A compact wideband SIW-DGS filter with two independently controllable transmission zeros and sharp attenuation slopes

Yu Guo¹,², Jinghui Zhang¹, and Haodong Wu²a)

¹ School of Internet of Things Engineering, Jiangnan University, No 1800 Lihu Avenue, Wuxi, Jiangsu, 214122, China
² Nanjing University, No. 22, Hankou Road, Nanjing, Jiangsu 210093, China
a) haodongwu@163.com

Abstract: In this paper, the analysis and design of a wide band bandpass substrate integrated waveguide (SIW) filter are presented. A middle layer metal patch is designed in the SIW not only to create two transmission zeros due to 3D separate electric and magnetic coupling paths (SEMCP) but also miniaturize size of the filter. Since 3D electric and magnetic coupling paths are separate, the two transmission zeros above and below the passband can be independently controlled. Defected ground structure (DGS) is designed with substrate integrated waveguide not only for sharp rejection but also for its bandstop characteristics. The design is then verified by simulation and experiment.

Keywords: wide band filter, SIW, SEMCP, independently controlled, transmission zeros

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

References

[1] Y.-C. Chiou, et al.: “Broadband quasi-Chebyshev bandpass filters with multimode stepped-impedance resonators (SIRs),” IEEE Trans. Microw. Theory Techn. 54 (2006) 3352 (DOI: 10.1109/TMTT.2006.879131).
[2] Q. X. Chu, et al.: “Novel UWB bandpass filter using stub-loaded multiple-mode resonator,” IEEE Microw. Wireless Compon. Lett. 21 (2011) 403 (DOI: 10.1109/LMWC.2011.2160526).
[3] H. Zhu and Q. X. Chu: “Compact ultra-wideband (UWB) bandpass filter using dual-stub-loaded resonator (DSLR),” IEEE Microw. Wireless Compon. Lett. 23 (2013) 527 (DOI: 10.1109/LMWC.2013.2278278).
[4] N. Janković, et al.: “Compact UWB bandpass filter based on grounded square patch resonator,” Electron. Lett. 52 (2016) 372 (DOI: 10.1049/el.2015.4087).
[5] M. M. Honari, et al.: “Two-layered substrate integrated waveguide filter for UWB applications,” IEEE Microw. Wireless Compon. Lett. 27 (2017) 633 (DOI: 10.1109/LMWC.2017.2711510).
[6] Q. X. Chu and L. L. Qiu: “Wideband balanced filters with high selectivity and...
common-mode suppression,” IEEE Trans. Microw. Theory Techn. 63 (2015) 3462 (DOI: 10.1109/TMTT.2015.2454497).

[7] X. Guo, et al.: “Strip-loaded slotline resonators for differential wideband bandpass filters with intrinsic common-mode rejection,” IEEE Trans. Microw. Theory Techn. 64 (2016) 450 (DOI: 10.1109/TMTT.2015.2509065).

[8] J.-S. Lim, et al.: “A spiral-shaped defected ground structure for coplanar waveguide,” IEEE Microw. Wireless Compon. Lett. 12 (2002) 330 (DOI: 10.1109/LMWC.2002.803208).

[9] K. M. Shum, et al.: “A UWB bandpass filter with two transmission zeros using a single stub with CMRC,” IEEE Microw. Wireless Compon. Lett. 17 (2007) 43 (DOI: 10.1109/LMWC.2006.887253).

[10] H. Wang, et al.: “Design of ultra-wideband bandpass filters with fixed and reconfigurable notch bands using terminated cross-shaped resonators,” IEEE Trans. Microw. Theory Techn. 62 (2014) 252 (DOI: 10.1109/TMTT.2013.2296530).

[11] Z.-C. Hao, et al.: “Compact super-wide bandpass substrate integrated waveguide (SIW) filters,” IEEE Trans. Microw. Theory Techn. 53 (2005) 2968 (DOI: 10.1109/TMTT.2005.854232).

[12] P. Vélez, et al.: “Ultra-compact (80 mm²) differential-mode ultra-wideband (UWB) bandpass filters with common-mode noise suppression,” IEEE Trans. Microw. Theory Techn. 63 (2015) 1272 (DOI: 10.1109/TMTT.2015.2401555).

