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BROAD BAND-STOP FILTER USING FREQUENCY SELECTIVE SURFACES IN UNIPLANAR MICROWAVE TRANSMISSION LINE

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Abstract—We present a band-stop filter (BSF) by using a periodic structure property of frequency selective surfaces (FSSs) embedded in a microstrip transmission line. The proposed BSF is designed with FSS unit cells modifying the cross-loop slots. The center frequency (f_o) of the BSF is 6.6 GHz, and the 3-dB bandwidth varies by the number of cascading unit cells. The BSF is interpreted with an equivalent circuit model and a dispersion diagram, and exhibits uniplanar geometry, low return loss, simple fabrication, smaller size, and wide bandwidth.

1. INTRODUCTION

A microstrip resonator filter with various periodic structures has constantly been investigated. The periodic structures with identical reactive elements are loaded in transmission lines [1]. From the transmission line theory, this periodic repetition along the direction of propagation allows for the L (inductance) or C (capacitance) values to be controlled [1]. This establishes the transmission line of resonators. Typical periodic structures with reactive elements need specialized structures such as photonic bandgap (PBG), electromagnetic bandgap (EBG), defected ground structure (DGS), split ring resonator (SRR), etc. [2–11]. The PBG or EBG structures in a microwave or millimeter-wave regime have been implemented by etching the periodic patterns in the ground plane [2, 3]. However, this has some drawbacks such as the difficulties of the modeling, the large size, and the disturbance of the shield current distribution in the ground plane. Thus, a

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number of researches on compact DGS or SRR have been done for miniaturization [4, 5]. Also, researches have been conducted on the microstrip filter employing periodic structures with etched pattern on a signal line [6–11]. Likewise, the frequency selective surface (FSS) is one of the periodic structures. The FSS can transmit electromagnetic wave of the desired frequency band or reflect any undesired frequency band, and is mostly designed as a spatial filter [12].

In this letter, we use the one-dimensional (1D) periodic structure composed of the FSS unit cell (FU) on the microstrip line for the BSF operation. The proposed BSF consists of uniplanar configuration, and the twisted cross-loop slots are used in the FU [13]. By means of the proposed FU geometry, the L and C values are customized. This filter has following features. The geometrical structure of the proposed BSF is simpler than other periodic structures, and is embedded in the signal line comfortably. In addition, the return loss is very low, and the frequency response is varied by adjusting the dimensions of the FU. The bandwidth is altered by using cascaded FUs, and wide band operation is available. Also, the design freedom is enhanced by using a number of existing FSS structures.

2. CONFIGURATION OF FSS UNIT CELL AND SIMULATION RESULT

Figure 1 shows the basic structure of the FU and the simulated spectra of reflected (S_{11}) and transmitted microwaves (S_{21}). The structure of the FU is a modified cross-loop slot [13].

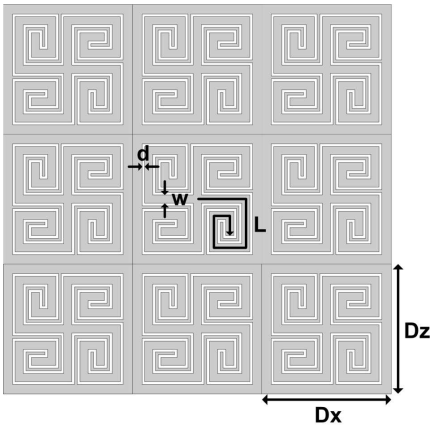

Figure 1. Schematic of the FSS unit cell (FU).

First, the four arms of the proposed FU are twisted, for the purpose of giving it a smaller size. The FU is embedded in the microstrip line and the operating frequency of the FU is performed at a lower frequency band. Second, the commercial low loss microwave dielectric substrate (TLY-5: $\varepsilon_r = 2.2$, $\tan\delta = 0.0009$) is used to implement the microstrip filter, with a substrate thickness of 1.57 mm. The FSS unit cells (FUs) have been arranged in a square array with inter-element $Dx = 4.8$ mm, and $Dz = 4.8$ mm. The parameters of the twisted cross-loop slot element are $L = 7.35$ mm, $w = 0.3$ mm, and $d = 0.1$ mm.

