Co-designed defected ground structure filter with UWB slot antenna

Hailong Yang¹, Xiaoli Xi¹,², Yuchen Zhao¹, Yumeng Tan¹, Zhonghong Du¹, and Lili Wang¹

¹ Electronic Engineering Department, Xi’an University of Technology, Xi’an 710048, People’s Republic of China
² Science and Technology on High Power Microwave Laboratory, Northwest Institute of Nuclear Technology, Xi’an 710024, China

Abstract: In this study, one kind of novel co-designed defected ground structure (DGS) filter with slot antenna is proposed to realize bandpass reflection coefficient and gain performance. This antenna consists of two parts: 1) a 50Ω feeding line and 2) a modified stepped slot with additional narrow slot and defected ground structure. The extra narrow slot, which can effectively prolong the current path of low frequency and generate reflection zero, is introduced to improve the lower band-edge selectivity. DGS is used to improve the upper band-edge selectivity, which can produce transmission zeros in certain frequencies and provides excellent stopband characteristics. In addition, the modified stepped slot with DGS can produce additional resonance frequency, which is helpful to improve the in-band impedance characteristics and radiation efficiency of the antenna. Measured results show that not only the band-edge selectivity of the antenna is improved, but also the in-band impedance matching and radiation efficiency are improved. The experimental results show that the proposed design could be a good candidate for UWB applications.

Keywords: UWB antenna, band-edge selectivity, defected ground structures (DGS)

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

Ultra-wideband (UWB) communication has received extensive attention and development since the Federal Communications Commission (FCC) released the frequency band of 3.1–10.6 GHz [1]. Since the UWB system has a wide operating frequency band (3.1–10.6 GHz), it is easily interfered by other wireless signals near the band-edge. The unwanted signals out-of-band will really affect the performance of the UWB receiver. Therefore, for some out-of-band interference signals, a band-pass filter is usually connected in series behind the antenna to improve the band-edge frequency selectivity and to suppress out-of-band interference. However, just combining the antenna and filter in series will increase the size and cost of the RF front-end. Therefore, it is an interesting topic to design a UWB antenna with a filtering function to realize miniaturization and reduce the cost of the RF front-end [2].

In the design of the antenna, we found that the authors pay more attention to the size, bandwidth and radiation characteristics of the antenna but seldom focus on the band-edge selectivity characteristics and out-of-band suppression of the antenna. However, good band-edge selectivity is also important for the antenna. It not only improves the suppressive of out-of-band signals but also eliminates bandpass filters, thus greatly reducing the size of RF front-end. Recently, there are some antenna with filtering function are proposed [3, 4, 5]. In [3], a third-order SIW
integrated filter/antenna with good band-edge selectivity are obtained by using two resonant cavities. However, the center frequency is 3.71 GHz and it is difficult to redesign for UWB applications. Some UWB antennas with integrated bandpass filters have also been demonstrated [4, 5]. Following the concept of cascading bandpass filters and UWB antenna, UWB antennas with good filtering function are obtained. However, the dimension of these antennas is 53 mm × 22 mm [4] and 53 mm × 42 mm [5], which are still much bigger when they are compared with most of the UWB antennas presented in [2, 3, 4, 5].

In our previous design [6], a compact filtering UWB antenna with band-notched function is studied. Good upper band-edge selectivity are obtained by using the stepped impedance resonator feeding line with low-pass characteristics. However, our study indicates that there will be losses after the signal passes through the modified feeding line with low-pass characteristics. It means that the feeding line with low pass characteristics has a negative effect on the radiation efficiency of the antenna and the radiation efficiency of the reference antenna is 80%. In addition, the reflection coefficient of the reference antenna is only −10 dB, and it is difficult to continue the optimization improvement in the existing structure. This may be due to the single resonant mode of the stepped slot, and it is difficult to get better impedance characteristics in the band.

