Wide Stopband Planar Microwave Bandpass Filter Design

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***Abstract*— This paper describes a high selectivity microstrip bandpass filter fabricated using microstrip integrated technology with a wide stopband. The proposed filter consists of electromagnetically coupled 50Ω input and output feedlines that are strategically loaded with spiral inductors in order to introduce transmission zeros in the filter's stopband response. Simulation results reveal that the proposed design enables the upper and lower transmission zeros to be adjustable independently by (±16.5%) prior to fabrication. Moreover, the coupling scheme employed allows the filter's centre frequency to be adjusted by 8.69% and 3dB fractional bandwidth by 7.1% with insignificant effect on the stopband characteristics. The measured result confirms the filter exhibits a relatively sharp roll-off skirt with a passband insertion-loss of 1.51 dB and return-loss that is better than 15 dB. The proposed filter is suitable for applications in high interference environments and cognitive radio systems.**

Keywords*— Planar filters, microstrip integrated technology, microwave filters, high selectivity filters, wide out-of-band rejection

I. INTRODUCTION

Rapid development in wireless communication systems such as 5G has increased the demand of microwave bandpass filters possessing stringent characteristics of low passband insertion-loss, sharp roll-off, wide stopband, smaller physical footprint, and ease of fabrication. Such filters with large attenuation in stopband are essential to reject interference signals that can compromise the performance of other systems. Filter designs based on distributed resonators do not behave as their ideal lumped element counterparts since they suffer from a limited unloaded Q-factor and generation of spurious harmonic resonances [1]. Although microwave filters are designed around the fundamental resonance frequency of the resonators, spurious passbands are almost always present at integer multiples of the first passband.

Frequency response of microwave filters based on planar microstrip resonators may be readily altered by introducing various structural changes, for example, by (i) introducing transmission zeros using lumped element bisected-pi sections at the filter input/output [2]; (ii) using dual-band filtering cells that are internally connected at one node of the input/output coupled-line stages to create transmission zeros at both sides of the two dual passbands so that an overall quasi-elliptic type dual band filtering transfer function is realized [3]; (iii) controlling the length and impedance ratios to remove the unwanted responses [4]; (iv) by using slow-wave effect to produce an ultrawide upper stopband [5]; and (v) over coupling the end stages of a parallel-coupled passband filter to suppress unwanted harmonics [6]. Various design methodologies have been adopted in filter designs to suppress unwanted responses to realize a wide stopband including the use of stepped impedance resonators (SIR) [7-10], cross coupling resonators, using the spur-lines, open-stub and split-ring resonators [11-13].

In this article, the design of a highly selective planar bandpass filter is presented that exhibits a wide stopband which is necessary to suppress unwanted interference over approximately two octaves. The filter comprises electromagnetically coupled input and output 50Ω transmission-lines, and the transmission-lines are loaded strategically with spiral inductors to insert transmission zeros in the filter's response in order to realize a wide stopband. The proposed coupling scheme allows the independent adjustment of the transmission zeros prior to fabrication to ensure a wide stopband is realized. It is also shown that the centre frequency and 3-dB fractional bandwidth can be controlled without degrading the passband characteristics. The measured results confirm the proposed bandpass filter design that is manufactured on a lower dielectric substrate exhibits low passband insertion-loss and highly selective characteristics.

II. ANALYSIS OF THE PROPOSED BANDPASS FILTER CONFIGURATION

A. *Theoretical Model of a Transmission-line Loaded with an Inductive Stub*

In a two-way radio communication link, it is undesirable to transmit harmonic signals, as they are likely to interfere with other systems and degrade their performance. These harmonic responses are generated by distributed based bandpass filters. To eradicate these spurious responses, it is necessary to introduce notch bands at frequencies corresponding to the spurious artifacts. Notch band can be created by loading a transmission-line with an inductive stub, as shown in Fig. 1. This structure can be theoretically modelled using ABCD matrix.

