Novel Dual-band Bandpass-to-Bandstop Filter Using Shunt PIN Switches Loaded on the Transmission Line

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Abstract—A novel method to design the bandpass-to-bandstop (BP-to-BS) filter is presented in this paper. This method demonstrates that using shunt switches to select bandpass or bandstop mode does not deteriorate the passband insertion loss (IL) in the bandstop mode. On the basis of this mechanism, a dual-band BP-to-BS filter was designed, fabricated and measured. The filter consists of two pairs of stepped impedance resonators with mixed electric and magnetic coupling, resulting in dual bands for each filter configuration. In the bandpass mode, five transmission zeros (TZs) are generated which substantially enhances the filter selectivity. The generation of these TZs is carefully studied. Their positions could be easily controlled by changing the coupling magnitude. In the bandstop mode, the filter also demonstrates high selectivity with five transmission poles. Large in-band rejection and low passband IL are achieved simultaneously. The in-band rejection is beyond 30dB and 40dB for the first and second stopband, respectively. As for passband IL, the measured minimum passband IL is 0.34 dB. The measured and simulated results are in good agreement for both the bandpass and bandstop modes, achieving excellent dual-band reconfigurable filtering performance.

Keywords—Dual-band BP-to-BS filter, mixed electric and magnetic coupling, shunt switches, transmission zeros.

I. INTRODUCTION

Reconfigurable filters have drawn significant attention with the unprecedented growth of wireless communication, which are considered as an efficient way to solve the problem of spectrum scarcity, meeting the strong demand of higher communication rate and capacity [1]. Many studies focus on reconfigurable filters with tunable frequency, bandwidth and transmission zeros [2-4]. Another form of reconfigurability is the ability to switch the filter to the bandstop (BP-to-BS), which is highly desirable in the dynamic interference environment [5].

Several studies have been proposed to design single-band BP-to-BS filters [5–7]. A BP-to-BS filter with frequency and bandwidth control is presented in [5], but its selectivity is not high. In [6], dual-mode resonators with T-type inductive coupling are applied to achieve BP-to-BS reconfigurability. The filter shows a high selectivity in the bandpass mode, but a flat roll-off at lower sideband for the bandstop mode. In [7], a double-layer coupling topology based on substrate integrated evanescent mode cavity-resonators is adopted to design high performance BP-to-BS filter. However, it is very complicated to fabricate, and limited to a single band operation only.

As for dual-band BP-to-BS filters, there are only a few studies focusing on this topic [8]-[10]. The first dual-band BP-to-BS filter is reported in [8]. RF-MEMS switches are used in the design to select bandpass or bandstop mode. Following this study, literature [9] adopts the same method to switch between the bandpass and bandstop modes, achieving a dual-band BP-to-BS filter with tunable frequency. However, this filter shows large passband insertion loss (IL) in the bandstop mode due to the poor return loss. In [10], a new class of dual-band BP-to-BS filters are reported and validated. This filter shows good performance with high selectivity in both the bandpass and bandstop modes. It also has the capability to adjust its center frequency independently using the mechanically adjustable trimmer capacitors.

To the best of author’s knowledge, almost all of the reported BP-to-BS filters, whether single-band or dual-band, adopt series switches in the main transmission line (TL) to select bandpass or bandstop mode. Different from this universal method, this paper proposes a novel method to change the operation mode: by paralleling the grounded (shunt) switches to the TL. It exhibits two obvious benefits including: 1) significantly reducing the passband IL introduced by switches in the bandstop mode; 2) generating an extra transmission zero (TZ) at lower band for the bandmode. To validate the proposed method, a dual-band BP-to-BS filter was designed, fabricated and measured. Two pairs of stepped impedance resonators (SIRs) with different electrical length are used to form two frequency bands. By introducing the mixed electric and magnetic coupling between the SIRs, multiple TZs are generated in the bandpass mode, forming two highly selective passbands. There are also multiple transmission poles (TPs) for the bandstop mode, with very large in-band rejection for this 2nd order filter.

The organization of the rest of this paper is summarized as follows: Section II compares the transfer responses of a TL by using a series switch and a shunt switch respectively. Section III illustrates the design and analysis of the proposed dual-band BP-to-BS filter. Section IV presents the measured and simulated results of the filter. Finally, Section IV draws the main contributions and conclusions of this work.