In this study, instead of using the stepped impedance resonator feeding line in Ref. [6], DGS structures are introduced to effectively improve the band-edge selectivity of the slot antenna. DGS is achieved by etching defected structure in the ground plane, which can produce transmission zeros in some frequencies and provides excellent stopband characteristics [7]. Therefore, three DGS with different dimensions are designed to obtain a wide stopband and integrated into the stepped slots. Additionally, by adding narrow slots near the modified stepped slots, the bandwidth and lower band-edge selectivity are also improved. To verify the good performance of the co-designed filtering antenna, numerical and experimental results are analyzed and studied. The measured results show that the proposed antenna has a good band-edge selectivity and the shape factor (ratio of the −3 dB bandwidth to the −10 dB bandwidth) is 1.05. The radiation efficiency of the proposed design is 90%, which is 12.5% higher than antenna in Ref. [6]. This co-designed filtering slot antenna also has other excellent features such as a compact size of 22 mm × 12 mm and good in-band impedance matching of −14 dB reflection coefficient.

2 Antenna design

Fig. 1(a) shows the basic structure of the antenna. This structure is based on the reference design reported in [8]. Due to the unique and simple structure, the slot antenna has been studied in miniaturization [9], band-notched technique [10] and MIMO technology [11]. In this study, we will study and design a slot antenna with good band-edge selectivity. The size of Type-I antenna is 24 mm × 16 mm. The antenna is designed on an RT/Duroid 5880 substrate with the relative dielectric constant of 2.2 and thickness of 0.787 mm. By using an open-end microstrip feeding line to excited the stepped slot at the bottom of the substrate,
multiple resonant frequencies and ultra-wideband functions can be achieved. The corresponding reflection coefficient is shown in Fig. 1(b). It is observed that the band-edge selectivity at the upper band of the Structure-I is poor, and initial frequency of the operating frequency is 3.75 GHz, which can not meet the requirement for UWB with a lower initial frequency of 3.1 GHz. It is well known that the first resonant frequency mainly depends on the length of the stepped slot and the size of the antenna. However, the small size of the antenna restricts the controllable range of the stepped slot. Therefore, a new method of adding an additional narrow slot to reduce the first resonant frequency of the antenna has been studied in our previous work [6]. As shown in Fig. 2(a), Type-II antenna is designed with an opening slot in the opposite direction is added parallel to the stepped slot. When the parallel slot is added, the current path at low frequency is effectively extended, which has been studied in ref. [6]. It can also be seen from Fig. 2(b) that a new reflection zero $f_1$ is generated, and the bandwidth and band-edge selectivity at lower frequencies are improved after adding the additional slot.

Fig. 1. (a) Geometry of the basic structure namely Type-I, (b) The corresponding reflection coefficient and radiation efficiency of Type-I antenna.

Fig. 2. (a) Geometry of the slot antenna namely Type-II. (b) The corresponding reflection coefficient and radiation efficiency of Type-II antenna.
To further improve the band-edge selectivity of the antenna, specifically at upper frequency end, a stepped-impedance microstrip line with low pass characteristics is designed in Ref. [6], the corresponding reflection coefficient and radiation efficiency is shown in Fig. 3(b). Although this kind of feeding line with low-pass characteristics plays a crucial role in improving the upper band-edge selectivity, it has a negative effect on radiation efficiency, and the in-band reflection coefficient is only −10 dB. The radiation efficiency of the previous design is 80% which is lower than that of Type-I and Type-II antenna. In this study, a modified stepped slot with three DGS of different sizes are designed, shown as Type-III in Fig. 3(a). DGS is achieved by etching defected structure in the ground plane, which can produce transmission zeros in some frequencies and provide excellent stopband characteristics [7]. In [12], the authors presented a UWB bandpass filter with wide upper stopband using defected ground structures (DGS). In this letter, we keep the basic idea of using DGS to design a low pass filter and integrated into the stepped slot of the antenna to obtain good upper band-edge selectivity, as shown in Fig. 3(b).

It is noticed in Fig. 3(b) that the band-edge selectivity of Type-III antenna has been significantly improved, and the DGS does not show a negative effect on the radiation efficiency of the antenna. Although the band-edge selectivity of the proposed antenna is reduced compared with the reference antenna, the radiation efficiency of the Type-III antenna is 90%, which is 12.5% higher than that in Ref. [6]. It is also noticed that the in-band impedance matching is improved (−14 dB reflection coefficient) when the DGS are added. This is because the DGS can provide additional resonance modes and a wideband matching of the antenna to obtain good reflection coefficient. In addition, the comparison of the simulated results of our design with previously published reports has been carried out and listed in Table I. As seen from the Table I, the bandwidth, size and band-edge selectivity of Structure-III have been significantly improved. It is also noticed that the radiation efficiency and in-band impedance of the antenna are significantly improved compared with the reference antenna.

