Journal of Southeast University (English Edition) Vol. 25, No. 4, pp. 431 – 434 Dec. 2009 ISSN 1003—7985

Novel S-slot DGS with high quality factor

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Abstract: In order to solve the problem that the quality factor (Q factor) of the conventional defected ground structure (DGS) is not high and cannot produce a sharp resonant band, a novel S-slot DGS is presented. Compared with the conventional DGS, the proposed S-slot DGS has a much higher Q factor, a quite simpler layout and a steeper band rejection. Its equivalent circuit model is extracted by analyzing the transfer characteristics, and design parameters are calculated according to the deducted equations. Characteristics of this type of DGS are investigated with variable dimension parameters and an experiential method for the design of the S-slot DGS is summarized. Finally, a sample of a compact S-slot DGS unit resonated at 4. 64 GHz is fabricated. Its Q factor is as high as 39. 66 and its size is only 5. 00 mm × 1. 40 mm, with a steep resonant band and a low insertion-loss passband. The measured results show a good agreement with simulation, which demonstrates the applicability of the S-slot DGS in practical engineering.

Key words: S-slot; defected ground structure (DGS); quality factor

Since the defected ground structure (DGS) was proposed in 1999[1], it has been highly concerned with the research of the electromagnetic and microwave fields. A microstrip line with DGS is realized by etching off a certain defected pattern from the ground plane. This structure creates a transmission line with band rejection and slow-wave characteristics[2]. It is applicable for frequency restraint and circuit miniaturization. In recent years, DGS has been applied to many designs of passive and active devices, such as filters[3], power dividers[4], amplifiers[5] and so on.

The originally proposed DGS was a dumbbell-shaped DGS[3]. Later some other types of DGS with different defected block patterns were proposed, including circle DGS[6], cross-shaped DGS[7], spiral DGS[5], U-slot DGS[8-9], V-slot DGS[9], concentric ring DGS[10], meander-slot DGS[11] and so on. However, their quality factor (Q factor) was usually not very high and their band rejection characteristics were also not sharp enough to produce good forbidden gaps. Additionally, some of them have complex configurations and take sizeable layouts, which are not suitable for miniaturization and integration. Here we simulate some slot DGSs with relatively high Q factors that appeared in recent publications and list their Q factors in Tab. 1. Among these, the U-slot DGS has the most simple configuration but it is too large, which is not suitable for miniaturization and integration.

Tab. 1 Q factors and sizes of some slot-pattern DGSs

Illustrations	Reference	Q factor	Size of defected pattern
Spiral DGS	Ref. [5]	15. 3	5. 00 mm × 12. 40 mm
U-slot DGS	Ref. [8]	16. 5	9. 00 mm × 1. 80 mm
Concentric ring DGS	Ref. [10]	13. 5	ϕ24. 00 mm (round)
Meander-slot DGS	Ref. [11]	22. 39	5. 00 mm × 2. 00 mm
S-slot DGS	This paper	39. 66	5. 00 mm × 1. 40 mm

1 S-Slot DGS and Its Circuit Model

The typical S-slot DGS is sketched in Fig. 1(a). Its defected pattern, which looks just like the letter "S", consists of a central slot, two side slots and two joint slots. The joint slots and side slots are centrally symmetric. The dimension parameters of the S-slot DGS include the slot width w, the slot length l and the distance d between the central slot and the side slot, which are marked in Fig. 1(b).

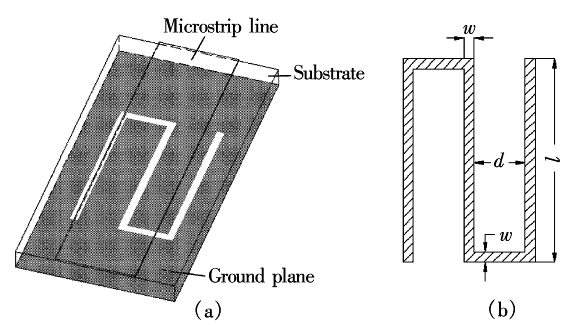

Fig. 1 The proposed S-slot DGS unit. (a) Sketch view; (b) Defected pattern dimensions