1 Introduction

The increasing/unceasing demands for high data rate communication and high accuracy positioning capabilities have driven research into new ultra-wideband (UWB) techniques, since the release of the unlicensed commercial application of UWB communication systems from 3.1 to 10.6 GHz. As the essential key components in ultrahigh-speed wireless communication and radar systems, UWB bandpass filters simultaneously with sharp cutoff regions, low insertion loss and a wide stopband are in great demand [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12].

Various demonstrated UWB filters excel in some performance parameters while at the expense of others. For example, microstrip UWB filters based on multi-mode resonator are easy to achieve a wide passband due to the resonator have multiple resonate frequencies [1, 2]. However, due to the relatively low Q of the planar microstrip filters, attenuation slopes of the filters are always low. It also has a narrow stopband at high frequency. Using dual-stub-loaded resonators (DSLR), a UWB filter is proposed in [3]. Four resonant modes can be tuned by the DSLR between 3.1 GHz and 10.6 GHz, and a pair of transmission zeros (TZ) can be generated at the lower and upper stopband when the DSLR is applied to a UWB filter. However, attenuation slope of the filter is 30.0 dB/GHz at higher band. UWB filter can also be designed based on a grounded square patch resonator with slots [4]. The filter has a very small size of only $0.26\lambda_g \times 0.26\lambda_g$. However the combination of slot and minimized patch make it has a low Q and its lower band attenuation slope is about 6.0 dB/GHz. Based on substrate integrated waveguide (SIW) using ridge resonator, a UWB filter was designed with sharp attenuation slopes 60.0 dB/GHz and deep stop band $-47$ dB. However, it has a footprint of $90 \times 32$ mm² [5].
In conclusion, it is still a challenge to achieve a UWB filter with simple structure, compact size, wide stop band, sharp attenuation slopes, low insertion loss and so on.

In this letter, a novel design of UWB bandpass filter is proposed to achieve targeted performance while alleviating the constraints imposed by aforementioned size, passband selectivity and outband suppression issues. Based on common three layer PCB technique, a middle layer metal patch is not only used to reduce working frequency of the filter for a compact size, but also enable a separate electric and magnetic energy coupling paths (SEMCP) which contributed two transmission zeros at both sides of the passband. Since the electric and magnetic coupling paths are separated, each transmission zero can be independently controlled. The transmission zero at right side of the passband can not only improve attenuation slope of its passband, but also can achieve a notch band with controllable center frequency in the passband, which has great value for practical applications. In comparison with other planar microstrip filters, SIW is used for its high Q and compact size. With introduced transmission zeros and high Q SIW structure, sharp attenuation slopes of passband is achieved. The operation mechanism of the proposed filter is verified by the simulation and experiment.

2 Design of 3D-SEMCP SIW-DGS filter

Implemented in a common three-layer PCB, 3D diagram of a compact UWB filter is shown in Fig. 1. The filter utilizes co-planar waveguide (CPW) on top plate to couple energy into substrate integrated waveguide defined by a filter frame. Conventional DGS structure is redesigned as spiral DGS on top metal plate to achieve both high out-of-band rejection and low energy consumption of the filter. The spiral DGS consists of spiral defects embedded in the uniplanar ground plate. The size of spiral dominates the frequency of band rejection, while spacing and metal width affect the frequency and Q-factor of the response. The smaller the size of defect, the higher the frequency of transmission zero is induced. Since the DGS is connected to the surrounding ground plate as shown in Fig. 1(b), a magnetic energy coupling between resonators is achieved by this kind of design.

Cross section of the filter is depicted in Fig. 1(c). A floating metal patch is inserted as an additional middle copper layer and a capacitive energy coupling between resonators is achieved as shown in Fig. 1(c). Equivalent circuit model of the 3D electric coupling path is shown in Fig. 1(d).

The metal patch not only can achieve 3D-SEMCP, but also can reduce size of filter. As can be seen in Fig. 2, by employing this metal patch, the resonant frequency is shifted down to a lower value compared to filter without metal patch.