II. COMPARISON OF SHUNT SWITCHES WITH SERIES SWITCHES

Employing series switches is the universal scheme to change operation mode between bandpass and bandstop responses. Taking a simple example, Fig. 1(a) shows the transmission line loaded with a series switch. In the bandpass mode of a BP-to-BS filter, the switch should be disconnected, which is equivalent to a capacitor because of its parasitic capacitance. Fig. 1(b) depicts the transfer responses of the transmission line under different capacitance. It can be seen that smaller capacitance would result in less energy being transmitted from Port 1 to Port 2.

Relating to duality principle in electromagnetic theory, it is possible to select bandpass or bandstop mode if the switch is...
connected in parallel with the TL, which is shown in Fig. 1(d). Reversely, in the bandpass mode of a BP-to-BS filter, the switch should be switched on, which is equivalent to an inductor because of the parasitic inductance. Various transfer responses under different inductance are plotted in Fig. 1(f), exhibiting the same frequency responses as the series switch. Similarly, it also can be seen that the smaller the inductance is, the less energy is transmitted to Port 2.

According to the comparison, it can be inferred that both series and shunt switches are able to select the through or isolation mode of a TL. Therefore, it is also possible for shunt switches to design BP-to-BS filters. An important advantage of shunt switches is that they do not cause obvious IL in the transmission line. Despite such superiority, there is also a shortcoming that cannot be ignored. Generally, switches, especially PIN switches, have relatively large parasitic inductance. Therefore, they are not suitable for the design of BP-to-BS filters at high frequencies. For example, the switches used in this paper are SMP1320-079LF PIN diodes from Skyworks, of which the parasitic inductance is 0.7 nH. The frequency range of the proposed filter is 0.5-4.2 GHz.

III. FILTER DESIGN AND ANALYSIS

A. Filter Configuration

Fig. 2(a) shows the layout of the proposed filter, consisting of two pairs of SIRs with mixed electric and magnetic coupling. These SIRs are directly connected to the main TL, and the connection points are about one quarter wavelength apart. Four PIN diode switches are in parallel connected to the main TL, which are used to select bandpass or bandstop operation mode. It is noted that the TL near D2 and D3 becomes narrow, which is for better impedance matching of the TL in the bandstop mode. At this stage, four diodes are off and their parasitic capacitance is parallel connected leading to strong effects on the TL. Similarly, it also can be seen that the smaller the inductance is, the less energy is transmitted to Port 2.

Fig. 2. (a) Configuration of the proposed dual-band bandpass-to-bandstop filter. (b) Coupling topology of the filter. (c) Equivalent circuits of the SMP1320-079LF PIN diode in through and isolation mode respectively.
Fig. 2 (b) depicts the coupling topologies of the proposed dual-band BP-to-BS filter in the bandpass and bandstop modes, respectively. Two frequency bands are generated by two pairs of resonators with mixed electric and magnetic coupling. Two resonant nodes are about one quarter wavelength apart.

The working principle of the dual-band BP-to-BS can be described as follows. In bandpass mode, diodes D1-D4 are in through (on) modes, and diodes D5-D6 are in isolation (off) modes. The electromagnetic signal is coupled through two pairs of quarter wavelength SIRs, resulting in dual passbands. While in the bandstop mode, reversely, diodes D1-D4 are in isolation (off) modes, and diodes D5-D6 are in through (on) modes. The main TL is working by default and the two isolation bars prevent the coupling between the resonators under this condition. The SIRs are working as shunt resonators which provide transmission nulls only. As a result, the filter is transformed to the bandstop configuration with dual-band response and high in-band rejection.

B. Analysis of Bandpass Mode

It is well known that mixed inter-resonator coupling is one of the prevalent mechanisms to obtain finite TZs. According to [11], there are one lower side TZ for electric-dominant mixed coupling, and two TZs in the upper stopband for magnetic-dominant case. On the basis of this mechanism, two pairs of mixed coupled SIRs are used to design dual-band bandpass filter with high selectivity in this paper. As shown in Fig. 2(a), the open end of the coupled lines is responsible for electric coupling, while the other end contributes to the magnetic coupling. The coupling strength can be controlled by the gaps of the coupled lines. The narrower gaps generate stronger coupling. External quality factors of the input and output can be determined by the distance from the diodes (D1 and D2) to connection parts that link the SIRs and the TL.