Scholars have proved that the parallel LC circuit can represent the equivalent circuit of the DGS unit. Practically, the proposed S-slot DGS can also be equivalent with a parallel LC resonator. It is necessary to extract the equivalent circuit parameters to apply the proposed DGS unit to a microwave circuit design. The one-pole low-pass filter with an attenuation pole is proved to be the representative equivalent circuit of the DGS[3]. In order to simultaneously explain the cutoff and attenuation pole characteristics of the proposed DGS unit, the equivalent circuit should exhibit performances of low-pass and bandstop filters at the same time. The simple circuit shown in Fig. 2(a) can explain the phenomenon for the proposed DGS unit, where the dotted box shows the DGS unit.

The circuit parameters for the derived equivalent LC circuit can be extracted from its frequency response. Suppose that the resonant frequency of the S-slot DGS is f_0 and the 3 dB cutoff frequency of the DGS is f_c. The series reactance

Received 2009-07-08.
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Foundation items: The National Natural Science Foundation of China (No. 60890071), the National High Technology Research and Development Program of China (863 Program) (No. 2009AA01Z132).
Citation: Zhu Yizhi, Zhang Xiaojuan, Fang Guangyou. Novel S-slot DGS with high quality factor[J]. Journal of Southeast University (English Edition), 2009, 25(4): 431 – 434.

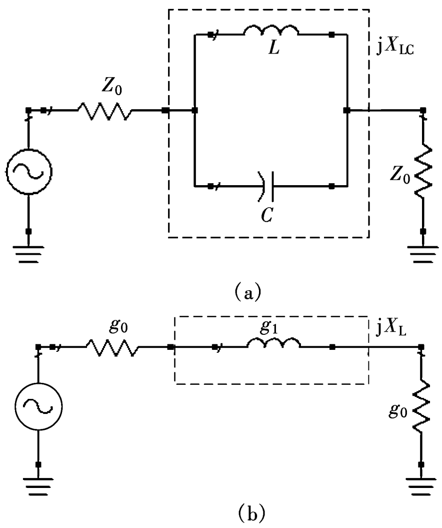

Fig. 2 Equivalent circuit of the proposed DGS unit. (a) Equivalent LC circuit; (b) Butterworth one-pole prototype low-pass filter circuit

value shown in Fig. 2(a) can be easily calculated by the prototype element value of the one-pole Butterworth low-pass filter shown in Fig. 2(b). The parallel capacitance value for the DGS unit can be extracted from the attenuation pole location, which is the parallel LC response frequency, and prototype low-pass filter characteristics. The deduction procedures are given below. The reactance value of the DGS unit can be expressed as

$$X_{\mathrm{LC}} = \left[2\pi f_0 C\left(\frac{f_0}{f} - \frac{f}{f_0}\right)\right]^{-1} \tag{1}$$

where f_0 corresponds to attenuation pole location. The series inductance of the Butterworth low-pass filter shown in Fig. 2 (b) is

$$X_{\mathrm{L}} = \omega' Z_0 g_1 \tag{2}$$

where ω' is the normalized angular frequency; Z_0 is the scaled impedance level of the in/out terminated ports and g_1 is determined by the prototype value of the Butterworth low-pass filter. The two equivalent circuits in Fig. 2 at the cutoff frequency should be equal, so

$$X_{\mathrm{LC}}\big|_{f=f_c} = X_{\mathrm{L}}\big|_{\omega'=1} \tag{3}$$

From Eqs. (1) to (3), the series capacitance and the series inductance of the equivalent LC circuit can be obtained as

$$C = \frac{f_c}{2\pi Z_0 g_1}\frac{1}{f_0^2 - f_c^2} \tag{4}$$

$$L = \frac{1}{4\pi^2 f_0^2 C} \tag{5}$$

In practical design, we can calculate the circuit parameters L and C according to the required resonant frequency and 3 dB bandwidth. In the next section, an example will be given to demonstrate that the derived equivalent circuit and parameters for this match with the practical circuit.

