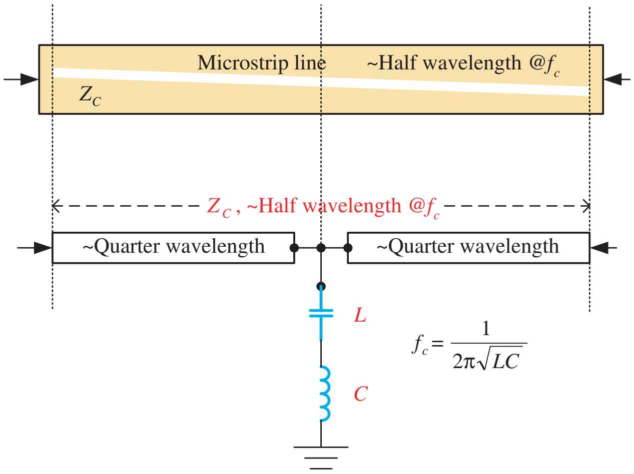


Figure 3. Equivalent circuit of proposed bandstop structure.

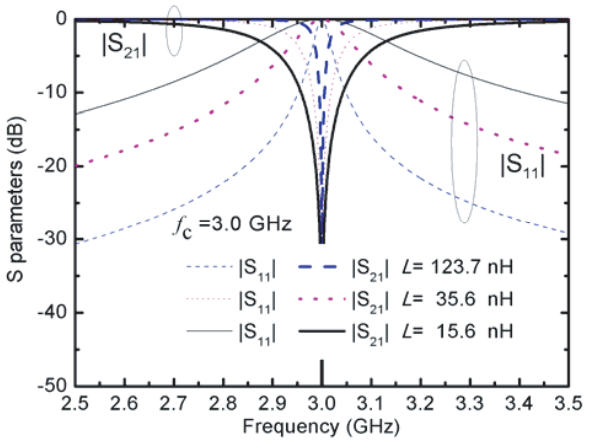


Figure 4. Simulated results of equivalent circuit.

Fig. 2(a). In addition, two uniform transmission line sections, having the same characteristic impedance (Z_c) as the un-slotted microstrip line, are added to the model to compensate the length of the microstrip line in which the slot occupies.

Figure 4 depicts the simulated frequency responses based on the circuit model. In the simulation, the characteristic impedance is set to be 50 Ohm, the resonant frequency of the LC resonator is locked at 3.0 GHz to model the slot with fixed length. Under different values of L, one can find apparently that the responses are very similar to those in Fig. 2(b). The smaller L, or the smaller external Q for the resonator [10], means the wider rejection bandwidth, or the tighter coupling between the slot and the line. When L is large enough (infinity), signal at any frequency could not pass through the resonator branch, in other words, the circuit performs as a uniform transmission line.

To validate the model further, a two-stage configuration is given in Fig. 5. Two identical slots are added in sequence, with spacing of a quarter (guided) wavelength, therefore, its equivalent LC circuit can be drawn directly from Fig. 3. Taking the compensate lines (Fig. 3) into account, the length of the connecting line (Fig. 5) between the two lumped LC resonators are three-quarter wavelength.

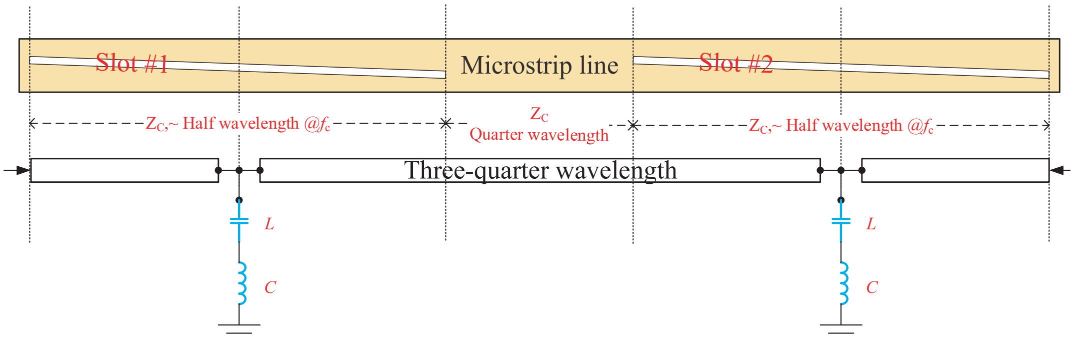


Figure 5. Two-stage bandstop filter and its equivalent circuit.

Here, two simulations are performed for comparison. The results are given in Fig. 6, achieves good agreement. The actual microstrip circuit is analyzed by using IE3D, with the same slot parameters as given in Fig. 3(b) ($\theta = 2°$) and slot spacing of 16.7 mm (end to front). Its corresponding circuit model is simulated with ADS, with $f_c = 3.0$ GHz and $L = 35.6$ nH. Comparing with the single stage filter, not only the rejection level and roll-off coefficient are strengthened, but two extra reflection zeroes are also added besides the stopband of the two-stage BSFs. This example validates the possibility of high order filter implementation by using this structure.

