Novel U-Slot and V-Slot DGSs for Bandstop Filter With Improved Q Factor

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***Abstract*—Novel slot-shaped defected ground structures (DGSs) on the microstrip line are presented to provide a band-rejection property with an improved Q factor. Two different geometries (U-slot and V-slot) are investigated. U-slot and V-slot DGSs have simple shapes compared to the conventional DGSs, however, they provide more steep rejection characteristics. The Q factor of the band-rejection property for the U-slot DGS increases when the distance between two slots in the U-shape decreases. Similarly, the V-slot DGS provides a higher Q characteristic when the slot angle is reduced. Two bandstop filters are designed and fabricated employing three cascaded U-slot DGSs and V-slot DGSs, respectively. Experimental result shows that the high-Q band-rejection filter with three U-slot DGSs provides Q of 38.6. A fabricated filter with three cascaded V-slot DGSs also rejects the signals at the frequencies from 3.5 to 4.3 GHz with more than 20-dB suppression.**

***Index Terms*—Q factor, U-slot defected group structure (DGS), V-slot DGS.**

I. INTRODUCTION

RECENTLY, there has been an increasing interest in using electronic bandgap (EBG) and defected ground structure (DGS) in microwave and millimeter-wave applications. The EBG has a periodic structure and it provides band-rejection property due to the bandgap effect [1], [2]. The DGS in the microstrip line utilizes an artificial defect on the ground and it provides a band-rejection characteristic from the resonance property. The DGS structure is advantageous in the design of microwave and millimeter-wave circuits since it can be modeled by simple resonant circuits and the parameter extraction is simple. The applications of the DGS are developed in divider, filter, and amplifier circuits [3]–[15]. The defect of the conventional DGS is with the dumbbell or spiral shape.

The band-rejection filters are developed by using DGS for the suppression of unwanted signals. The asymmetric defected ground structure (ADGS) is employed on the quarter-wave branches of a Wilkinson power divider to suppress second and third harmonics simultaneously [13], [14]. To suppress an unwanted signal, which is closely located from the desired signal in the spectrum, it is necessary to use a high-Q filter. The characteristics of the conventional DGSs with a dumbbell- and spiral-shaped defect are not satisfactory in the applications of narrowband rejection. The spiral DGS can provide more steep rejection property than the dumbbell-shaped DGS. However, the Q factor of the spiral DGS is usually smaller than 10.

In this paper, we propose novel DGS units, which have a U- and V-shaped slot on the ground plane to provide improved Q factors. The transfer characteristics of the two slot-shaped DGSs are calculated with the change in the parameters of each defect structure. The proposed U- and V-slot DGS can provide a higher Q factor compared to the conventional DGSs. The proposed DGSs also show flat and low-loss properties in the passband characteristic.

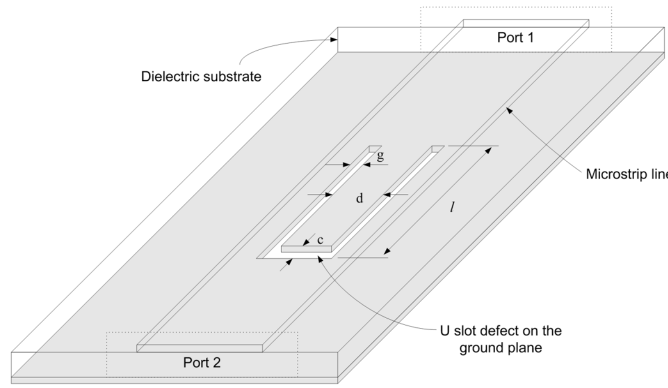

Fig. 1. Microstrip line with U-slot DGS on the ground plane.

II. HIGH-Q U-SLOT DGS AND CASCADED FILTER

The configuration of the proposed U-slot DGS on the ground plane of the microstrip line is shown in Fig. 1. On the ground plane, there are two slots of width g along with the transmission line and those slots are connected at one end with a slot of the width c. The lengths of two slots are the same and denoted by l. The distance between two slots is d. For the dimensions $l = 9.0$ mm, $c = g = 0.2$ mm, and $d = 1.0$ mm, the transfer characteristics of the U-slot DGS are calculated. The characteristic impedance of the microstrip line is assumed to be 50 Ω and the simulation is performed by using IE3D. The substrate with the thickness of 1.27 mm and a dielectric constant of 10.2 was used for all simulation. In Fig. 2, S_{11} and S_{21} are plotted as functions of signal frequency. The designed U-slot DGS provides the band-rejection property of 27 dB at 3.36 GHz (3-dB bandwidth of 0.203 GHz). The wavelength at the resonance frequency in the transmission line is 33.64 mm. It can also be seen that the Q factor of the proposed U-slot DGS is 16.5 and it is higher than