2 Fabricated S-Slot DGS Unit

The S-slot DGS unit provides a steep forbidden band at the designed frequency. A DGS unit example is given in this section. Suppose that this DGS is built on a microwave substrate whose relative permittivity $\varepsilon_r = 10.2$ and thickness is 1.27 mm. The microstrip line on the signal layer is a 50 Ω transmission line (Its width is 1.16 mm at the resonant frequency). Let the slot width $w = 0.2$ mm, the slot length $l = 5.0$ mm, and the distance d between side slots and the central slot is 0.4 mm. Thus the size of this defected "S" pattern is 5.0 mm × 1.4 mm. Afterwards, EM simulation is executed to this unit by the finite element method (FEM). The transmission and reflection characteristics of simulation are plotted in Fig. 3. According to EM simulation results, the resonant frequency is 4.640 GHz and the 3 dB cutoff bandwidth is 117 MHz. The suppression at resonant frequency is 16.68 dB. Q factor is calculated according to the ratio of the 3 dB cutoff bandwidth to resonant frequency. Thus, the Q factor of this illustrational S-slot DGS is 39.66. This indicates that the S-slot DGS theoretically provides a steep narrow forbidden gap.

According to Eqs. (4) and (5), replacing f_0 and f_c with the simulated value, we obtain that the equivalent circuit parameters $C = 13.517$ pF, $L = 87.043$ pH. We also plot the simulated curves for the equivalent LC circuit in Fig. 3. According to circuit simulation results, the resonant frequency is also 4.640 GHz and the 3 dB cutoff bandwidth is 114 MHz. The suppression at resonant frequency is 60.96 dB, which corresponds to the idealized circuit model. This indicates that the circuit model and the design parameters equation are applicable for practical design.

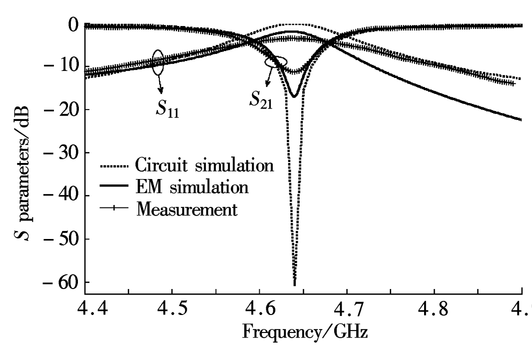

Fig. 3 Simulation and measured characteristics of illustrational S-slot DGS

The sample of this S-slot DGS unit is fabricated and its characteristics are tested to check the validity. Fig. 4 shows the photograph of the fabricated DGS unit. It is measured with a vector network analyzer. The measured S parameters are also plotted in Fig. 3 for the convenience of comparison. The measured resonant frequency is 4.6375 GHz and the measured 3 dB bandwidth is 124.98 MHz. Thus, the Q factor of this illustrational S-slot DGS is 37.11 according to

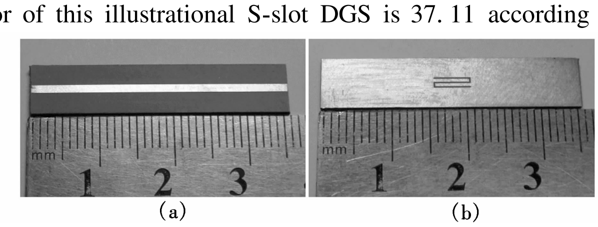

Fig. 4 Photograph of the fabricated S-slot DGS unit. (a) Top view; (b) Bottom view

measurement. The steepness of the stopband is similar to the simulated results. Additionally, the suppression at resonant frequency is 11.25 dB. The insertion loss of passband is less than 0.8 dB and the return loss of the passband is more than 12.05 dB, which also shows that the measured results of the passband are basically consistent with the simulation.

