Reconfigurable Bandwidth Bandpass Filter With Enhanced Out-of-Band Rejection Using π-Section-Loaded Ring Resonator

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Reconfigurable Bandwidth Bandpass Filter Using π-Section-Loaded Ring Resonator with Enhanced out-of-band Rejection

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***Abstract*—A novel ring resonator bandpass filter (BPF) with reconfigurable bandwidth with central frequency at 2.4 GHz is demonstrated. Theoretical analysis for computing the resonant frequencies is shown, and the design approach of implementing π-section stubs connected to the ring to obtain the bandwidth reconfigurability is explained. The use of reconfigurable π-section allows the alteration of the stub's effective width and therefore the filter's bandwidth reconfigurability. PIN diodes are used as switching elements to achieve the narrowband and wideband response. Coupled line sections are used for suppressing the higher modes by generating out-of-band transmission zeros, resulting in a significantly enhanced out-of-band rejection. Measurements indicate that the 3 dB fractional bandwidth (FBW) can be switched from 58.5 % to 75% at a fixed center frequency of 2.4 GHz with an insertion loss (IL) better than 1.1 dB. Moreover the -20 dB stopband performance is extended to 2.7f$_0$.**

***Index Terms*—Bandpass filter (BPF), PIN diode, ring resonator, switchable bandwidth, reconfigurable bandwidth.**

I. INTRODUCTION

RECENTLY switchable and reconfigurable/tunable bandpass filters (BPFs) have been an important research topic since they are one of the key components in the development of cognitive RF/Microwave systems. Reconfigurable filters are supposed to have agile characteristics while maintaining the commonly desired filter characteristics, like, low IL, sharp rejection and good matching with cascaded devices. Earlier work on reconfigurable filters, concentrated in controlling the center frequency by adjusting the electrical lengths of the resonators in either a continuous way where varactors are employed [1] or in discrete steps with the use of PIN diodes [2], [3]. In contrast to controlling the center frequency there have not been many attempts in tuning the passband width. This is largely due to the fact that, only a limited number of adequate methods to vary the inter-resonator coupling exist, which is necessary for bandwidth control. Some papers address this issue by focusing in tuning the bandwidth while keeping the center frequency fixed [4], [5], [6] while some others give attention in controlling the center frequency as well as the bandwidth simultaneously [7]. Moreover, on a careful examination in literature most published methods only apply for narrowband filters which is in contrast with the increasing demand for tunable wideband filters. This paper investigates a new approach to realize a wideband filter with reconfigurable bandwidth.

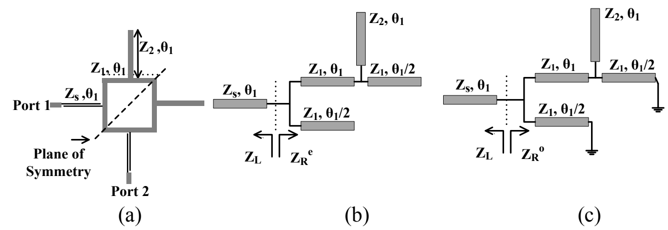

Fig. 1. (a) Initial filter design, (b) Even-mode equivalent circuit, (c) Odd-mode equivalent circuit.

This approach is based on the ring resonator loaded with two π-sections which effectively operate as open stubs, in order to implement bandwidth reconfigurability for the proposed BPF. The passband bandwidth of the filter is dictated by the characteristic impedance of the open stubs and the use of the π-section stubs allows the effective change of the characteristic impedance by physically changing the width of the equivalent open stubs. With the center frequency fixed, the resonator exhibits four or six transmission poles for narrowband and wideband response respectively. The proposed filter has low IL of 1.1 dB, very sharp roll-off characteristics and excellent out-of-band performance 2.7f$_o$.

II. FILTER DESIGN

Fig. 1(a) shows the initial configuration of a stub-loaded ring resonator driven by two $\lambda_g/4$ coupled transmission line sections of characteristic impedance Z_S at the two ports. The two transmission lines are connected in orthogonal configuration i.e. at the center of the bottom and left sides of the ring. The ring is loaded with a pair of $\lambda_g/4$ open stubs of electrical length θ_1 and characteristic impedance Z_2 which are connected at the center of the right and top sides of the ring. The square ring has perimeter equal to one guided wavelength (λ_g) and characteristic impedance Z_1. The electrical length of one quarter of the ring is also θ_1.