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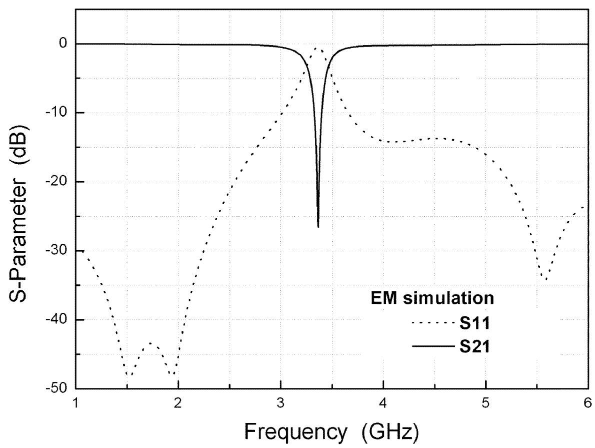


Fig. 2. Transfer characteristics of U-slot DGS ($l = 9.0$ mm, $c = 0.2$ mm, $g = 0.2$ mm, $d = 1.0$ mm, ε_r of substrate $= 10.2$, thickness of substrate $= 1.27$ mm).

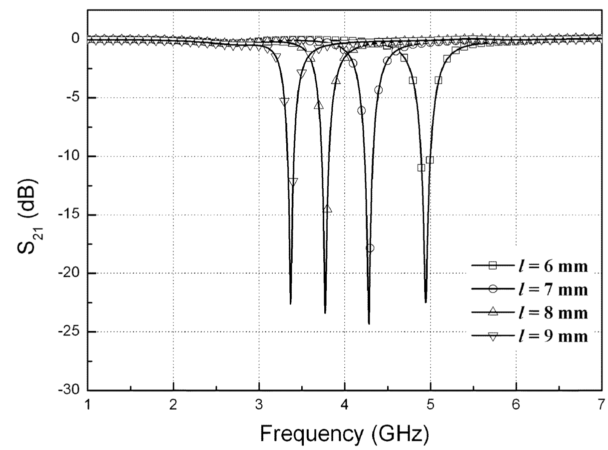


Fig. 4. Transfer characteristics for changes in slot length (l) ($c = 0.2$ mm, $g = 0.2$ mm, $d = 1.0$ mm).

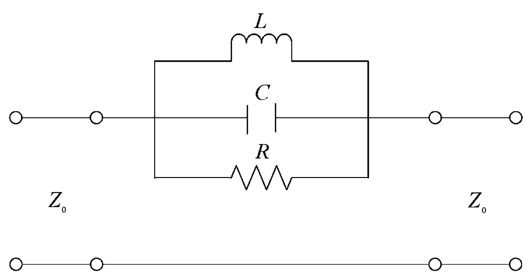


Fig. 3. Equivalent circuit of the proposed U-slot DGS.

those of the dumbbell-shaped and spiral DGS, which are usually lower than 10.

The frequency characteristic of the DGS can be modeled by a parallel RLC resonance circuit in the transmission line to block the signal transfer at the resonance frequency. The equivalent circuit of the U-slot DGS is shown in Fig. 3, where the circuit parameters are $L = 0.289$ nH, $C = 7.762$ pF, and $R = 1.738$ kΩ for the structure in Fig. 1. The circuit parameters of the equivalent circuit are extracted from the simulated scattering parameters as [3]

$$C = \frac{\omega_c}{2Z_0\left(\omega_0^2 - \omega_c^2\right)} \tag{1}$$

$$L = \frac{1}{4\pi^2 f_0^2 C} \tag{2}$$

$$R = \frac{2Z_0}{\sqrt{\frac{1}{|S_{11}(\omega_0)|^2} - \left(2Z_0\left(\omega_0 C - \frac{1}{\omega_0 L}\right)\right)^2 - 1}}. \tag{3}$$

Here, ω_0 is the angular resonance frequency, ω_c is the 3-dB cutoff angular frequency, and Z_0 is the characteristic impedance of the microstrip line.

The characteristics of the U-slot DGS such as the resonance frequency, rejection bandwidth, and Q factor are dependent on the structural parameters of the defect. The dimensions of slot length, slot width, and distance between two slots are the parameters changing those transfer characteristics of the DGS. In Fig. 4, the simulated transfer characteristics for the U-slot DGS are plotted as functions of slot length (l). The dimensions of the U-slot DGS are $d = 1.0$ mm and $c = g = 0.2$ mm. As the slot length increases, the rejection bandwidth and the resonance frequency decreases. As the slot length increases, both the equivalent capacitance and equivalent inductance increase. In the parallel resonance circuit, the Q factor is proportional to the susceptance slope parameter $\sqrt{C/L}$. From the calculated data in Table I, it can be seen that both the equivalent capacitance and equivalent inductance extracted by using (1) and (2), respectively, increase with the increase of slot length. The change in the calculated Q factor is observed to be very small as the slot length varies.

