Compact Bandpass Filter with Wide Stopband and Low Radiation Loss Using Substrate Integrated Defected Ground Structure

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Abstract — In this paper, a bandpass filter (BPF) with wide upper stopband and low radiation loss based on the substrate integrated defected ground structure (SIDGS) is presented. The BPF is composed of two sets of stepped-impedance SIDGS resonant cells with two microstrip feed-lines. Such slow-wave SIDGS cells can introduce the passband resonances with a wide upper stopband. Besides, the SIDGS surrounded by the bottom ground layer with metal-vias can not only suppress the radiation loss but also can be flexible for integration. To verify the mechanisms mentioned above, a wide upper stopband BPF with a passband centered at 2.4 GHz (i.e., \( f_0 \)) is implemented and fabricated. The measured stopband is up to 19.3 GHz (i.e., \( 8f_0 \)) with a rejection level of 29 dB, while the total loss (i.e., including radiation, metal, and substrate loss) is less than 30% up to 19 GHz. The core size of the BPF is about 0.16 \( \lambda_g \times 0.16 \lambda_g \), where \( \lambda_g \) is the microstrip guided wavelength at the center frequency.

Keywords — Bandpass filter (BPF), low radiation loss, slow-wave, substrate integrated defected ground structure (SIDGS), wide stopband.

I. INTRODUCTION

With the increasing development of the highly integrated modern wireless communication systems, high performance bandpass filters (BPFs) with harmonic suppression and electromagnetic interference (EMI) suppression are highly demanded. The substrate integrated waveguide (SIW) filters [1]–[3] are proposed with good in-band performance. However, the stopband bandwidth of these filters is limited. To extend the stopband, two BPFs using stepped-impedance resonators (SIRs) are proposed [4]–[8], which suffer from the stopband bandwidth of these filters is limited. To extend the stopband, two BPFs using stepped-impedance resonators (SIRs) are proposed [4]–[8], which suffer from the stopband bandwidth of these filters is limited. To extend the stopband, two BPFs using stepped-impedance resonators (SIRs) are proposed [4]–[8], which suffer from the stopband bandwidth of these filters is limited. 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II. SCHEMATIC AND OPERATION

Fig. 1 shows the configuration of the proposed BPF, which is composed of two microstrip feed-lines and two SIDGS resonant cells. Each resonant cell consists of two stepped-impedance DGSs. Note that the physical size of these DGSs cannot meet the theoretical definition of slotline [14]. Meanwhile, the bottom ground and metal-vias are located surrounding the DGS resonators for the SIDGS implementation. To further investigate the mechanisms of the proposed structures for filter design, the dielectric substrate RO4003C (i.e., \( \varepsilon_r = 3.55, h_1 = 0.203 \) mm, and \( h_2 = 0.303 \) mm) and full-wave EM-simulator IE3D are used.

A. Resonance

To discuss the resonant principles of such SIDGS cells, the effects of the physical dimensions on the resonances (i.e., the total length \( l_{\text{SIDGS1}} \) and \( l_{\text{SIDGS2}} \) - substrate thickness \( h_2 \)) are shown in Fig. 2(a) and (b). Due to the characteristics of the folded structures and the influence of the bottom ground, the \( l_{\text{SIDGS1}} \) (i.e., \( 2l_2+l_4+s_2+s_5+s_6+s_7 \)) and \( l_{\text{SIDGS2}} \) (i.e., \( l_1+l_3+s_1+s_3+s_4 \)) are shorter than \( \lambda/2 \) at \( f_1 \) and \( f_2 \), respectively. Then, the dual-resonance SIDGS cell is implemented by...
combining such two DGS resonators. The configuration and frequency responses are exhibited in Fig. 2(c). It is notable that the resonant frequencies are shifted downwards with the decreasing of $h_2$.

### B. Spurious Suppression

As depicted in Fig. 3, to investigate the stopband characteristics, the dual-resonance SIDGS cell is implemented under the cases of weak- and strong-coupled feed-line (i.e., Case A and Case B). It is notable that the stopband performance is poor on account of the harmonics in Case A. Thus, a strong-coupled feed-line with an additional patch is introduced to enhance the slow-wave effect by increasing the effective capacitance between feed-line and ground. To further verify the mechanism of such effect, the electrical current density of SIDGS cell in Case B is simulated at the typical stopband frequency $f_s = 13.44$ GHz of the strong-coupled feed-line with dual-resonance SIDGS cell. Simulated frequency responses of various coupled feed-lines with SIDGS cell.

