Compact 1.75–2.7 GHz Tunable BPF With Wide Stopband Up to 9.5 GHz Using Harmonic-Controlled SIDGS Resonators

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Abstract—In this brief, a harmonic-controlled substrate-integrated defected ground structure (SIDGS) resonator with tuning capacitor is proposed for the design of tunable filter. Such resonator exhibits a harmonic-controlled characteristic. The fundamental resonant frequency can be properly tuned, while the spurious resonance is controlled at much higher frequency to achieve a wide stopband. To verify the principle, a tunable bandpass filter (BPF) is designed and fabricated based on the resonator. The center frequency can be tuned from 1.75 to 2.7 GHz. Meanwhile, the stopband can extend up to 9.5 GHz with a rejection level of 20 dB for all tuning cases. The BPF also exhibits low insertion loss (i.e., 1.1–1.9 dB) and compact size (i.e., 0.07 λg × 0.08 λg, where λg is the microstrip guided wavelength at the 1.75 GHz).

Index Terms—Harmonic-controlled, substrate-integrated defected ground structure (SIDGS), tunable bandpass filter (BPF), wide stopband.

I. INTRODUCTION

WITH the rapid development of modern wireless systems, the requirement of reconfigurability for a multi-mode operation becomes a major challenge for the circuit design [1]. As a crucial component in transceiver front ends, tunable bandpass filters (BPFs) have aroused increasing interests [2]. Generally, two main types of tunable BPFs are mechanically tuned filters and electronically tuned filters, respectively. The mechanically tuned filters can achieve a stable filtering performance with low insertion loss and good selectivity over a wide tuning range [3]–[5]. However, it suffers from large volume and usually a cumbersome tuning module. Thus, such kind of filters is not suitable for highly integrated system. The electronically tunable planar filters are commonly implemented with electrical tuning elements in planar circuits, including micro-electromechanical system (MEMS) [6]–[8], varactor diode [9]–[15], p-i-n diode [16], and so on. Such kind of filters show the merits of compact size, low cost, and ease of integration. However, relatively narrow stopband caused by the intrinsic harmonics of most reported tunable structures limits the application. Meanwhile, passband insertion loss and return loss of tunable filters are not easy to control due to the resistance introduced by the electronically tuning elements. Recently, substrate-integrated defected ground structure (SIDGS) [17]–[18] is proposed for various kinds of high-performance passive components with wide stopband, low radiation loss, and compact size. However, such filters with fixed operating frequency can hardly satisfy the requirement of multi-standard communication circuits and systems. Meanwhile, how to remain the characteristic of wide stopband when transforming the SIDGS resonator to tunable version is also a great challenge.

In this brief, a harmonic-controlled SIDGS resonator with cascaded varactor is proposed. The first harmonic of the resonator can be controlled at higher frequency while the fundamental resonance is tuned. Thus, such harmonic-controlled SIDGS resonator can exhibit wide stopband more than five times of the fundamental resonant frequency. Compared to the previous works of SIDGS [17]–[18], the main advantage of the harmonic-controlled resonator is that the fundamental resonant frequency can be tuned by varactor while wide stopband can be achieved in all tuning cases. Then, to verify the mechanism mentioned above, a tunable BPF using the harmonic-controlled SIDGS resonator is designed and measured. The stopband can extend up to 9.5 GHz with a rejection level of 20 dB for the entire passband tuning range from 1.75 to 2.7 GHz. Meanwhile, low insertion loss (i.e., 1.1–1.9 dB) and compact size (i.e., 0.07 λg × 0.08 λg, where λg is the microstrip guided wavelength at the 1.75 GHz) are achieved by the tunable filter.

II. SCHEMATIC AND OPERATION

Fig. 1 shows the configuration of the proposed tunable filter, which is composed of two tunable SIDGS resonators, two feed-lines with an interdigital capacitor, and four varactors. Note that the etched defect is defined as DGS since the physical dimensions cannot meet the theoretical definitions of slotline [19]. To investigate the mechanism of the proposed structure, the EM simulator IE3D, design tool ADS, and conventional PCB fabrication technology with dielectric substrate RO4003C (i.e., εr = 3.55, h1 = 0.203 mm, and h2 = 0.303 mm) are used.

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A. Schematic Analysis of Harmonic-Controlled Resonator

Fig. 2(a) shows a conventional capacitor-loaded half-wavelength tunable resonator. Then, the input-impedance of this resonator (i.e., \( Z_1 \)) is derived as

\[
Z_1 = \frac{Z_0(1 - \omega C Z_0 \tan \theta_a)}{j(\omega C Z_0 + \tan \theta_a) + j\omega C Z_0(1 - \omega C Z_0 \tan \theta_a)}. \tag{1}
\]