The simulated transfer characteristics for various slot width (g) are shown in Fig. 5. The dimensions of the U-slot DGS are $l = 9.0$ mm, $d = 1.0$ mm, and $c = 0.2$ mm. As the slot width grows, the equivalent capacitance decreases and the equivalent inductance increases; the resonance frequency slowly decreases due to the inductance increase. In Table II, it is confirmed that the calculated Q factor increases as the slot width decreases. When the slot width decreases, the increase in the capacitance causes the increase of Q factor. Fig. 6 shows the simulated transfer characteristics as functions of distance between two slots (d), and the extracted equivalent-circuit parameters and calculated Q factors are given in Table III. The key feature is the rapid increase in the Q factor with the decrease of the distance between two slots. From Table III, one may clearly observe that the decrease in the distance between two slots causes rapid increase in the effective capacitance.

To compare the transfer characteristics of the U-slot DGS with that of the conventional DGS, the spiral-shaped DGS and U-slot DGS are designed to provide the same resonance frequency. Fig. 7 illustrates the geometry of the spiral-shaped and U-slot DGS with the resonance frequency of 2.92 GHz. The slot widths in two DGS configurations are selected as narrow as possible to provide high-Q factors. For both structures, the slot widths are 0.2 mm and the distance between two slots of

TABLE I
CALCULATED Q FACTORS AND EQUIVALENT-CIRCUIT PARAMETERS FOR CHANGES IN SLOT LENGTH (L) ($c = 0.2$ mm, $g = 0.2$ mm, $d = 1.0$ mm)

l (mm)	Resonance Frequency (GHz)	Cutoff Frequency (GHz)	3dB Bandwidth (GHz)	Q-factor	Capacitance (pF)	Inductance (nH)
6	4.938	4.775	0.326	15.147	4.782	0.217
7	4.277	4.135	0.284	15.059	5.512	0.251
8	3.770	3.650	0.240	15.708	6.528	0.273
9	3.365	3.255	0.220	15.295	7.118	0.315

TABLE II
CALCULATED Q FACTORS AND EQUIVALENT-CIRCUIT PARAMETERS FOR CHANGES IN SLOT WIDTH (G) ($c = 0.2$ mm, $d = 1.0$ mm, $l = 9.0$ mm)

g (mm)	Resonance Frequency (GHz)	Cutoff Frequency (GHz)	3dB Bandwidth (GHz)	Q-factor	Capacitance (pF)	Inductance (nH)
0.4	3.306	3.150	0.321	10.299	4.980	0.466
0.8	3.222	2.955	0.535	6.022	2.853	0.856
1.2	3.143	2.765	0.756	4.157	1.972	1.302
1.6	3.086	2.590	0.992	3.111	1.465	1.705

TABLE III
CALCULATED Q FACTORS AND EQUIVALENT-CIRCUIT PARAMETERS FOR VARIOUS DISTANCES BETWEEN TWO SLOTS (d)
($c = 0.2$ mm, $g = 0.2$ mm, $l = 9.0$ mm)

d (mm)	Resonance Frequency (GHz)	Cutoff Frequency (GHz)	3dB Bandwidth(GHz)	Q-factor	Capacitance (pF)	Inductance (nH)
0.4	3.451	3.409	0.084	41.080	18.940	0.113
0.8	3.393	3.306	0.174	19.500	9.032	0.244
1.2	3.340	3.200	0.280	11.929	5.565	0.408
1.6	3.289	3.089	0.400	8.223	3.856	0.608

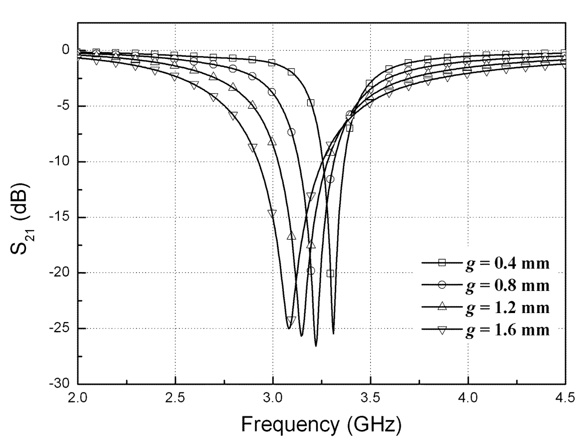


Fig. 5. Transfer characteristics for various slot widths (g) ($l = 9.0$ mm, $c = 0.2$ mm, $d = 1.0$ mm).