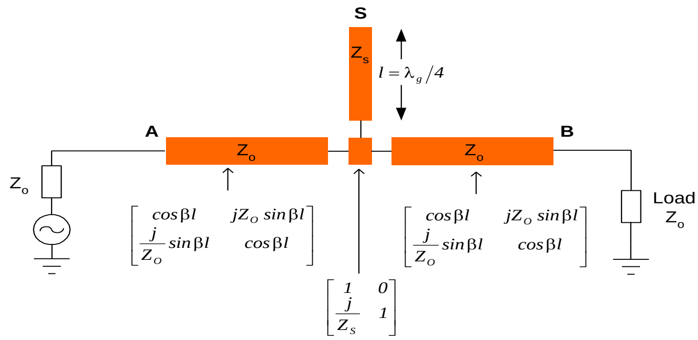


Fig. 1. ABCD matrix representation of a stub loaded transmission-line.

$$Normalized\ ABCD\ matrix = \begin{bmatrix}\bar{A} & \bar{B}\\ \bar{C} & \bar{D}\end{bmatrix} = \begin{bmatrix}cos\beta l & jsin\beta l\\ jsin\beta l & cos\beta l\end{bmatrix}\times\begin{bmatrix}1 & 0\\ \frac{jZ_0}{Z_S} & 1\end{bmatrix}\times\begin{bmatrix}cos\beta l & jsin\beta l\\ jsin\beta l & cos\beta l\end{bmatrix}$$

$$Normalized\ ABCD\ matrix = \begin{bmatrix}cos\beta l - \frac{Z_0}{Z_S}sin\beta l & jsin\beta l\\ jsin\beta l + \frac{Z_0}{Z_S}cos\beta l & cos\beta l\end{bmatrix}\times\begin{bmatrix}cos\beta l & jsin\beta l\\ jsin\beta l & cos\beta l\end{bmatrix}$$

$$= \begin{bmatrix}\cos^2\beta l - \frac{Z_0}{Z_S}sin\beta lcos\beta l - \sin^2\beta l & jsin\beta lcos\beta l - j\frac{Z_0}{Z_S}\sin^2\beta l + jsin\beta lcos\beta l\\ jsin\beta lcos\beta l + j\frac{Z_0}{Z_S}\cos^2\beta l + jsin\beta lcos\beta l & -\sin^2\beta l - \frac{Z_0}{Z_S}sin\beta lcos\beta l - \cos^2\beta l\end{bmatrix} \quad (1)$$

$$\bar{B} = j2sin\beta l.cos\beta l - j\frac{Z_0}{Z_S}\sin^2\beta l$$

$$\bar{C} = j2sin\beta l.cos\beta l + j\frac{Z_0}{Z_S}\cos^2\beta l$$

so $$\bar{B} - \bar{C} = j\frac{Z_0}{Z_S}(\sin^2\beta l + \cos^2\beta l)$$

$$\bar{B} - \bar{C} = -j\frac{Z_0}{Z_S}$$

$$\frac{\bar{B} - \bar{C}}{2} = -j\frac{Z_0}{2Z_S}$$

$$\text{Insertion-loss} = 10log\left|\frac{\bar{A} + \bar{B} + \bar{C} + \bar{D}}{2}\right| \quad (2)$$

For symmetrical, reciprocal, & dissipation less network, the following conditions apply:

A = D
A and D are real
AD – BC = 1

Where B and C are imaginary values, hence by replacing

$$\frac{\bar{B} - \bar{C}}{2} = -j\frac{Z_0}{2Z_S}$$

$$\text{Insertion loss} = 10log\left[1 + \left(\frac{Z_0}{2Z_S}\right)^2\right] \quad (3)$$

This indicates that when Z_S (thinner width) > Z_0 then the insertion-loss →0

B. The Proposed Bandpass Filter Structure

The structure of the proposed microstrip bandpass filter is shown in Fig. 2. It consists of input and output transmission-lines that electromagnetically coupled through high impedance open-circuited stubs that overlap with each other by a certain amount. The transmission-lines are loaded with inductive spirals.