![Fig. 2. (a) Configuration of the SIDGS resonator I and the effect of $h_2$ and $l_{SIDGS1}$ on the resonant frequency; (b) Configuration of the SIDGS resonator II and the effect of $h_2$ and $l_{SIDGS2}$ on the resonant frequency; (c) Effect of $h_2$ on the resonant frequencies of the dual-resonance SIDGS cell.](image)

![Fig. 3. (a) Configuration of SIDGS using weak-coupled feed-line. (b) Configuration of SIDGS using strong-coupled feed-line with a patch. (c) Typical electric current density at the stopband frequency $f_s = 13.44$ GHz of the strong-coupled feed-line with dual-resonance SIDGS cell. (d) Simulated frequency responses of various coupled feed-lines with SIDGS cell.](image)

**C. Filter Design**

Based on the SIDGS cell mentioned above, a BPF centered at 2.4 GHz with 3-dB fractional bandwidth (FBW) of 24.6% is implemented. The configuration of four resonators and coupling-node diagram are shown in Fig. 4(a) and (b), respectively. Then, the couplings of BPF could be concluded in 6 parts: 1) broadside coupling $k_{12}$ between R2 and R3; 2) embedded couplings between R1 and R2 (i.e., $k_{12}$) and R3 and R4 (i.e., $k_{34}$); 3) cross coupling $k_{14}$ between R1 and R4; 4) external quality factor $Q$ between microstrip feed-line and R1 or R4 [13], [15]; 5) tiny couplings between microstrip feed-line and R2 or R3; 6) diagonal couplings including $k_{13}$ and $k_{24}$. The coupling coefficients in parts 5) and 6) are slight since the indirect coupling routing in Fig. 4(a). Two transmission zeros are allocated by the cross coupling $k_{14}$. In order to extract the aforementioned coupling coefficients for filter design, the simulated $k_{12}$, $k_{34}$, and $k_{23}$ are shown in Fig. 5(a) and (b). The coupling coefficients $k_{12}$, $k_{34}$, and $k_{23}$ are increased with the decreasing widths of the gaps (i.e., $w_4$ and $w_6$). Thus, the bandwidth of proposed filter can be decreased by increasing $w_4$ or $w_6$. Meanwhile, Fig. 5(c) reveals that the external quality factor $Q$ is decreased with the increase of $l_1$.

### D. Radiation

Based on the surrounding ground with metal-vias, the radiation loss could be reduced compared to the conventional DGS. The magnetic and electric field are restricted in the substrate by the fully surrounding ground II and the metal-vias, as shown in Fig. 6. To investigate the radiation effects, a radiation loss rate $R_r$ of the BPF without and with ground...
II is simulated under the case of lossless substrate and metal. The $R_r$ is calculated by

$$R_r = 1 - |S_{11}|^2 - |S_{21}|^2.$$  \hspace{1cm} (1)

As depicted in Fig. 6, the BPF using SIDGS exhibits a much lower radiation loss compared to the conventional DGS BPF.

III. FABRICATION AND EXPERIMENTAL RESULT

Based on the mechanisms mentioned above, a BPF with an ultra-wide stopband is designed, implemented, and fabricated. The photograph of the BPF is shown in Fig. 7. The core circuit-size of the BPF is $12.3 \text{ mm} \times 12.2 \text{ mm}$ (i.e., $0.16 \lambda_g \times 0.16 \lambda_g$), where $\lambda_g$ is the microstrip guided wavelength at the center frequency $f_0$ of 2.4 GHz. The S-parameter measurement exhibited in Fig. 7 are performed using the Agilent 5230A network analyzer over the frequency range from 0.01 to 20 GHz. The measured 3-dB fractional bandwidth (FBW) is $24.6\%$ with a minimum passband insertion loss of $1.66 \text{ dB}$. Meanwhile, the stopband is up to 19.3 GHz with a rejection level higher than $29 \text{ dB}$. The measured total loss is less than $30\%$ up to 19 GHz. The calculated radiation loss under the case of lossless substrate and metal is less than $6\%$ up to 19 GHz. A comparison of the proposed filter with the state-of-the-arts with wide stopband using various structures is shown in Table 1. It is notable that this filter inherits the merits of DGS including the wide upper stopband with a compact size. Moreover, it exhibits a strong advantage in the suppression of radiation.