The input-impedance of the resonator \((Z_a = 50 \text{ } \Omega \text{ and } \theta_a = 180^\circ \text{ at } 2 \text{ } \text{GHz})\) under different capacitance is depicted in Fig. 2(b). Fig. 2(c) depicts the fundamental resonant frequency (i.e., \( f_0 \)), first harmonic resonant frequency (i.e., \( f_1 \)), and \( f_1/f_0 \) of the resonators. With the increase of capacitance, both \( f_0 \) and \( f_1 \) decrease rapidly. Though \( f_1/f_0 \) increases slightly due to the slow-wave effect, such resonator is not easy to achieve wide stopband. Fig. 2(d) shows a harmonic-controlled resonator with cascaded tuning capacitor. Then, the input-impedance of this resonator (i.e., \( Z_2 \)) is derived as

\[
Z_2 = \frac{j\omega L(\tan \theta_a + \omega C Z_a)}{(1 - \omega^2 LC)\tan \theta_a + \omega C Z_a}. \tag{2}
\]

The resonant frequency can be obtained under the case of \(|Z_2| = \infty\), which is equivalent to

\[
(1 - \omega^2 LC)\tan \theta_a + \omega C Z_a = 0. \tag{3}
\]

When the resonator operates at higher frequency (i.e., \( \omega^2 LC \gg 1 \)), (3) can approximate to

\[
\omega C Z_a - \omega^2 LC \tan \theta_a = 0. \tag{4}
\]

Here, the solution of (4) is not affected by \( C \). Thus, the resonances at higher frequency are almost unaffected by the cascaded capacitor. When the resonator operates at lower frequency, \( 1 - \omega^2 LC \) cannot approximate to \(-\omega^2 LC\). According to (3), the resonance at lower frequency can be affected by the cascaded capacitor. To verify the principle, the input-impedance of the resonator \((Z_a = 35 \Omega \text{ and } \theta_a = 90^\circ \text{ at } 4.5 \text{ } \text{GHz}, L = 6 \text{ } \text{nH})\) under different capacitance is depicted in Fig. 2(e). Fig. 2(f) depicts \( f_0, f_1, \) and \( f_1/f_0 \). The fundamental resonance (i.e., \( f_0 \)) can be tuned by the cascaded capacitor. Meanwhile, the first harmonic (i.e., \( f_1 \)) is controlled at higher frequency, which is almost unaffected by the cascaded capacitor. Thus, a large ratio of \( f_1/f_0 \) and a wide stopband can be achieved under all tuning cases. Compared to the traditional capacitor-loaded resonator, the harmonic-controlled resonator with cascaded tuning capacitor is more convenient to achieve wide stopband.

To further investigate the characteristic of the stopband bandwidth and the tuning range of the proposed harmonic-controlled resonator, \( f_0, f_1, \) and \( f_1/f_0 \) under different inductance and characteristic impedance of transmission line are presented in Fig. 3(a) and (b). The increasing inductance and decreasing characteristic impedance are beneficial to achieve higher \( f_1/f_0 \) and wider stopband. Meanwhile, \( f_1/f_0 \) under \( C = 5 \text{ } \text{pF} \) and tuning ratio (i.e., \( f_{0U}/f_{0L} \)), where \( f_{0U} \) is the resonant frequency under \( C = 0.8 \text{ } \text{pF} \) and \( f_{0L} \) is the resonant frequency under \( C = 5 \text{ } \text{pF} \) with the variation of \( L \) and \( Z_a \) are depicted in
Fig. 4. (a) Layer diagram. (b) 3-D view. (c) Implementation of transmission line using SIDGS. (d) Implementation of inductor using SIDGS.

Fig. 3(c) and (d). The tuning ratio is not affected by $L$, while $f_1/f_0$ and tuning ratio increase with the decrease of $Z_a$.

B. Implementation of Harmonic-Controlled Resonator

The proposed harmonic-controlled resonator is composed of an inductor, transmission lines, and a tuning capacitor. The reasons for choosing SIDGS to implement the proposed resonator are as follows: 1) In this resonator, higher inductance of the inductor and lower characteristic impedance of the transmission line are profitable to achieve wider stopband, as shown in Fig. 3(a) and (b). Transmission line with lower characteristic impedance can be easily achieved by SIDGS, since the parasitic capacitance of the DGS-based transmission line can be increased by metal-vias and surrounding ground of SIDGS [17]. Meanwhile, quasi-inductors with high inductance can be achieved by properly using the impedance discontinuity of the DGS [19]. 2) Self-packaged SIDGS can reduce the radiation loss in passband and stopband [17]. Based on the above reasons, SIDGS is more suitable to implement the proposed harmonic-controlled resonator with a wider stopband.

Fig. 4(a) and (b) exhibit the layer diagram and 3-D view of the proposed harmonic-controlled SIDGS resonator. Fig. 4(c) and (d) depict the implementation of transmission line and inductor using SIDGS. Compared to the model in Fig. 2(d), the folded structure of SIDGS in the implementation is used for compact size. The inductors are mainly caused by the impedance discontinuity of DGS [19]. Then, to form a tunable resonator, a tuning capacitor connects the inductor to the transmission line, as shown in Fig. 5(a). Fig. 5(b) illustrates the equivalent circuit. The calculated and simulated input-impedance (i.e., $Z_A$) with ideal capacitor under different capacitance are shown in Fig. 5(c). Compared to the calculated input-impedance of ideal harmonic-controlled resonator in Fig. 2(f), the tunable SIDGS resonator exhibits an agreement in harmonic-controlled characteristic and wide stopband. Fig. 5(d) exhibits simulated input-impedance of the proposed SIDGS resonator using practical varactor (i.e., SMV1233 with adjustable capacitance range of about 0.8–5 pF in the variable voltage of 0–15 V). The difference between Fig. 5(c) and (d) is mainly caused by the parasitic inductor from the package and the resistance of varactor diodes. The parasitic inductors of the varactor can slightly decrease $f_0$ and $f_1$, while the harmonic-controlled characteristic remains well. Limited by fabrication requirement and capacitance of the varactor, the maximum value of $f_1/f_0$ in this design is 6.