The circuit in Fig. 1(a) is symmetrical and can be separated using the diagonal line as the plane of symmetry into an open circuit or a short circuit to form the even- and odd-mode equivalent circuit respectively. The even-mode equivalent circuit is displayed in Fig. 1(b) and the odd-mode equivalent circuit is displayed in Fig. 1(c). The even- and odd-mode resonant frequencies can then be computed and analysed using the even- and odd-mode equivalent circuits if they satisfy [6],

$$Z_L + Z_R^e = 0 \quad (1)$$

$$Z_L + Z_R^o = 0 \quad (2)$$

Where

$$Z_L = -jZ_S \cot\theta_1 \quad (3)$$

$$Z_R^e = -j\frac{-m^5 + m^3(4K+4) - 3m}{m^4(2K+4) - m^2(6K+8) + 4} \quad (4)$$

$$Z_R^o = j\frac{3m^4 - m^2(4K+4) + 1}{-4m^5 + m^3(6K+8) - m(2K+4)} \quad (5)$$

The even-mode resonance occurs via substituting (3) and (4) into (1). As a result,

$$-4K'm^6 + m^4(6KK' + 12K' + 6) - m^2(8KK' + 12K' + 8K + 8) + 2KK' + 4K' + 2 = 0 \quad (6)$$

On the other hand, the odd-mode resonance occurs via substituting (3) and (5) into (2). As a result,

$$-m^6(2KK' + 4K' + 2) + m^4(8KK' + 12K' + 8K + 8) - m^2(6KK' + 12K' + 6) + 4K' = 0 \quad (7)$$

where, $K = Z_1/Z_2, K' = Z_S/Z_1, m = \tan(\theta_1/2)$

Fig. 2 displays simulated results of the ring resonator of Fig. 1 under weak and strong coupling and also shows the frequency response of the coupled lines alone. In weak coupling two transmission zeros are observed and six resonances which are combined to realize a sextuple-mode ring resonator. The two transmission zeros (f_{zc1} and f_{zc2}) caused by the coupled lines whose length is $\lambda_g/4$ are approximately at 0 and 4.9 GHz. Furthermore an extra resonance is observed very close to f_{zc2} and is considered to be the first harmonic. By adjusting the length of the coupled line sections f_{zc2} can be shifted and used to suppress this harmonic frequency which is approximately at 4.5 GHz [9].

Fig. 3 plots the first three even-mode resonant frequencies (f_e'), the first three odd-mode resonant frequencies (f_o'), and the first two transmission zeros (f_z) against K under three different values of K' such as 1.8, 2.4 and 3. The lower and upper transmission poles are due to the presence of the coupled line sections at the input/output. The electrical length of the open stubs θ_1 is kept constant at $\lambda_g/4$. The passband bandwidth can be considered as f_{e3}-f_{o1} for the desired center frequency of 2.4 GHz. It can be seen that f_{o1}', f_{e1}', and f_{z1} progressively shift to lower frequencies whereas f_{o3}', f_{e3}', and f_{z2} move to higher frequencies as K increases for all three values of K'. The middle resonances f_{o2}', f_{e2}' are kept almost constant. Furthermore for low values of K the lower and upper frequencies coalesce, thus reducing the number of resonances in the passband providing a narrowband response with four resonances whereas as K increases to higher values the separation between the lower and upper frequencies also increases. As a result, as K increases a wideband response is observed with six resonances in the passband. More importantly the FBW can be tuned easily with the center frequency remaining at 2.4 GHz by changing the characteristic impedance Z_2 of the open stubs which in turn changes the value of K.

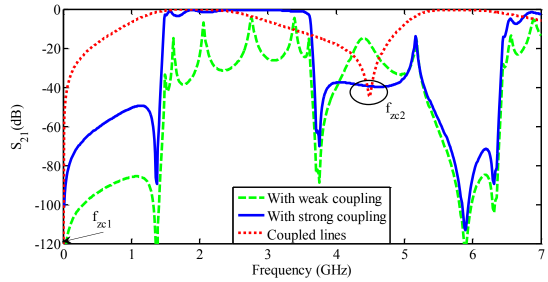

Fig. 2. Simulated S_{21} of coupled lines and ring resonator loaded with open stubs under weak and strong coupling.