IV. CONCLUSION

In this paper, a compact bandpass filter using SIDGS resonant cells is proposed. The surrounding ground with metal-vias is introduced to suppress the radiation loss of the proposed BPF, which is less than $6\%$ from dc to 19 GHz. Meanwhile, based on the SIDGS cells, the proposed BPF exhibits an ultra-wide upper stopband up to 19.3 GHz (i.e., $8f_0$) with attenuation level of $29 \text{ dB}$. With such good performance, the miniaturized SIDGS cells and BPF are attractive for the practical applications.

![Fig. 6](image1.png)  \hspace{1cm} (a) The proposed SIDGS. (b) The conventional DGS. (c) Radiation rate $R_r$ under the condition of lossless substrate and metal.

![Fig. 7](image2.png)  \hspace{1cm} Fig. 7. Measured and simulated results of the developed BPF prototype and the photograph of the developed BPF prototype ($l_1 = 4.6, l_2 = 4.11, l_3 = 3.75, l_4 = 3.93, l_5 = 3.15, d_1 = 0.2, d_2 = 0.2, d_3 = 0.15, d_4 = 0.17, d_5 = 0.17, w_1 = 0.17, w_2 = 0.1, w_3 = 2.25, w_4 = 0.22, w_5 = 0.1, w_6 = 0.5, s_1 = 6.9, s_2 = 5.07, s_3 = 7.52, s_4 = 1.55, s_5 = 1.7, s_6 = 4.49, w_{t1} = 2.4, \text{ and } l_t = 3.28, \text{ unit: mm}$.)

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Technology</th>
<th>SIW</th>
<th>Microstrip</th>
<th>DGS</th>
<th>SIDGS</th>
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<tr>
<td>[3]</td>
<td>$f_0$(GHz)</td>
<td>4.83</td>
<td>1.25</td>
<td>2.48</td>
<td>2.4</td>
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<tr>
<td>[8]</td>
<td>IL(dB)</td>
<td>1.2</td>
<td>2.52</td>
<td>1.081</td>
<td>1.66</td>
</tr>
<tr>
<td>[12]</td>
<td>FBW(%)</td>
<td>1.4</td>
<td>8.9</td>
<td>10.8</td>
<td>24.6</td>
</tr>
<tr>
<td>Stopband</td>
<td>Rejection</td>
<td>&gt;15 dB</td>
<td>&gt;23.7 dB</td>
<td>&gt;30 dB</td>
<td>&gt;29 dB</td>
</tr>
<tr>
<td></td>
<td>up to 1.4f0</td>
<td>up to 10.6f0</td>
<td>up to 12f0</td>
<td>up to 8f0</td>
<td></td>
</tr>
<tr>
<td>Radiation</td>
<td>Loss$^\Delta$</td>
<td>Low</td>
<td>High</td>
<td>30% at 19 GHz</td>
<td>&lt;6% up to 19 GHz</td>
</tr>
<tr>
<td>Peak Total</td>
<td>Loss$^\Delta$</td>
<td>$\approx 37%$ at 6.25 GHz</td>
<td>$\approx 98%$ at 4.1 GHz</td>
<td>$\approx 60%$ at 19 GHz</td>
<td>$\approx 30%$ at 19 GHz</td>
</tr>
<tr>
<td>Total Loss &lt;30%</td>
<td>Up to 6.1 GHz</td>
<td>Up to 4 GHz</td>
<td>Up to 14 GHz</td>
<td>Up to 19 GHz</td>
<td></td>
</tr>
<tr>
<td>Core Size</td>
<td>1000 mm$^2$</td>
<td>0.0192 $(\lambda_0^2)$</td>
<td>0.1122 $(\lambda_0^2)$</td>
<td>0.0526 $(\lambda_0^2)$</td>
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<tr>
<td></td>
<td>777 mm$^2$</td>
<td>847 mm$^2$</td>
<td>150 mm$^2$</td>
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$^\Delta$: Estimated from the paper.

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REFERENCES