C. Filter Design

Two identical tunable harmonic-controlled SIDGS resonators are utilized to a two-order tunable filter. Fig. 6 shows the configuration and the coupling scheme of the tunable filter. $C_1$ and $C_2$ are connected to SIDGS resonators through the metal-pad and blind-vias. The physical size of the SIDGS resonator is optimized after the implementation of metal-pads and blind-vias. The source-load coupling is introduced by the feed-line to generate two transmission zeros. Then, the coupling coefficient $k_{12}$ of two resonator can be extracted from...
Fig. 7. (a) Effects of the dimension $w_t$ and capacitance $C_1$ on the coupling coefficients $k_{12}$. (b) Effects of the capacitances $C_1$ and $C_2$ on the external quality factor $Q_e$. 

![Image](image.png)

Fig. 8. Simulated results of the developed tunable filter prototype. Bias voltage variation: $V_1 = 0 \sim 15$ V and $V_2 = 2.3 \sim 8$ V. 

![Image](image.png)

Fig. 9. Photograph of the proposed tunable filter. (a) Top view. (b) Bottom view. ($l_1 = 6.33, l_2 = 3.91, l_3 = 1.11, l_4 = 3.62, l_5 = 2.43, l_6 = 0.88, w_1 = 0.1, w_2 = 0.1, w_3 = 0.1, w_4 = 0.1, w_5 = 0.11, w_6 = 0.5, w_7 = 0.1, and w_8 = 0.1. unit: mm). 

![Image](image.png)

Fig. 10. Measured results of the developed tunable filter prototype. Bias voltage variation: $V_1 = 0 \sim 15$ V and $V_2 = 2.3 \sim 8$ V. 

![Image](image.png)

III. Fabrication and Experimental Result

To verify aforementioned principle, a tunable BPF using harmonic-controlled SIDGS resonators is designed and fabricated. The photograph of the fabricated tunable BPF is shown in Fig. 9. Fig. 10 depicts the measured results of the fabricated BPF. The passband frequency can be tuned from 1.75 to 2.7 GHz with 3-dB FBW of 27.8% to 29.6% (Bias voltage variation: $V_1 = 0 \sim 15$ V and $V_2 = 2.3 \sim 8$ V). The return loss is better than 20 dB for the entire tuning range of the passband. The insertion loss varies from 1.1 to 1.9 dB. The stopband is better than 20 dB up to 9.5 GHz. Mean-while, tunable capacitor $C_2$ is used to remain a suitable external quality factor under different loading capacitance $C_1$ and different $w_t$. Meanwhile, tunable capacitor $C_2$ is used to remain a suitable external quality factor under different $C_1$. The external quality factor $Q_e$ can be extracted from simulation [2]. Fig. 7(b) illustrates the external quality factor $Q_e$ under different cascaded capacitance $C_1$ and feeding capacitance $C_2$. $Q_e$ increases with the increase of $C_1$ while $Q_e$ decreases with the increase of $C_2$. By tuning $C_2$, suitable $Q_e$ can be found, when the resonator operating at different frequencies. In the practical application, $C_1$ and $C_2$ are realized by varactor (i.e., SMV1233). $C_{dc}$ acts as dc-block, which is chosen as GRM155R series capacitors from Murata (i.e., $2.2 \mu$F). $R_{RF}$ is set as RF-choke using resistor from Murata (i.e., 20 k$\Omega$). The tunable BPF is implemented with specifications as follows: center frequency from 1.7 to 2.7 GHz and 3-dB FBW about 28%. Fig. 8 depicts the simulated results of the proposed BPF with models of the varactors and capacitors under different bias voltages. Note that the source-load coupling in Fig. 6(c) can only generate one TZ at upper stopband. Additional TZs at upper stopband are mainly caused by the parasitic inductor of practical varactor. Meanwhile, the harmonic-controlled characteristic remains well and wide stopband is achieved under all tuning cases.

![Image](image.png)
In this brief, a harmonic-controlled SIDGS resonator with cascaded tuning capacitor is proposed. Such type of resonator exhibits a strong harmonic-controlled characteristic, which shows wide stopband for all tuning cases. Based on the proposed resonator, a tunable filter is designed, fabricated, and measured. The design prototype shows the merits of wide stopband, low insertion loss, low return loss, and compact size. With such good performances, the proposed tunable BPF is attractive for reconfigurable multi-standard communication circuits and systems with wideband spurious suppression.

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