To analyze size reduction of filter, effective capacitance induced by middle metal plate is shown below. In Fig. 1(c), the parallel capacitor to the ground (between the patch and the bottom plate) and two capacitors (between the top plate and the patch) are given as $C_{fb}$, and $C_{ft}$, respectively. For simplicity, the metal plates are assumed perfect conductors. As can be seen, effective capacitance induced by the metal patch is given by:
From this equation, in order to increase the effective capacitance value, $C_{ft}$ needs to be maximized. The effect of the size and location of the patch on shifting down the resonance frequency is studied by simulation, and the results are shown in Fig. 3. In this figure, $h_p$ needs to be maximized to increase $C_{ft}$, and to achieve a high miniaturization factor. However, it is limited by the height of the standard substrate thickness used for filter fabrication. Therefore, $h_c$ is chosen to be 0.1 mm, while the whole thickness of three layer PCB is 0.52 mm. A miniaturization factor of 66.0% is achieved. The miniaturization factor for a particular miniaturized resonator operating at a frequency of $f_0$ is given by:

$$C_{eff} = \frac{C_{ft}^2}{C_{fb} + 2 \times C_{ft}}$$

Fig. 1. Schematic of the proposed filter design. (a) 3D view (b) Top view (c) A-A’ Cross section view (d) Equivalent circuit model of electric coupling.

Fig. 2. Resonance peaks on $|S_{21}|$ of filter change when metal patch is designed.
Miniaturization factor \( \% = \frac{A_{\text{siw},f_0} - A_c}{A_{\text{siw},f_0}} \times 100 \) (2)

Where \( A_{\text{siw},f_0} \) is the area of a conventional cylindrical SIW resonator, which fundamentally operates at \( f_0 \) and \( A_c \) is the area of the proposed resonator.

![Miniaturization factor changes with different size and height of metal patch.](image)

**3 Numerical simulations**

Utilizing commercial full-wave EM simulation software Ansoft HFSS, a filter is simulated with dimensions shown in Table I.

| Table I. Filter dimensions |
|-----------------------------|
| \( L \) (Length of filter)  | 12.0 mm |
| \( W \) (Width of filter)   | 12.0 mm |
| \( h_c \) (Height of top substrate) | 0.1 mm |
| \( h_p \) (Height of bottom substrate) | 0.4 mm |
| \( l_p \) (Length of metal patch) | 4.4 mm |
| \( w_p \) (Width of metal patch) | 3.2 mm |
| \( l_1 \) (Length of spiral slot1) | 2.4 mm |
| \( l_2 \) (Length of spiral slot2) | 1.5 mm |
| \( g_1 \) (Gap width of spiral slot) | 0.1 mm |
| \( w_1 \) (Width of spiral slot) | 0.6 mm |
| \( w_{s1} \) (Width of capacitive slot1) | 0.1 mm |
| \( w_{s2} \) (Width of capacitive slot2) | 0.4 mm |

With top Rogers RO4350 substrate’s thickness of 0.10 mm and bottom substrate’s thickness of 0.42 mm, the filter works at 8.2 GHz and its simulation results are shown in Fig. 4. In this figure, due to the 3D-SEMCP, there are two TZs generated at both sides of passband. In addition, there is a wide stopband of 10.0 dB from 11.2 GHz to 20.0 GHz due to the designed DGS.
The two TZs can be independently controlled. First, frequency shift of the left TZ generated by E-dominant coupling is studied by simulating the filter with different patch widths ($w_p$) and heights ($h_p$), and the results are shown in Fig. 5. As shown in Fig. 5(a), keeping the height of bottom substrate $h_p$ of 0.42 mm and increasing patch width $w_p$ from 2.5 mm to 4.0 mm, the frequency of lower TZ is shifted from 5.46 GHz to 4.73 GHz accordingly and the other two TZs are not shifted. In Fig. 5(b), the lower TZ shifts from 5.83 GHz to 4.61 GHz as $h_p$ increases from 0.40 mm to 0.48 mm, while the other two TZs are almost not shifted.

Second, frequency change of the upper TZ generated by M-dominant coupling is studied by simulation of filter with different spiral slot lengths ($l_1$). The results are shown in Fig. 6. As shown in Fig. 6(a), by increasing spiral slot length $l_1$ from 2.35 mm to 2.55 mm, frequency of the TZ generated by M-dominant coupling moves from 11.20 GHz to 10.76 GHz with little effect on other TZs.