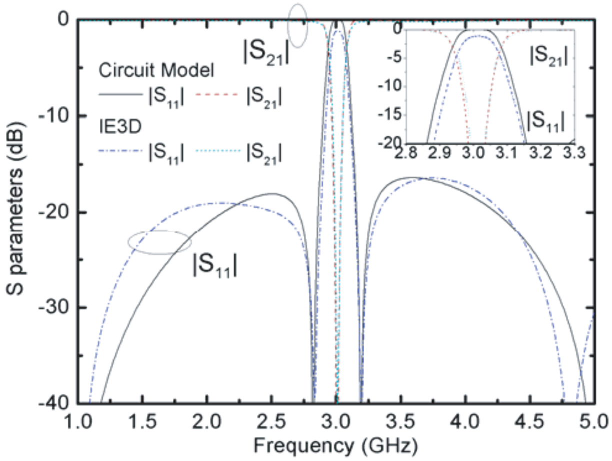


Figure 6. Simulated frequency responses of different models.

4. EXPERIMENTAL VERIFICATION

Filter samples are designed and fabricated for verification. In simulations, the operating frequency is located at 3.0 GHz. The measurement is performed on a Network Analyzer (R&S ZVA67), via a test fixture (Anritsu 3680K). The summarized parameters and measured performance are given in Table 1. Fig. 7 shows the photograph of the fabricated samples. Fig. 8 illustrates the measured S parameters. It can be observed that sample #1 and #2 have different FBWs (3.3% and 7.5%), as a result of the different inclined angles (2° and 3°). Both the center frequencies are about 2% higher than 3.0 GHz, which is mainly caused by the substrate uncertainty and fabrication tolerance. In the stopband, the highest rejections ($-|S_{21}|$) are 15.4 dB at 3.057 GHz and 21.2 dB at 3.072 GHz, respectively. The minimal return losses ($-|S_{11}|$) are 2.0 and 1.0 dB, respectively. In the passband, $|S_{11}|$ is good from DC to 5.8 GHz and shows good matching. The experimental data show that the proposed structure has a good bandstop response as predicted.

Table 1. Parameters of fabricated filter samples.

	Description		**Sample**		**Unit**
			#1	#2	
Filter	Center Frequency	f_c	**3.057**	**3.072**	GHz
	Fractional Bandwidth	**FBW**	**3.3**	**7.5**	%
	Maximum Rejection Level	$-\|S_{21}\|$	**15.4**	**21.2**	dB
	Maximum Reflection Loss	$-\|S_{11}\|$	**2.0**	**1.0**	dB
Slot	Length	L_S	**37.5**	**37.0**	mm
	Width	W_S	**2.0**	**1.0**	mm
	Inclined Angle	θ	**2**	**3**	Degree
Microstrip Line	Width	W	**2.4**		mm
Substrate	Height	**N/A**	**0.7874**		mm
	Relative Permittivity	ε_r	**2.2**		N/A

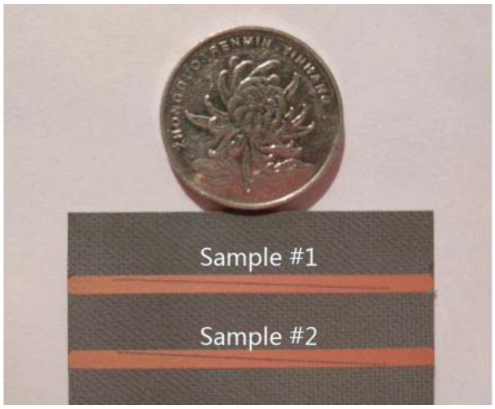


Figure 7. Photograph of fabricated filter samples.

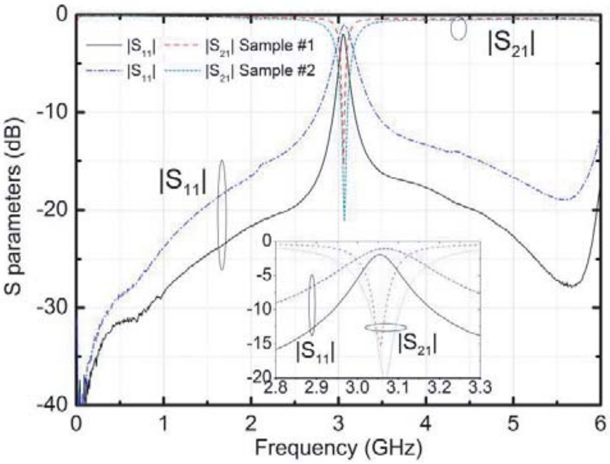


Figure 8. Measured S parameters of fabricated filter samples.

5. CONCLUSION

A new bandstop structure has been proposed and studied. It has several advantages, such as compact size, low loss and easy integration. The tuning approaches for operation frequency and FBW are given. Equivalent circuits are given to demonstrate its operation mechanism. Prototypes are designed and fabricated. The measured results show that the structure has good rejection characteristic and can be used to design BSF with narrow FBW. It is an alternative bandstop unit in planar microwave circuit design, especially can be used as a complementary candidate for the well-known spurline structure with wide stopband.

ACKNOWLEDGMENT

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