The effect of cross-loop slot element is adapted by adjusting the size of the parameters (cross length $= L$, cross width $= w$, slot width $= d$). Most importantly, the operating frequency is shifted downward, increasing the cross length ($L =$ about $\lambda/8$), since the path of the radio frequency (RF) current increases relatively. The twisted cross-loop slots perform as the band-pass filter (BPF) at a normal angle of incidence. The simulated attenuation is 27.5 dB at 5.09 GHz as shown in Figure 2. The simulation is performed using a Floquet mode in the High Frequency Structure Simulator (HFSS).

3. CONFIGURATION OF BAND STOP FILTER AND SIMULATION RESULTS

The microstrip line loaded with the modified structure of twisted cross-loop slots is depicted in Figure 3. This shows the 3D view of the

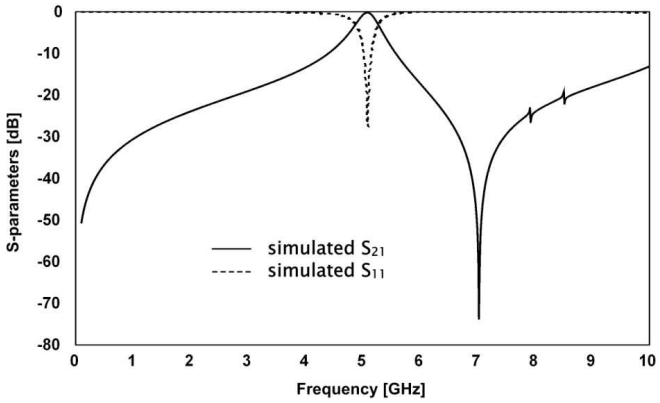

Figure 2. The simulated spectra of reflected (S_{11}) of the FU is plotted along the dashed line and the transmitted microwaves (S_{21}) of the FU is plotted along the solid line.

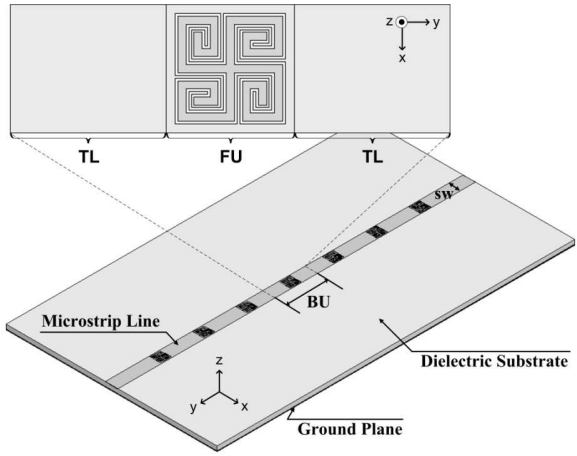

Figure 3. Geometry of the BSF loading the FUs.

Table 1. Full-wave simulation results of BSF with a FSS unit cell from one to seven.

	First resonant frequency [GHz]	First lower 3 dB-cutoff frequency [GHz]	First band-width [GHz]	First quality factor
FSS1	6.64	6.13	0.83	8
FSS3	6.63	4.95	2.33	2.85
FSS5	6.58	4.9	2.49	2.64
FSS7	6.58	4.97	2.44	2.7
	First return loss [dB]	Second resonant frequency [GHz]	Second lower 3 dB-cutoff frequency [GHz]	-
FSS1	−1.3	9.51	9.46	-
FSS3	−0.8	9.51	9.43	-
FSS5	−0.7	9.52	9.4	-
FSS7	−0.7	9.48	9.38	-

proposed filter. The dimension of substrate is $135.7 \times 80\,\text{mm}^2$. The width (SW) of the signal line for matching $50\,\Omega$ is 4.8 mm. Since the FU is embedded in the signal line, the actual size of the filter is very small and does not require extra component with volume. The BSF unit cell (BU) is composed of the FU between the transmission lines (TL). The FUs are separated by TLs of equal lengths. The physical length

of a FU is 4.8 mm and the length of the front and the rear TL are the same, 5.8 mm. The length of the BU is 16.4 mm ($\lambda g/2$). These values are obtained according to the Bragg's law ($d = n\lambda/2\sin\theta$) [14]. On this account, the BSF with the constant spacing at a particular guided wavelength is able to produce intense peaks of reflected propagation. We carried out the full-wave simulations of BSF using the two-dimensional commercial software Ansoft Designer. The simulated results are presented in Table 1. The first attenuation pole frequency shows a band-stop behavior close to 6.6 GHz in the simulated result with one BU or with cascaded BUs. Also, the bandwidth becomes broad by using cascaded BUs.