In the bandpass mode, diodes D1-D4 are in through (on) modes, and diodes D5-D6 are in isolation (off) modes. The main TL is grounded without signal going through. As shown in Fig. 3, the filter exhibits high selectivity with five TZs. For TZ1, it is generated by the parallel resonance, which is contributed by the parasitic inductance of diodes and shunt capacitance of TL. It leads to an unexpected and nice effect since this parallel resonance moves the TZ from DC to a finite frequency, at which the position of this TZ is fixed and not easy to change. TZ2 - TZ5 are created by mixed electric and magnetic coupling, and they are controllable under different coupling strength. As is shown in Fig. 3, by increasing the gap g, which reduces the electric coupling, TZ2 and TZ3 experience the process from hiding to appearing, then to further splitting from each other. Similar phenomenon for TZ4 and TZ5 can be observed when changing the electric coupling between the other pair of SIRs. However, it also has slight effects on the positions of TZ2 and TZ3 simultaneously.

C. Analysis of Bandstop Mode

In the bandstop mode, diodes D1-D4 are in isolation (off) modes, and diodes D5-D6 are in through (on) modes. The key point of the design is to prevent inter couplings between the resonators, otherwise is may cause adverse impact on the bandstop performance. That is why isolation bars are placed between resonators. The grounded isolation bars can conduct electric signals to GND, thus prevent the coupling between the resonators. Fig. 4 shows the transfer responses of the first stopband under different isolation bar length L1. It is can observed that TZ2 is gradually moving away from TZ1 with the reduction of isolation bar’s length, resulting in increased bandwidth and declined in-band rejection. It is also noted that the inherent loss for diodes D1 to D4 would not contribute the passband IL since they are in off status, and the loss from diodes D5 and D6 would only reflect in the stopband which adds the rejection.

IV. EXPERIMENTAL RESULTS

To validate the design, the proposed dual-band BP-to-BS filter was fabricated and measured with a VNA. Fig. 5 shows the photograph of the manufactured filter prototype. It was fabricated on a Rogers 5880 substrate with the following parameters: relative permittivity 2.2, dielectric thickness 0.508mm, and loss tangent 0.0009. Two DC blocking capacitors of 56 pF are added at the input and output of the filter to prevent DC leakage. Three 370 nH inductors are etched which act as RF chokes to avoid RF signals being leaked into the DC network, and three resistors of 470 Ω are used in the DC network to limit the current. The size of the filter is 27.2×40 mm², about 0.15λg×0.22λg, where λg is guided wavelength at the center frequency of the lower passband.

Figs. 6 and 7 show the measured and simulated results in bandpass and bandstop modes respectively. In bandpass mode, the bias voltages of the diodes are as following: V1=18.4 V, V2～30.6 V. Diodes D1-D4 are in through states and diodes D5-D6 are in isolation states under this scenario. As it can be observed that the measured results and simulated results exhibit consistent frequency responses, agreeing with each
Fig. 5. Photograph of the manufactured dual-band BP-to-BS filter prototype.

Fig. 6. The measured and simulated S-parameters in the bandpass mode. (Measurement condition: V1 = 18.4 V, V2 = 30.6 V)

Fig. 7. The measured and simulated S-parameters in the bandstop mode. (Measurement condition: V1 = -30.6 V, V2 = 8.4 V)

other very well. Five transmission zeros can be detected at the corresponding positions as we expected. The measured center frequencies of the two passbands are at 1.2 GHz and 2.31 GHz respectively. The measured minimum insertion loss is 2.57 dB for the first passband, and 2.46 dB for the second passband.

In the bandstop mode, diodes D1-D4 are in isolation states and diodes D5-D6 are in through states, and the bias voltages are V1 = -30.6 V, V2 = 8.4 V respectively. As is seen in Fig. 7, the measured and simulated bandstop responses are in good agreement. The in-band rejection of the first stopband is beyond 30 dB, and the second stopband has a rejection around 40 dB. As for passband insertion loss, the measured minimum passband IL is 0.34 dB, which is much smaller than that of other reported works utilizing series switches (Table 1).

V. CONCLUSION

This paper demonstrates a new design method for BP-to-BS filter by using shunt switches loaded to the TL. A significant advantage to use shunt switches is that they do not cause extra passband IL in the bandstop mode. In addition, due to the parasitic inductance of the shunt diodes, an extra TZ is created at the lower band for the bandpass mode. To verify this method, a dual-band BP-to-BS filter with mixed electric and magnetic coupling is proposed and presented. The proposed filter shows excellent performance either in the bandpass mode or bandstop mode. In the bandpass mode, the filter exhibits the high selectivity with five transmission zeros. In the bandstop mode, large in-band rejection and low passband IL have been achieved. High selectivity has also been realized in this operation mode.

REFERENCES