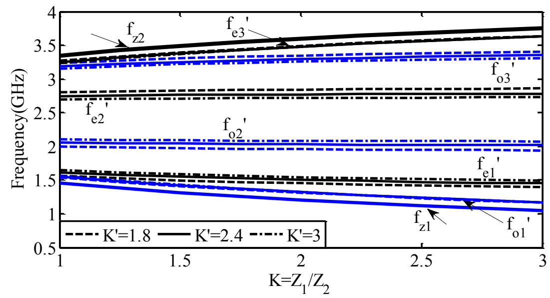

Fig. 3. Even-mode (Black lines) and odd-mode (Blue lines) resonant frequencies for sextuple-mode ring resonator with coupled lines at I/O with different variations of K.

Based on the above discussion, for switching the bandwidth from a narrowband to a wideband state, keeping the center frequency stationary, the characteristic impedance of the open stubs Z_2 needs to be changed from a higher to a lower value respectively. To achieve this width reconfigurability, the open stubs were replaced by π-section as shown in Fig. 4.

III. BPF With Reconfigurable Bandwidth Design

A. Reconfigurable Width Approach

The transformation of standard high impedance (narrower width) to a low impedance stub (wider width) is shown in Fig. 4. A conventional open stub with physical width w_1 can be replaced with a π-section with two legs of width w_2 and separation, 'G', between their inner edges. In both cases the two structures have the same physical and thus electrical length. Simulated results of the two structures connected perpendicularly with a conventional microstrip line as shown in Fig. 4(a) and Fig. 4(b) are shown in Fig. 4(c) from which it can be derived that their effect is almost identical. As a next step, two PIN diodes are incorporated in the π-section and the same simulation is carried out. Full-wave simulations indicate that the π-section with the two diodes in OFF state has the same behavior as a conventional open stub with width w_2, while with the two diodes in ON state th stub's effect is equivalent to the effect of a wider w_1 conventional open stub. The use of the agile π-sections instead of conventional open stubs eventually allows the effective passband bandwidth reconfigurability.

B. Sextuple-mode Ring Resonator BPF with Reconfigurable Bandwidth Using PIN Diodes

Fig. 5(a) shows the proposed BPF using PIN diodes. To switch the filter from a narrowband to a wideband response four PIN diodes (SMP1345-079LF) are employed. The bias

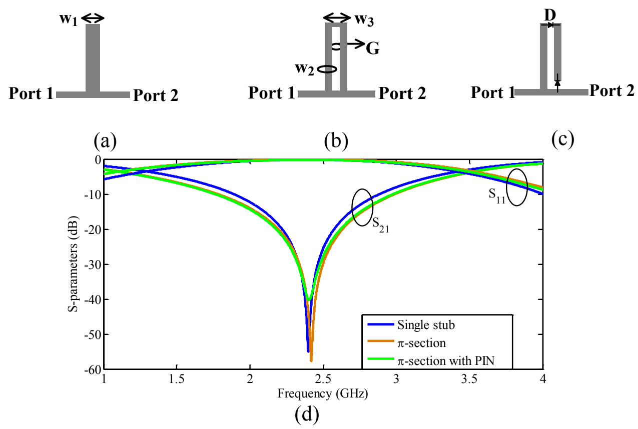

Fig. 4. Transformation of high impedance stub to its equivalent π-section. (a) High impedance open stub, (b) Equivalent π-section, (c) π-section with two PIN diodes,(d) Comparison between single stub equivalent π-section.

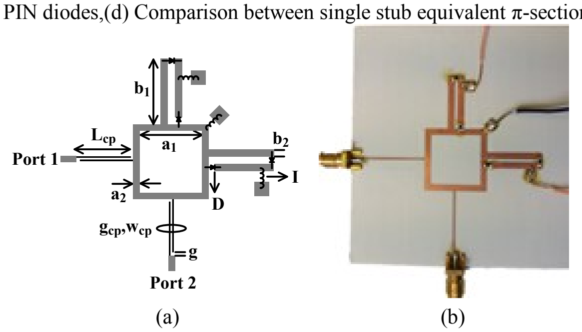

Fig. 5. The proposed reconfigurable bandwidth ring resonator BPF with narrowband and wideband states. (a_1= 20.8 mm, a_2= 1.8 mm, b_1= 17.8 mm,b_2= 2 mm, g= 0.3 mm, L_{cp}= 19.5 mm, g_{cp}= 0.23mm, w_{cp}= 0.23 mm, I= 82 nH,D=Diode), (b) Photograph of the fabricated reconfigurable BPF.