Furthermore, a controllable notch in passband, which is helpful for cutting off interference from other existing wireless devices like wireless local-area network (WLAN) (i.e., 5.8 GHz) and 8.5–10.68 GHz radar frequency, can be realized by designing the spiral slot. As shown in Fig. 6(b), a steep notch band at 9.1 GHz is generated with spiral slot length $l_1$ of 3.5 mm. It is worth note that the notch band can be controlled in a large passband range by tuning $l_1$ without changing the frequencies of other TZs.
Fig. 7 gives a more intuitive description about independently controllable TZs. First, as metal patch width $w_p$ changes from 2.5 to 4.0 mm, the lower TZ moves to lower frequency while the other two TZs are not changed. Second, as metal patch width $w_p$ is constant and length of spiral slot $l_1$ changes from 2.5 to 4.0 mm, frequency of TZ controlled by magnetic energy coupling decreases dramatically with little effect on other two TZs. Finally, when $w_p$ and $l_1$ are unchanged and height of bottom substrate $h_p$ increases from 0.40 to 0.44 mm, frequency of the lower TZ decreases.

Therefore, frequencies of both TZs could be designed independently to achieve sharp cutoff region of passband and achieve a controllable notch in passband, while the wide bandstop obtained by DGS are not affected.

4 Experimental results and discussions

To demonstrate the UWB filter, a full-wave simulation solver HFSS is used in theoretic design of the UWB filter. Rogers RO4350 substrate with a dielectric constant of 3.66 and loss tangent of 0.004 is used for experimental work. In implementing the filter, a standard three layer metal PCB process is used to construct the metal via posts, top and bottom metal plates. The fabricated filter
shown in Fig. 8(b) was measured using an HP 8510C network analyzer. A short-open-load-through was adopted for calibration of measurements.

![Figure 8](image_url)

**Fig. 8.** (a) Simulated and measured frequency responses of fabricated UWB BPF. (b) Photograph of fabricated UWB filter.

In Fig. 8(a), good agreement was obtained where the filter exhibited the passband. The deviation between simulated and measured results may be attributed to the fabrication errors and the parasitic effects of the SMA connectors. The 3-dB passband covers from 5.4 to 10.8 GHz, and it has a fractional bandwidth of 67.0%. The measured return loss is better than 12.0 dB and insertion loss is less than 1.5 dB within the UWB passband. In addition, the group delay within the UWB passband is between 0.15 and 0.70 ns. Sharp attenuation slopes are achieved. A comparison with other UWB filters is shown in Table II. As can be seen, the proposed solution achieves state-of-the-art performance with a compact footprint on the design, sharp attenuation slopes and introducing two independently controllable transmission zeros.

| Design | IL (dB) | RL (dB) | TZ@LS&US | LAS (dB/GHz) | UAS (dB/GHz) | Size ($\lambda_0 \times \lambda_0$) |
|--------|--------|--------|----------|--------------|--------------|-------------------|
| [3]    | <1.5   | >10    | two      | 30           | 26           | 0.51 x 0.33       |
| [4]    | <0.9   | >17    | one      | 6.0          | 25           | 0.26 x 0.26       |
| [5]    | <1.0   | >14    | no       | 40           | 70           | 1.80 x 0.64       |
| This work | <1.5 | >12    | two      | 60           | 55           | 0.32 x 0.35       |

IL: insertion loss; RL: return loss; TZ@LS&US: transmission zero at lower and upper stopband; LAS: lower attenuation slope; UAS: upper attenuation slope; $\lambda_0$: the free space wavelength at the center frequency $f_0$.

### 5 Conclusion

A novel UWB filter with 3D separate electric and magnetic coupling paths (SEMCP) is proposed and the detailed filter design methodology is presented in this paper. Two independently controllable transmission zeros are achieved by 3D-SEMCP which support the filter obtain a sharp passband selectivity. Besides, SIW
is utilized for its high Q property to improve attenuation slope of the filter. A wide stopband is also realized by spiral DGS design. Measurement results demonstrated the compact filter’s performances including insertion loss, return loss, stopband and so on.

**Acknowledgments**

This work is supported by the Natural Science Foundation of Jiangsu Province (BK20160190), the Fundamental Research Funds for the Central Universities (JUSRP11740), the Natural Science Foundation of China (61701195), the China Post Doctoral Science Foundation (2017M621710), the Jiangsu Post Doctoral Science Foundation (1701119B) and the National Key Research and Development Program of China (2016YFC0104802).