External quality-factor of this structure can be calculated using this equation [14] :

$$Qe = \frac{f_0}{\Delta f_{3-dB}}$$

Where f_0 is the resonant frequency of the resonator, and Δf is the 3-dB fractional bandwidth.

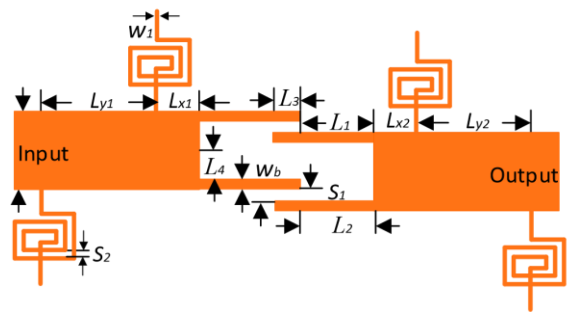


Fig. 2. (a) Proposed bandpass filter structure loaded with inductive lines.

The structure was analyzed using Advance Design System (ADS™) by Keysight Technologies. The simulation analysis revealed that the external quality-factor is influenced by the parameters L_3, L_4 and W_b. Fig. 3 shows the external quality-factor varies from 43 to 27.72 as the coupled resonator length L_3 varies from 2.84 mm to 3.74 mm, while all other parameters were kept fixed.

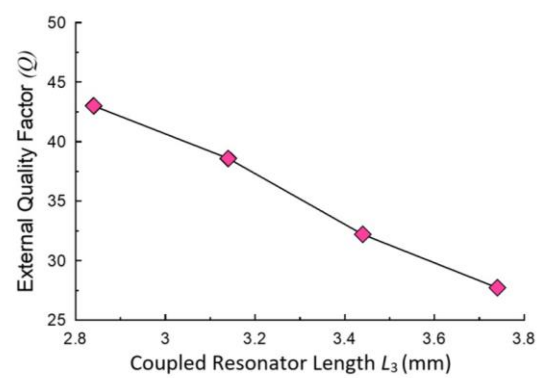


Fig. 3. External quality-factor as a function of length L_3.

The coupling coefficient between the coupled resonators can be calculated using the following equation [15]:

$$K_{ij} = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2}$$

Where Kij represents the coupling between the coupled resonators, and f2 and f1 are the high and low resonant frequencies of the coupled resonator. The coupling coefficient is analyzed by varying the coupling space between the resonators (S1) and the coupled resonator length (L3). Fig. 4 shows as the coupled resonator length L3 is reduced from 2.84 mm to 1.94 mm, the coupling coefficient changes from 0.06 to 0.12, while all other parameters were kept fixed.

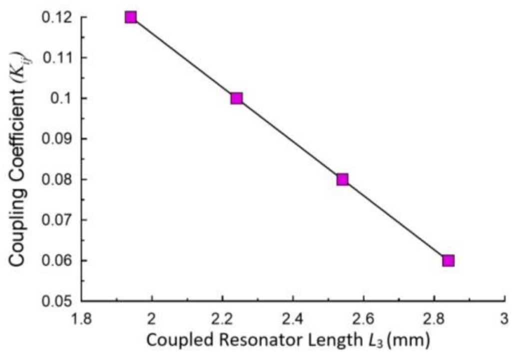
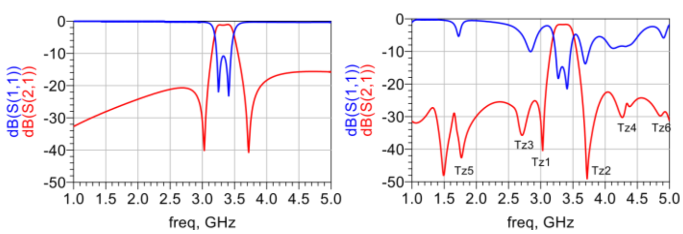


Fig. 4. Coupling coefficient as a function of length L_3.