4. EQUIVALENT CIRCUIT AND DISPERSION DIAGRAM

Figure 4 shows the equivalent circuit of the proposed BU. To clarify the band-stop characteristic of the BU, we carried out a circuit simulation using extracted parameters. Although a complete equivalent circuit of the BU would be complicated, we extract it here for simplicity. It consists of a dominant parallel L and C (L_{f1}, C_{f1}) and an extra series L and C (L_{f2}, C_{f2}) [1]. In addition, the parameters of the equivalent circuit can be obtained from the simulation result, which is the de-embedded result of BU. The C_{f1} is attained as

$$C_{f1} = \frac{\omega_{c1}}{2Z_o\left(\omega_{o1}^2 - \omega_{c1}^2\right)}, \tag{1}$$

where ω_{o1}, ω_{c1}, Z_o are the first attenuation pole frequency, the first lower cutoff frequency, and the characteristic impedance, respectively.

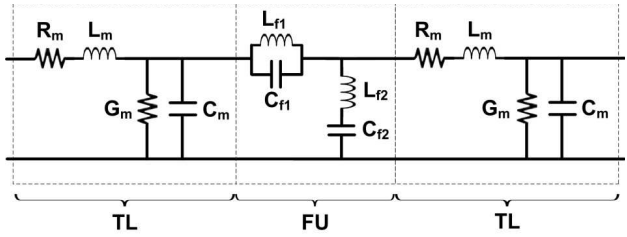

Figure 4. The equivalent circuit of the proposed BU. The extracted parameters are $L_{f1} = 0.385$ nH, $C_{f1} = 1.498$ pF, $L_{f2} = 39.684$ nH, and $C_{f2} = 0.007$ pF.

The L_{f1} can be determined by

$$L_{f1} = \frac{1}{\omega_{o1}^2 C_{f1}} = \frac{2Z_o\left(\omega_{o1}^2 - \omega_{c1}^2\right)}{\omega_{o1}^2 \omega_{c1}}. \tag{2}$$

The extracted L_{f1} and C_{f1} are 0.385 nH and 1.498 pF, respectively. Also, the C_{f2} is obtained as

$$C_{f2} = \frac{2\left(\omega_{o2}^2 - \omega_{c2}^2\right)}{Z_o \omega_{o2}^2 \omega_{c2}}, \tag{3}$$

where ω_{o2}, and ω_{c2} are the second attenuation pole frequency, and the second lower cutoff frequency, respectively. The L_{f2} can be acquired by

$$L_{f2} = \frac{1}{\omega_{o2}^2 C_{f2}} = \frac{Z_o \omega_{c2}}{2\left(\omega_{o2}^2 - \omega_{c2}^2\right)}. \tag{4}$$

The extracted L_{f2} and C_{f2} are 39.684 nH and 0.007 pF, respectively. The result of the extracted parameters is confirmed using the circuit simulation on the Agilent ADS software. The agreement between full-wave simulations of BSF and circuit simulations of the equivalent circuit is good.

Figure 5 shows the dispersion diagram of the simulated and measured BU. This indicates the band reject characteristic of the propagation along the line. The phase constant β has been calculated

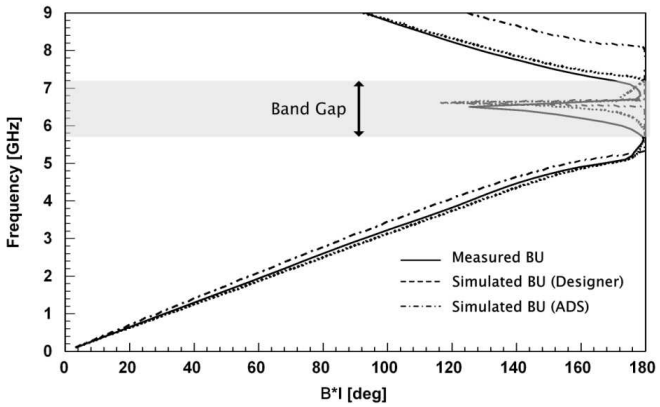

Figure 5. The dispersion diagram of the simulated and measured BU. The band gap shows the band-stop of the corresponding BU predicted with dispersion diagram.

from Equation (5) as explained in [15],

$$\beta l = \cos^{-1}\left(\frac{1 - S_{11}S_{22} + S_{12}S_{21}}{2S_{21}}\right) \tag{5}$$

The dispersion diagram is determined from scattering parameters. It demonstrates a more reflected propagation at band-stop range, 5.7–7.2 GHz. Hence, we shall expect the band-stop behavior in the transmission magnitude with the attenuation pole frequency of around 6.6 GHz.