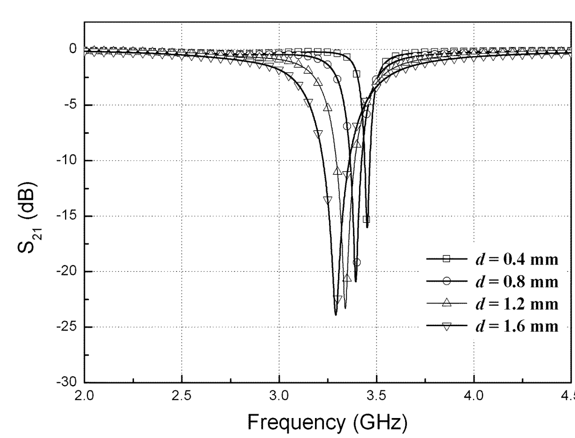


Fig. 6. Transfer characteristics for various distances between two slots (d) ($l = 9.0$ mm, $c = 0.2$ mm, $g = 0.2$ mm).

the U-slot DGS is 0.4 mm. Fig. 8 compares two transfer characteristics; the U-slot DGS shows a higher Q characteristic compared to the spiral DGS. The calculated Q factor of the spiral-shaped DGS is 7.478 (3-dB band width of 0.39 GHz), while the proposed U-slot DGS provides a high-Q factor of 36.05 (3-dB bandwidth is 0.081 GHz).

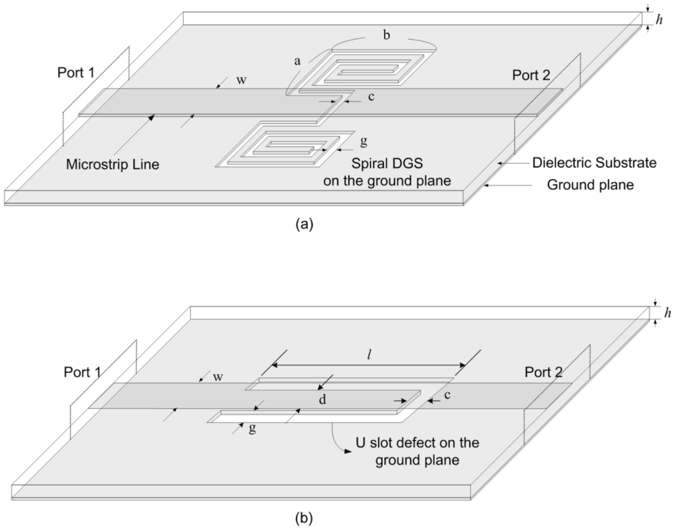


Fig. 7. Geometry of: (a) the spiral-shaped DGS ($a = b = 3.0$ mm, $c = 0.2$ mm, $g = 0.2$ mm, $w = 1.2$ mm, ε_r of substrate $= 10.2, h = 1.27$ mm) and (b) U-slot DGS ($l = 10.7$ mm, $c = 0.2$ mm, $g = 0.2$ mm, $d = 0.4$ mm, ε_r of substrate $= 10.2, h = 1.27$ mm) to provide resonance frequency at 2.92 GHz.

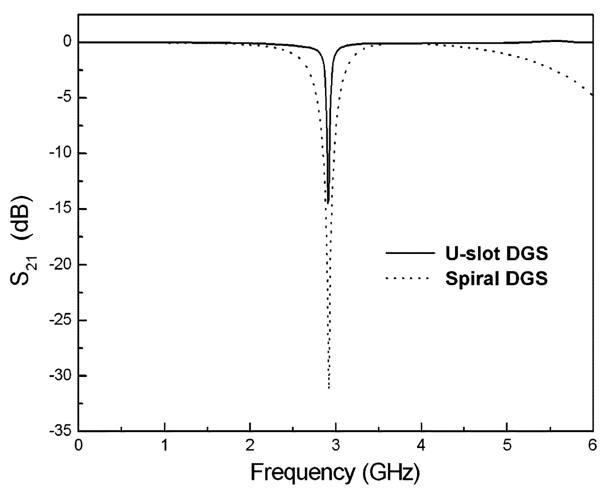


Fig. 8. Comparison results between the transfer characteristic of the spiral-shape and U-slot DGS in Fig. 7.