The simulated frequency response of the filter without spiral inductors in the input/output feedline shows the out-of-band rejection is about 15 dB, as depicted in Fig. 5(a). When the feedlines are loaded with spiral inductors the out-of-band rejection is >22 dB above and below the passband as shown in Fig. 5(b) resulting from addition of transmission zeros. The spiral positions are L_{y1} = 21.38 mm, L_{x1} = 13.37 mm, L_{y2} = 14.78 mm and L_{x2} = 29 mm. The additional transmission zeros suppress the spurious harmonics and enhance the out-of-band rejection level by 22 dB on both sides of the passband.

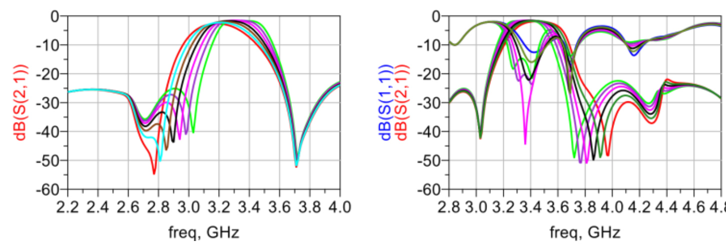


(a) (b)

Fig. 5. Simulated response of the filter (a) without spiral inductors, and (b) with spiral inductors.

Results of the simulation analyses in Fig. 6 and 7 show that the transmission zeros above and below the passband can be controlled independently. Fig. 6(a) shows the transmission zero T_{z1}, annotated in Fig. 5(b), can be adjusted from 3.03 GHz to 2.7 GHz as the resonator length L_1 is varied from 15.26 mm to 17.06 mm. Fig. 6(b) shows the transmission zero T_{z2} can be controlled with resonator length L_2, while all other parameters were kept fixed. It was also observed that the transmission zeros T_{z3}, Tz_4, T_{z5} and T_{z6}, annotated in Fig. 5(b), can be controlled independently with their respective space gap between the spiral inductors with negligible effect on other transmission zeros.

The center frequency can be tuned with resonator length L_4 with negligible effect on the filter's passband shape and overall transmission response, as shown in Fig. 7. The center frequency can be adjusted from 3.35 GHz to 3.07 GHz by changing the resonator length L_4, while all other parameters were kept fixed. It was also observed that the center frequency can be controlled with resonator length L_3 and coupled resonator width W_b, however these parameters can adversely affect the passband shape and out-of-band response of the filter.



(a) (b)

Fig. 6. Simulated results with respect to length (a) L_1, and (b) L_2.

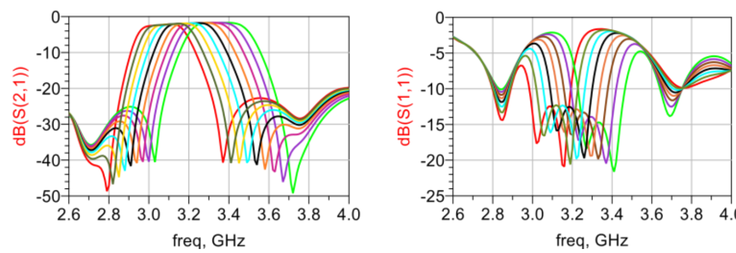
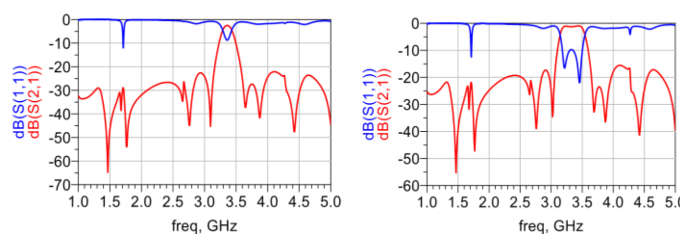


Fig. 7. Frequency response with respect to resonator length L_4.