Additionally, the deviations of the measurements from the EM simulations are expected mainly due to the finite conductivity of copper foil and the finitude of ground plane. As to S_{11}, we can see that the measured S_{11} in the stopband is at least below -3.5 dB, but still deviates 1 to 2 dB from expected simulation. The degradation of S_{11} is possibly because of reflection from the measure connectors and the mismatch of the input/output. In the area of 4.7 to 4.9 GHz, S_{11} of EM simulation departs from S_{11} of measurement and circuit simulation. This is because the element lattices in the FEM are divided at the resonant frequency and thus they are not very precise for the frequency band that is higher than the resonant frequency. While as to the measured S_{21}, there is also 3 to 4 dB deviation from expected simulation. This can be affected by the inaccuracy of fabrication, which would weaken the resonance of the DGS unit. Considering all of these factors, the fabricated S-slot DGS unit is concluded to provide expected good passband and steep band rejection with high Q factor and compact layout.

Comparatively, some other typical DGS units with relatively good resonance are simulated, such as dumbbell-shaped DGSs[3], U-slot DGSs[8] and meander-slot DGSs[11]. They are all designed at the same resonant frequency and on the same substrate as the above-mentioned S-slot DGS. Some pivotal data of simulations are listed in Tab. 2, and the resonant frequency $f_0 = 4.640$ GHz. Tab. 2 indicates that Q factors of the three latter slot DGS units are higher than those of the dumbbell-shaped DGS unit and the S-slot DGS has the highest Q factor. From the view of complexity, the meander-slot DGS has the most complex configuration and the U-slot DGS has the simplest one. At the same time, the U-slot DGS takes the most sizeable length and the meander-slot DGS is the shortest among the three slot DGS units. Conclusively the proposed S-slot DGS has the highest Q factor, accompanied with moderate complexity and an undersized layout.

Tab. 2 Comparison of several typical DGS units

Typical DGS	3 dB bandwidth/MHz	Suppression at resonant frequency/dB	Q factor	Size of defected pattern/(mm × mm)	Complexity of defected pattern
Dumbbell-shaped DGS	2 601	28.09	1.79	10.06 × 4.45	Complex
U-slot DGS	162	17.29	28.76	6.68 × 1.00	Simple
Meander-slot DGS	150	17.11	31.06	4.40 × 1.40	Complex
S-slot DGS	117	16.68	39.66	5.0 × 1.40	Simple

3 Characteristics of S-Slot DGS

As shown in Fig. 1(b), the S-slot DGS configuration lies on three dimension parameters. They are slot width w, slot length l and distance d between central slot and side slot. In this section, how these parameters affect transmission characteristics and Q factors of the DGS is discussed. Illustratively, the three dimension parameters of the example mentioned in section 2 are tuned respectively to investigate the effect.

First, the slot length l is changed. When l varies from 4.5 to 6.0 mm discretely, the corresponding S_{21} parameter curves are plotted in Fig. 5. The calculated Q factor in each case is also labeled. The figure indicates that the resonant frequency decreases with the increase in l. This is because the equivalent series inductance increases with the increase in l and it leads to the shrinkage of a 3 dB bandwidth. However, the Q factor and suppression in the stop band are approximately stable in spite of the movement of l.

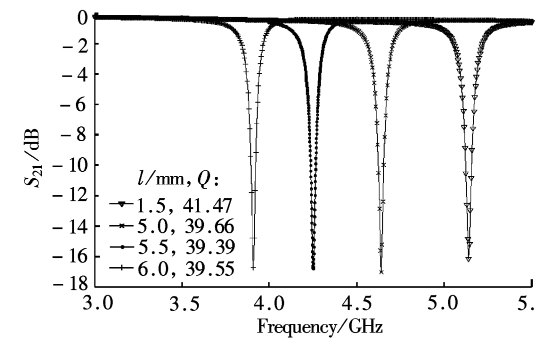

Fig. 5 Transfer characteristics with various slot lengths l

Secondly, the slot width w is shifted from 0.1 to 0.6 mm discretely. The corresponding S_{21} parameter curves and the calculated Q factors are marked in Fig. 6. This figure denotes that both the resonant frequency and suppression at this frequency increase with the increase of w. At the same time, the 3 dB bandwidth is widened very severely, which leads to the decline of the Q factor. This is because the equivalent shunt capacitance decreases when w increases. Especially, once w is greater than 1.0 mm, the Q factor may decline badly and may not satisfy the demand of steep narrow resonance.