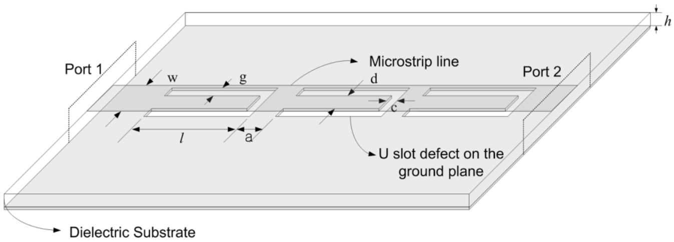


Fig. 9. Three-dimensional view of the three cascaded U-slot DGSs ($l = 9.0$ mm, $c = d = g = 0.2$ mm, $a = 0.4$ mm, $w = 1.2$ mm, ε_r of substrate $= 10.2, h = 1.27$ mm).

For a design of a filter satisfying the required bandwidth, as well as the high-Q factor, multiple DGS units are cascaded

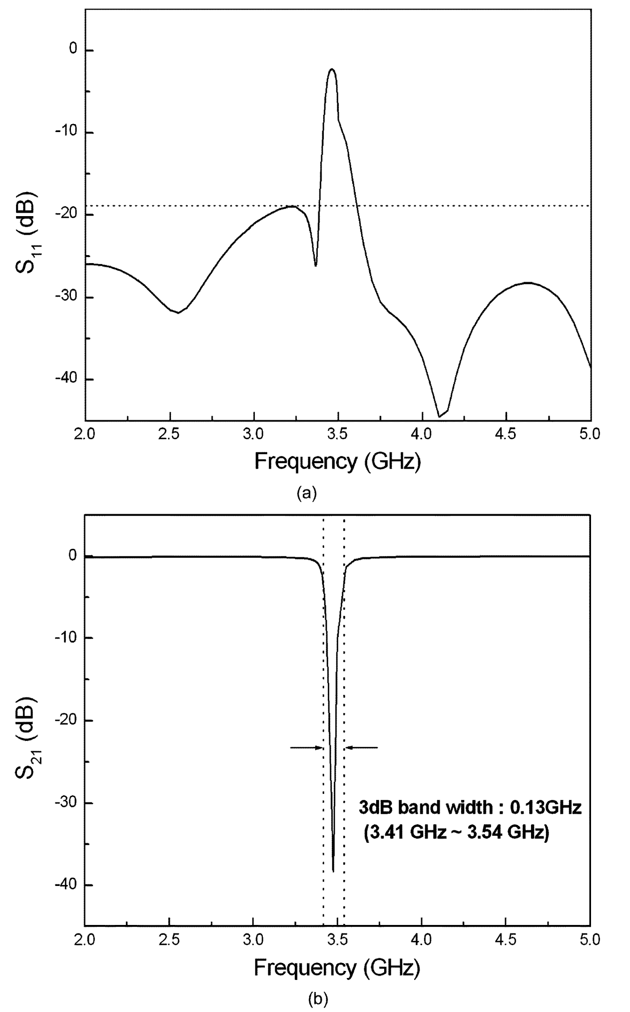


Fig. 10. Simulated S-parameters of the three cascaded U-slot DGSs. (a) S_{11}. (b) S_{21}.

along with the transmission line. Fig. 9 illustrates the configuration of the high-Q bandstop filter with three cascaded U-slot DGSs. The dimensions for the U-slot are $l = 9.0$ mm, $c = g = d = 0.2$ mm for each DGS and the characteristic impedance of the line is 50 Ω. The distance between the slots are fixed as $a = 0.4$ mm. In Fig. 10(a), the simulated S_{11} is shown and the return loss is under -18 dB over the passband. As shown in Fig. 10(b), the proposed band-rejection filter with three cascaded U-slot DGSs provides a steep rejection characteristic and a high-Q factor of 26.7.

Fig. 11 shows the top and bottom views of the fabricated high-Q bandstop filter with three cascaded U-slot DGS units. The substrate is an RO3010 circuit board with a thickness of 1.27 mm and a dielectric constant of 10.2. In the measurement, the substrate is located more than 5 cm above the metal plate and the effect of the metal wall below the defected ground is negligible [14]. In Fig. 12(a), the measured S_{11} is shown and the return loss is under -15 dB over the passband. The deviations of the measurements from the computations occurring in the passband are expected mainly due to the reflections from the connectors and the finite substrate. The measured S_{21} is plotted in Fig. 12(b) as a function of frequency. The suppression for the resonance frequency (3.475 GHz) is approximately 36 dB. The

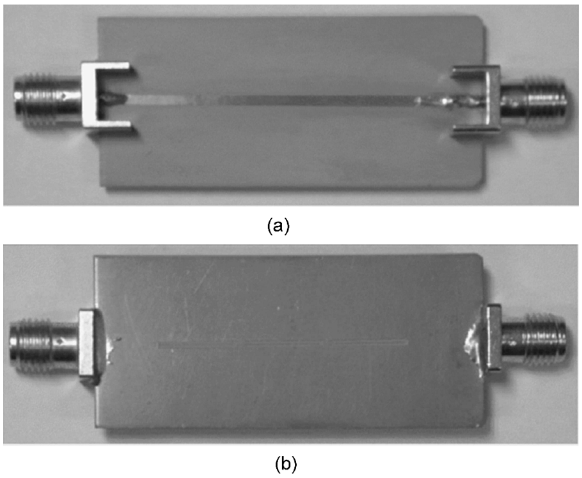


Fig. 11. Fabricated high-Q bandstop filter with three cascaded U-slot DGSs. (a) Top view. (b) Bottom view.