5. MEASURED RESULTS AND DISCUSSION

The fabrication of the proposed filters simply requires a standard lithography technique. The FSS structure is cascaded with one or a few

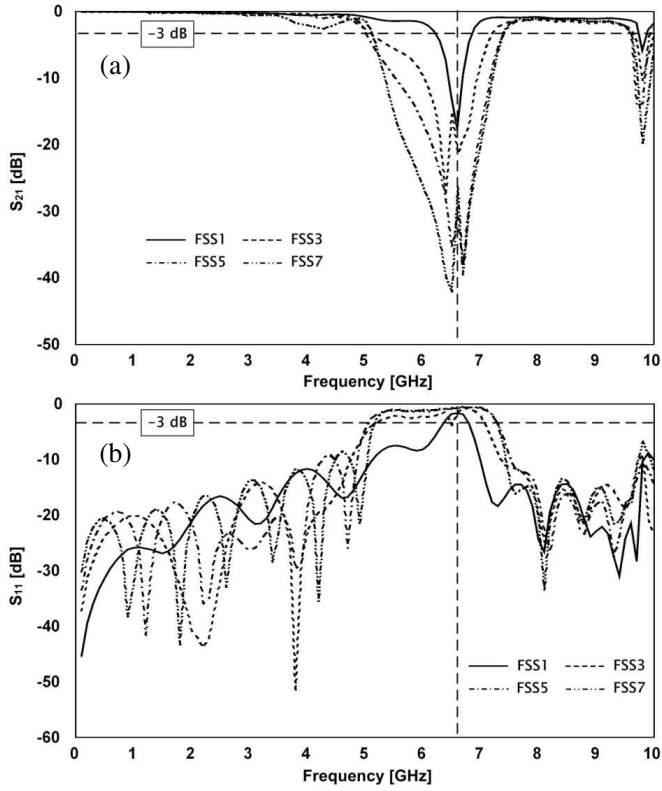

Figure 6. Measured results of BSF with a BU of one to seven. (a) Transmission spectra (S_{21}) and (b) reflection spectra (S_{11}).

BUs (1, 3, 5, or 7). Figure 6(a) indicates the measured s-parameter results of the proposed filter. The measured first attenuation pole frequency with one BU shows the band-stop behavior close to 6.6 GHz. The band-stop range of 3-dB cutoff frequency is from 6.2 GHz to 6.9 GHz. As the BU is completely embedded in the microstrip line, the return loss is very low, as shown in Figure 6(b). These measured results agree very well with the simulated results. Also, it is apparent that when the number of BUs is increased, the rejection slopes of the cutoff characteristics are very steep. Since it is considered that the number of BUs in the transmission line is proportional to the filter order of the BSF, the steepness of the proposed BSF increases and the 3-dB bandwidth enlarges correspondingly.

6. CONCLUSION

In conclusion, we have reported a uniplanar BSF design exploiting the modified FSS cell. Since the FSS cell can be modeled using distributed inductance and capacitance in the microwave frequency area showing the band-stop or band-pass characteristic, the wanted BSF can be synthesized by periodically allocating the FSS unit cells on microwave transmission line. For the design purpose, the FSS cell is analyzed by an equivalent circuit model and a dispersion diagram. Also, excellent BSF performances are verified by simulation and measurement results. In addition, the FSS unit cells are comfortably embedded in the microstrip line with compact size. The return loss, skirt property, and bandwidth are improved by increasing the number of cascaded BUs. It is expected that the proposed BSF using FSS cells is attractive in various microwave circuit applications to suppress parasitic and harmonic modes of frequencies. This technology pioneers the uniplanar filter design with FSS, and also the design freedom is available by employing numerous existing FSS structures.

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