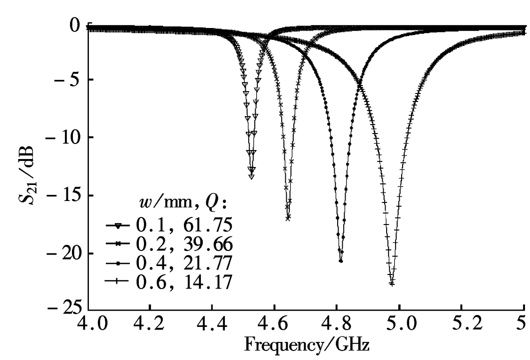

Fig. 6 Transfer characteristics with various slot widths w

Finally, the distance d between central slot and side slot is tuned. When d moves from 0.2 to 0.8 mm discretely, different S_{21} parameter curves are plotted in Fig. 7. The corresponding Q factors are also calculated. As d increases, the resonant frequency decreases and the suppression of the rejection band is strengthened. However, the 3 dB bandwidth is broadened simultaneously. This causes the Q factor to decrease rapidly. Additionally, the changing trend of the Q factor in Fig. 7 is similar to the trend in Fig. 6 but the change is milder.

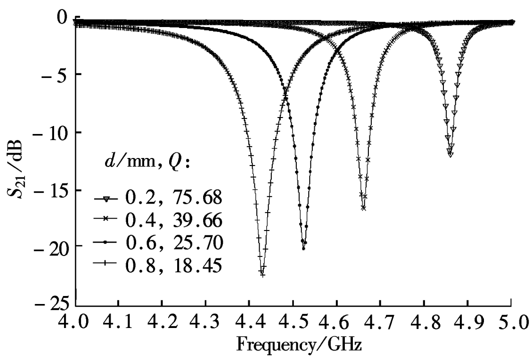

Fig. 7 Transfer characteristics with various slot distances d

Based on the above analyses, an experiential method for designing an S-slot DGS of a certain rejection band is obtained. Primarily, the narrow slot width w should be determined because it indicates that w impacts the Q factor severely and normally w should be less than 0.60 mm (see Fig. 6). Then an appropriate value is set for d to satisfy the demand of a 3 dB bandwidth. Finally, the DGS length l may be tuned to adjust the resonant frequency as l just moves the resonant point calmly without fierce effects on the band characteristics and the Q factor.

4 Conclusion

A novel S-slot DGS is presented with a high quality factor, simple configuration and compact layout. The equivalent LC circuit model is extracted and design parameters are deducted. Its theoretical feasibility is validated by the illustrated S-slot DGS unit. The measured results of the fabricated S-slot DGS unit illuminate the applicability in practical engineering. Finally, design steps for this DGS are proposed based on the relationship between structural dimensions and characteristics. Among exiting DGSs, this S-slot DGS is fairly competitive for its good resonance, simplification and compactification. It can be widely used in the design of passive and active components, such as antennas, mixers, amplifiers, multipliers and so on. Particularly, the S-slot DGS is quite suitable for the circumstances where both keen-edged filtration and integrated miniaturization are properly required. It shows imaginable potential in current flourishing RFIC and MMIC industries.

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新型高品质因数 S 形缝隙缺陷地结构

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摘要: 针对传统的缺陷地结构品质因数低、不足以产生尖锐的谐振特性问题, 提出了一种新颖的 S 形缝隙缺陷地结构. 与传统的缺陷地结构相比, 该结构具有更高的品质因数、相对更简单而紧凑的布局和更陡峭的阻带特性. 通过分析其传输特性提取了该结构的等效电路模型, 推导了其结构参数的设计方程, 研究了该结构的传输特性随结构参数变化的规律, 并总结了设计该 S 形缝隙缺陷地结构的经验方法. 根据此方法设计加工了一个中心频率为 4.64 GHz 的 S 形缝隙缺陷地结构样品, 其品质因数高达 39.66, 尺寸大小仅为 5.00 mm × 1.40 mm, 谐振带陡峭而通带插入损耗小, 测量结果和仿真结果相吻合, 从而验证了该 S 形缝隙缺陷地在实际工程上的适用性.

关键词: S 形缝隙; 缺陷地; 品质因数

中图分类号: TN713; TN455