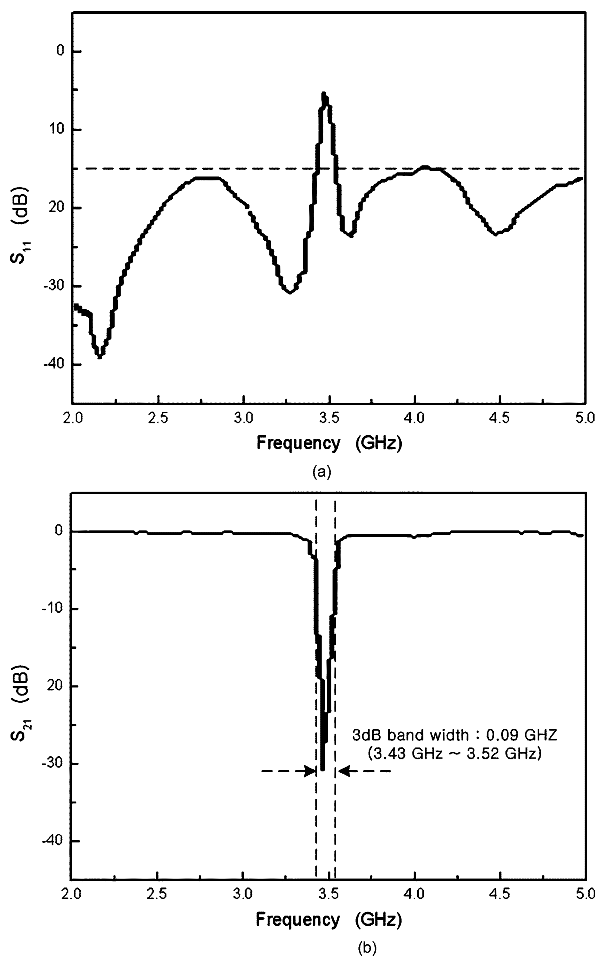


Fig. 12. Measured S-parameters of the fabricated high-Q bandstop filter with three cascaded U-slot DGSs. (a) S_{11}. (b) S_{21}.

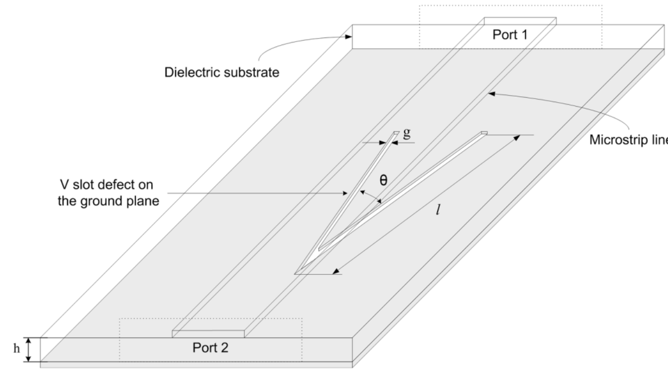


Fig. 13. Microstrip line with V-slot DGS on the ground plane.

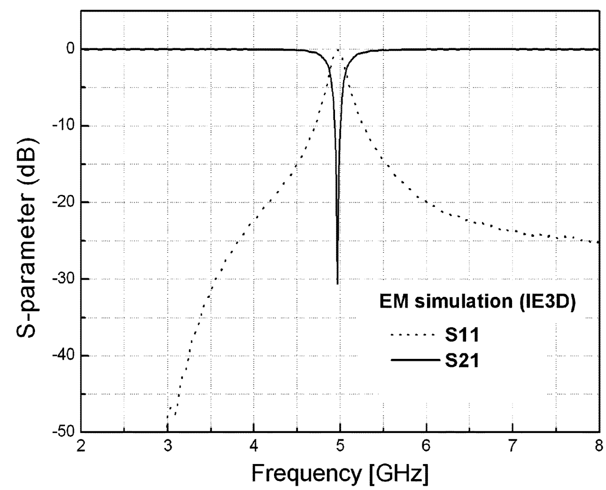


Fig. 14. Characteristics of V-slot DGS ($l = 7.0$ mm, $g = 0.2$ mm, $\theta = 30°, \varepsilon_r$ of substrate $= 10.2, h = 1.27$ mm).