The filter's bandwidth can be adjusted by varying the inter-resonator coupling gap (S_1), as shown in Fig. 8. The filter's 3-dB fractional bandwidth can be adjusted from 4.4% to 11.5% when the coupling gap is reduced from 1.0 mm to 0.4 mm, while all other parameters were kept fixed, however the corresponding return-loss deteriorates from 15 dB to 9 dB and insertion-loss increases marginally from 1.2 dB to 1.7 dB.



(a) (b)

Fig. 8. Insertion-loss and return-loss response for (a) coupling gap of 1 mm, and (b) coupling gap of 0.4 mm.

III. IMPLEMENTATION AND VERIFICATION OF THE BANDPASS FILTER CHARACTERISTICS

The proposed bandpass filter was fabricated to verify its analytical results. The filter was constructed on a lower dielectric substrate Arlon CuClad217LX with dielectric constant (ε_r) of 2.17, thickness (h) of 0.794 mm, copper conductor thickness (t) of 35 µm, and loss-tangent ($tan\ \delta$) of 0.0009. Fig. 9 shows the photograph of the fabricated filter. The input and output feedlines are loaded with a pair of spiral inductors of width 0.2 mm and gap spacing of 0.6 mm. The physical parameters of the filter were optimized using ADS™ software, which are: W_1 = 0.2 mm, W_2 = 2.42 mm, L_1 = 15.26 mm, L_2 = 11.89 mm, L_3 = 2.84 mm, L_4 = 0.9 mm, S_1 = 0.7 mm, S_2 = 0.6 mm, L_{x1}= 13.37 mm, L_{x2} = 29 mm, L_{y1} = 21.38 mm, L_{y2} = 14.78 mm, and W_b = 0.2 mm. The measured response of the proposed bandpass filter is shown in Fig. 10. The passband insertion-loss at 3.22 GHz is 1.51 dB and the out-of-band rejection is greater than 20 dB. The disparity between the simulated and measured results, shown in Fig. 5(b) and Fig. 10, respectively, is mainly attributed to fabrication tolerances.

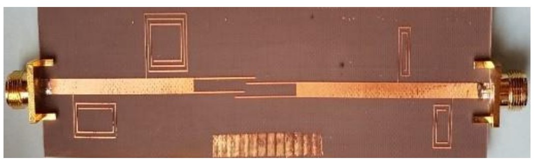


Fig. 9. Photograph of fabricated filter.

The proposed filter configuration has no metallic via-holes and is relatively simple to design and fabricated on a relatively low dielectric substrate using conventional PCB technology. The measured results confirm that the filter has a sharp bandpass response with low and a wide stopband performance.

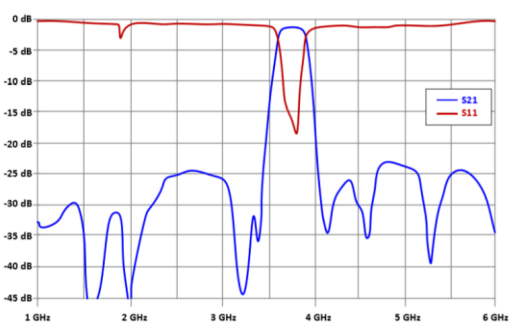


Fig. 10. Measured S-parameter response of the proposed filter with spiral inductors loading the feedlines.

The positions of the spiral inductors are: L_{y1} = 21.38 mm, L_{x1} = 13.37 mm, L_{y2} = 14.78 mm and L_{x2} = 29 mm.

IV. CONCLUSION

The proposed planar microwave bandpass filter is shown to exhibit desirable characteristics of a relatively low passband insertion-loss, high return-loss, sharp roll-off skirts, high selectivity with a wide out-of-band rejection. The filter essentially comprises electromagnetically coupled transmission-lines that are loaded with spiral inductors that introduce transmission zeros to create a wide out-of-band rejection response. These features make the filter applicable in wireless communication systems that operate in highly interfering environments and cognitive radio systems.

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