To further get the effect of the DGS, the DGS units are studied. Fig. 4(a) shows the simulation results of the DGS unit. Besides, the frequencies of the resonance of
DGS can be adjusted by changing the impedance ratio of DSG as seen in the bottom right corner of Fig. 4(a). It is found that each DGS unit designed on the bottom of the dielectric can create stopband characteristics and transmission zeros in corresponding resonant frequency. Therefore, designing three DGS with more transmission zeros will obtain wide upper stop band, as shown in Fig. 4(b). The transmission zeros of three DGS resonators are 16.5, 22, and 26 GHz, respectively.

The good performance and the optimum values of the proposed design are obtained using commercially software CST microwave studio. The final dimensions of the optimal antenna are manufactured and listed as follows:

\[
egin{align*}
L_1 &= 11.5 \text{ mm}, & L_2 &= 9 \text{ mm}, & L_3 &= 1.6 \text{ mm}, & L_4 &= 2 \text{ mm}, & L_5 &= 3 \text{ mm}, & L_6 &= 1 \text{ mm}, \\
L_7 &= 2 \text{ mm}, & W_1 &= 2 \text{ mm}, & W_2 &= 3.5 \text{ mm}, & W_3 &= 0.5 \text{ mm}, & W_4 &= 0.5 \text{ mm}, & W_5 &= 1 \text{ mm}, \\
W_6 &= 1.3 \text{ mm}, & W_7 &= 1 \text{ mm}, & W_8 &= 0.3 \text{ mm}, & W_9 &= 0.2 \text{ mm}, & W_{10} &= 0.2 \text{ mm}, & W_{11} &= 0.8 \text{ mm}, & W_{12} &= 1.1 \text{ mm}, & W_{13} &= 1.5 \text{ mm}.
\end{align*}
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### Table I. Comparison between Type-I, Type-II, Type-III, and Ref. [6] antennas.

| Antenna | Size (mm\(^2\)) | \(\text{BW}_{10\text{dB}}\) (GHz) | Shape Factor \(K = \frac{\text{BW}_{10\text{dB}}}{\text{BW}_{-10\text{dB}}}\) | Reflection Coefficient (dB) | Radiation Efficiency |
|---------|-----------------|---------------------------------|---------------------------------|------------------|-------------------|
| Type-I  | 24 × 16 = 384   | 3.75–15                         | 1.32                           | -10              | 87%               |
| Type-II | 24 × 12 = 288   | 3.5–15                           | 1.2                            | -10              | 87%               |
| Ref. [6]| 24 × 12 = 288   | 3.1–11                           | 1.038                          | -10              | 80%               |
| Type-III| 22 × 12 = 264   | 3.1–11.2                         | 1.05                           | -14              | 90%               |

![Fig. 4](image_url)

**Fig. 4.** (a) The S-Parameters of the DGS unit. (S21 variation with the impedance ratio of DGS unit). (b) Simulated S-parameters of the low-pass filter with three DGS.

DGS can be adjusted by changing the impedance ratio of DSG as seen in the bottom right corner of Fig. 4(a). It is found that each DGS unit designed on the bottom of the dielectric can create stopband characteristics and transmission zeros in corresponding resonant frequency. Therefore, designing three DGS with more transmission zeros will obtain wide upper stop band, as shown in Fig. 4(b). The transmission zeros of three DGS resonators are 16.5, 22, and 26 GHz, respectively.