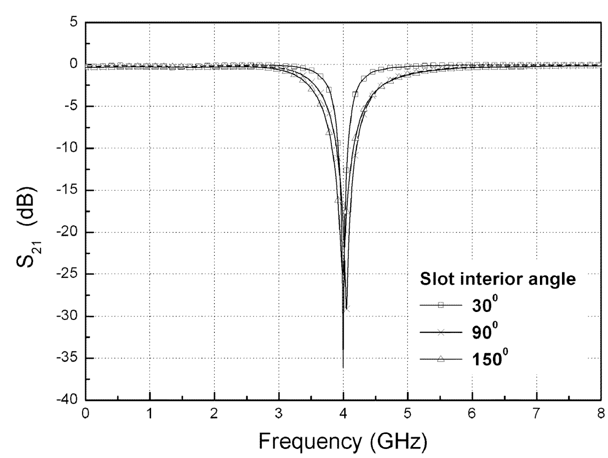


Fig. 15. Simulated transfer characteristics for various slot interior angles (θ) ($l = 7.0$ mm, $g = 0.2$ mm, ε_r of substrate $= 10.2, h = 1.27$ mm).

Q factor of the fabricated three cascaded U-slot DGS filter is 38.6. The measured transfer characteristic of the fabricated filter with the proposed structure shows steep band-rejection property and the filter provides a high-Q factor.

III. V-Slot DGS

For the application of the band-rejection filter in the limited area, it is necessary to make the whole size of the filter very small. The cascaded U-slot filter provides a high-Q characteristic and the whole length of the filter increases as the number

TABLE IV
CALCULATED Q FACTORS AND EQUIVALENT-CIRCUIT PARAMETERS FOR VARIOUS SLOT INTERIOR ANGLES (θ) ($l = 7.0$ mm, $g = 0.2$ mm)

θ (°)	Resonance Frequency (GHz)	Cutoff Frequency (GHz)	3dB Bandwidth (GHz)	Q-factor	Capacitance (pF)	Inductance (nH)
30	4.02	3.81	0.43	9.35	3.690	0.425
60	4.03	3.70	0.66	6.11	2.310	0.676
90	4.04	3.58	0.92	4.40	1.626	0.955
120	4.01	3.52	0.99	4.05	1.520	1.038
150	3.98	3.48	1.01	3.94	1.486	1.077
180	4.01	3.41	1.20	3.34	1.220	1.293

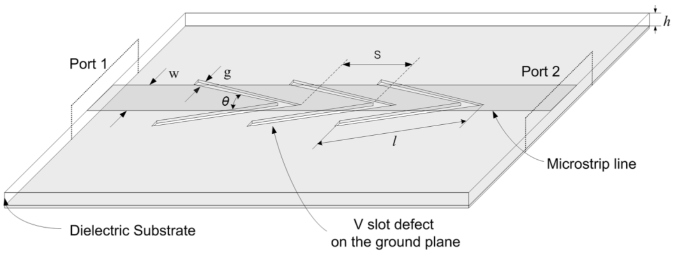


Fig. 16. Three-dimensional view of the three cascaded V-slot DGSs ($w = 1.2$ mm, $\theta = 30°, l = 9.0$ mm, $g = 0.2$ mm, $s = 6.0$ mm ε_r of substrate $= 10.2, h = 1.27$ mm).

of cascaded DGS units increases. To develop a cascaded DGS filter with the reduced whole length, as well as the high-Q factor, we propose a V-slot defect on the ground plane. Fig. 13 illustrates the configuration of V-slot DGS on the ground plane of microstrip line. For the dimensions $l = 7.0$ mm, $g = 0.2$ mm, and $\theta = 30°, S_{11}$ and S_{22} are plotted as functions of signal frequency. The designed V-slot DGS provides the band-rejection property of -30 dB at approximately 5 GHz, as shown in Fig. 14. It can also be seen that the Q factor of the proposed V-slot DGS is 27.6.

It is of interest to see how the characteristic of the V-slot DGS changes as the interior angle θ changes. From Fig. 15, it can be observed that the resonance frequency does not change due to the increase of the slot interior angle, while the bandwidth decreases. Table IV shows the equivalent-circuit parameters and calculated Q factors for various slot interior angles. The dimensions of the V-slot DGS are $l = 9.0$ mm and $g = 0.2$ mm. As the slot interior angle increases, the Q factor increases, while the resonance frequency does not changes. The changes in resonance frequency and the Q factor due to the slot width(g) and slot length (l) show similar behaviors as in the calculated results for the U-slot DGS in Section II.