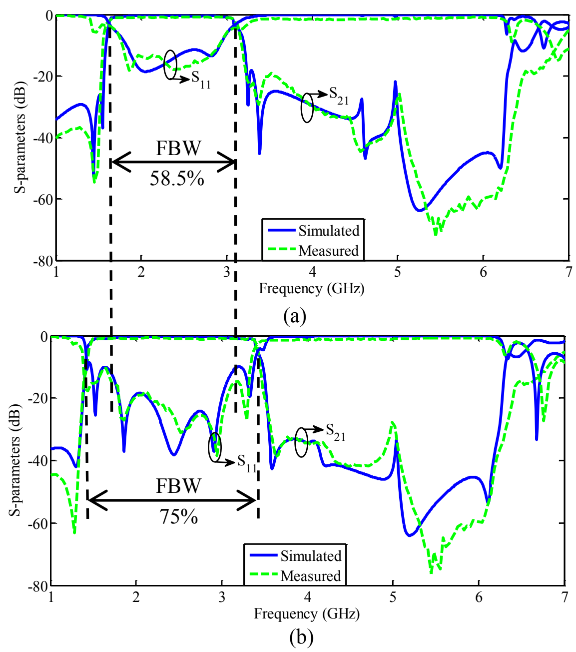

Fig. 6. Simulated and measured results (a) S-parameters in OFF state of the PIN diode, K=1.06 (b) S-parameters in ON state of the PIN diode, K=1.74.

circuitry is simple where three inductors of 82 nH are used as RF Chokes. The PIN diodes are switched ON/OFF to connect or disconnect, respectively the second leg of the π-section with the ring. If a wideband response is selected, all four diodes are forward biased with 5 mA. When the diodes are all in the ON state, two diodes effectively joint the two parallel stubs whereas the other two diodes connect them to the ring. As a result the π-section is formed thus increasing the equivalent open stub's width and decreasing their characteristic impedance. On the other hand, with the four diodes in OFF state, both parallel stubs are disconnected from each other and from the ring, leaving only the initial two $\lambda_g/4$ open stubs connected to the ring, and thus providing a narrowband response.

IV. Experimental Results

The filter is fabricated on a 0.813 mm Roger4003C substrate with $\varepsilon_r = 3.55$ and $tan\delta = 0.0027$. Two $\lambda_g/4$ coupled line sections are employed as feeding lines. Fig. 5(b) shows a photograph of the fabricated circuit. The simulated and measured S-parameters for the narrowband and wideband states are shown in Fig. 6(a) and Fig. 6(b) respectively. For measurements an Agilent E8363 Vector Network Analyzer (VNA), was used.

The size of the circuit is $0.514\lambda_g$ x $0.514\lambda_g$ $=0.264\lambda_g^2$ excluding the feed lines. The narrowband state demonstrates a return loss (RL) >12 dB and an IL <1.1 dB having a 3 dB FBW of 58.5 %. In the wideband response RL >15 dB is achieved from 1.71-3.11 GHz with the measured IL <1.1 dB and a 3 dB FBW of 75%. The RL is higher at the upper and lower passband edges due to the length of coupled lines [6]. The passband ratio between the two responses is 1.28:1, whereas the -20 dB upper-stopband rejection ratio is $2.7f_0$.

V. Conclusion

A novel sextuple-mode ring resonator BPF using π-section and quarter-wavelength coupled feedlines with reconfigurable bandwidth is presented in this letter. The coupled feedlines introduce two out-of-band transmission zeros achieving enhanced stopband and sharper rejection. Four PIN diodes are used as switching elements to connect or disconnect the π-sections on the ring resulting in a narrowband/wideband response accordingly. The measured results show, low IL, sharp roll-off characteristic, excellent stopband performance and a passband switching ratio of 1.28:1.

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