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L_7 &= 2 \text{ mm}, & W_1 &= 2 \text{ mm}, & W_2 &= 3.5 \text{ mm}, & W_3 &= 0.5 \text{ mm}, & W_4 &= 0.5 \text{ mm}, & W_5 &= 1 \text{ mm}, \\
W_6 &= 1.3 \text{ mm}, & W_7 &= 1 \text{ mm}, & W_8 &= 0.3 \text{ mm}, & W_9 &= 0.2 \text{ mm}, & W_{10} &= 0.2 \text{ mm}, & W_{11} &= 0.8 \text{ mm}, & W_{12} &= 1.1 \text{ mm}, & W_{13} &= 1.5 \text{ mm}.
\end{align*}
\]

### 3 Results and discussion

The proposed antenna is manufactured and tested on the final dimensions described above. In order to better demonstrate the good band-edge selectivity characteristics of the antenna and the suppression of the out-of-band interference signal, multiple simulated and measured results of the proposed antenna are presented and discussed, including its reflection coefficient, gain, radiation characteristics, and transfer functions of two identical antennas.
Fig. 5. The simulated and measured reflection coefficient of the proposed design.

Fig. 6. Simulated input impedances of the proposed design.

Fig. 7. Measured radiation patterns of the proposed design. (a) 3.1 GHz, (b) 6 GHz, (c) 10 GHz.
Fig. 5 shows the simulated and measured reflection coefficient of the proposed design. As shown in Fig. 5, the measured bandwidth for the reflection coefficient is approximately 113% spans from 3.1 to 11.2 GHz. The proposed antenna also has excellent out-of-band suppression, and the simulated and measured value of the out-of-band reflection coefficient is close to zero. The ratio of the \(-3\) dB bandwidth to the \(-10\) dB bandwidth is 1.05, which is as good as the previous design [6]. It is also noticed that the proposed antenna has good in-band impedance matching of \(-14\) dB reflection coefficient.

In order to further analyze the band-edge selectivity characteristics of the antenna, the simulated input impedance of the original antenna Type-I and the final design Type-III are given in Fig. 6. As shown in Fig. 6, in the passband, the real part of the Type-III antenna is close to 50 ohms, and the imaginary curve is nearly 0 ohms. Compared with the original antenna Type-I that the impedance characteristics of the Type-III antenna in the real and imaginary parts of the sideband have changed greatly after we added the additional slot and the DGS structure, which further illustrates the better sideband selection characteristics of the antenna.

Fig. 7 plots the measured and simulated radiation patterns of the proposed antenna at 3.1, 6, and 10 GHz, respectively. It is found that the measured results are in good agreement with the simulated results. The 3D radiation patterns with the antenna structure are also proposed. Again, the radiation patterns at 10 GHz become imbalanced and directional, which is mainly caused by the asymmetry of a ladder slot and imbalance of current distribution at high frequency.

The simulated and measured gain and efficiency curves of the proposed antenna are shown in Fig. 8. The excellent filtering characteristics can also be observed from the gain and efficiency curves. It is observed that the proposed antenna has steady gains (3.5 dBi) and efficiencies in operating frequency (3.1–10.6 GHz), but sharply decreases at the band-edge and have an excellent roll-off rate in sideband, where the gain and efficiency reduce dramatically by 13 dB and 80%, respectively. Compared with the referenced design, the radiation efficiency of the proposed design is 90%, which is 12.5% higher than filtering antenna in Ref. [6].

Fig. 9 shows the magnitude and phase characteristics of two identical antennas placed face-to-face with a 40 cm distance. It is observed in Fig. 9(a) that the magnitude characteristic of the antenna in operating frequencies is stable, and the fluctuation is small in the working frequency band. It is also noticed that the magnitude changes sharply in the band-edge and showed better filtering characteristics. Phase S_{21} for two identical antennas placed face-to-face are also shown in Fig. 9(b). It is found that the plot exhibits a linear variation of phase in the operating band. Compared with some other competitive UWB antennas is presented in Table II, the proposed antenna not only has a compact size and band-edge selectivity but also has better in-band impedance characteristics and radiation efficiency.
4 Conclusion

In this letter, the co-designed DGS filter with slot antenna is designed to realize a good filtering characteristics. By adding additional narrow slot and DGS, both the lower and upper band-edge selectivity are significantly improved. To verify the design concept, numerical and experimental results are analyzed and studied. Both the simulated and measured results have demonstrated the excellent band-edge
selectivity. In addition, the proposed design also has other attractive features such as good in-band impedance matching, good radiation efficiency, and compact size.

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