The filters with a high-Q factor for the stopband can be designed by cascading the U-slot DGS, as well as the V-slot DGS. The bandwidth can also be controlled by adjusting the parameters of the DGS units and the distance between the units. The V-slot DGS is advantageous in cascading the units since the whole length along the transmission line is reduced by putting one V slot into another V slot, as shown in Fig. 16, where the

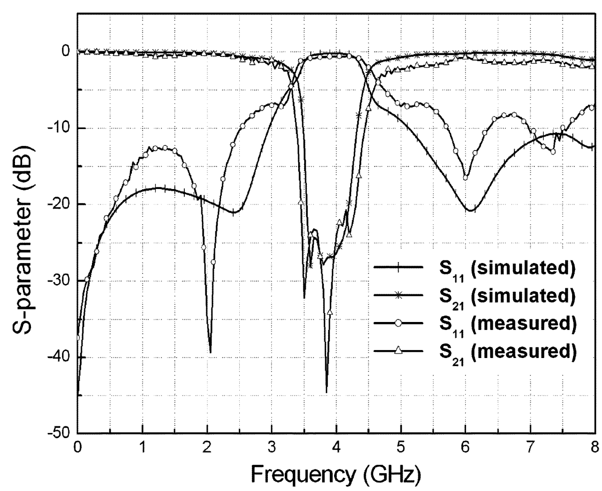
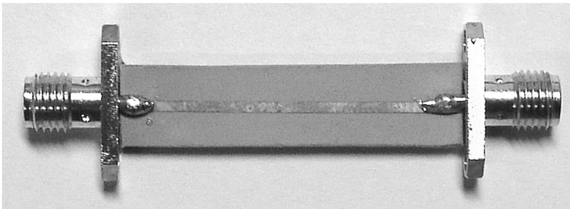


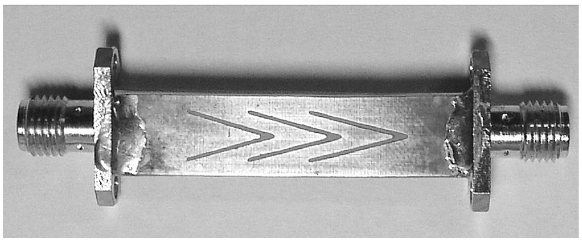
Fig. 17. Comparative results between simulation and measurement on the fabricated bandstop filter with three cascaded V-slot DGSs.

configuration of the bandstop filter with three cascaded V-slot DGSs are illustrated. When the neighboring V slots are sufficiently separated, the cascaded V-slot DGS filter has nearly the same bandwidth with the single V-slot DGS, but the stopband attenuation is higher. If the distance s between the V-slot DGS units is reduced, the cascaded V-slot DGS filter provides wider bandwidth, maintaining the sharp transition characteristic.

Fig. 17 shows the comparative results between simulation and measurement on the fabricated three cascaded V-slot DGSs. The dimensions for the V slot are $l = 9.0$ mm, $g = 0.2$ mm, and $\theta = 30°$ for each DGS, and s is fixed to be 6.0 mm. Measurements agree well with simulation results in the rejection band, as shown in Fig. 16. It is shown that the fabricated filter with three cascaded V-slot DGSs rejects the signals at the frequencies from 3.5 to 4.3 GHz with more than 20-dB suppression. The deviation in bandwidth of the measured result from the computational result is due to the inaccuracy of the slot width in fabrication. The wideband-rejection filter with a steep rejection characteristic is achieved by using V-slot DGSs. The transfer characteristic in the passband shows low loss and flatness as a function of the frequency. The whole length of the filter is 22 mm. Fig. 18 shows the top and bottom views of the fabricated three cascaded



(a)



(b)

Fig. 18. Fabricated bandstop filter with three cascaded V-slot DGSs. (a) Top view. (b) Bottom view.

V-slot DGSs. The substrate is an RO3010 circuit board with a thickness of 1.27 mm and a dielectric constant of 10.2. Experimental results show good agreements with electromagnetic (EM) simulations.

IV. Conclusion

Novel U-slot and V-slot DGSs with an improved Q factor of the band-rejection characteristic have been proposed in this paper. The transfer characteristics have been calculated with the change in the parameters of the U- and V-slot DGS, respectively. The band-rejection filter with cascaded U- or V-slot DGS can provide a high-Q factor. The V-slot DGS has a wide control range of rejection bandwidth and a steep rejection characteristic. The fabricated band-rejection filter with three cascaded U-slot DGSs provides a high Q factor for 38.6 in the stopband, and exhibits a flat and lossless passband. The fabricated filter with three cascaded V-slot DGSs also rejects the signals at the frequencies from 3.5 to 4.3 GHz with more than 20-dB suppression. The proposed structures may have wide applications in the design of microwave components and antenna arrays.

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