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Quad Band Filter with Controllable Transmission Zeros using Vertical and Diagonal Coupling of Triple and Dual Step Impedance Resonators

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ABSTRACT

A quad-band pass filter using back-to-back Tri-State Step Impedance Resonator (TSSIR) for Wireless Applications is presented in this article. The achieved passband center frequencies are 2.45 GHz (for WLAN), 3.5 GHz (for WiMAX), 5.4 GHz (for WLAN), and 8.05 GHz (for Satellite Communications). A unique method of simultaneous vertical and diagonal coupling between TSSIR and conventional two-step SIR structures is introduced here to create Transmission Zeros (TZs) in the stop bands of a quad-band filter. The main objective is to produce controllable TZs through shunt capacitive coupling. In the overall filter design, there are a total seven TZs, and the minimum Insertion Losses (ILs) at the mentioned passband center frequencies are found to be −0.4, −0.6, −0.4, and −0.7 dB. The simulation results (using HFSS 13) are in good correlation with the measured prototype (using Arlon AD 250, height 0.76 mm, Dielectric Constant 2.5).

Index Terms—Spurious Passbands, Symmetric and Asymmetric Resonators, Transmission Zero, Mutual Coupling, vertical and diagonal coupling

I. INTRODUCTION

In the view of wireless microwave transceiver design, multiband filters are a very crucial design component. The stop band selectivity, suppression of spurious passbands, good Insertion Loss (IL), and moderate Return Loss (RL) are some covered research topics in the recent past. The approaches to passband characteristic improvement have been well taken care of throughout the years, whereas there are still scope to find some innovative ways to improve stop band issues. Different scientific approaches were presented [1-5] in recent times, which established methods of achieving good stop band performance.

In a true sense, a quasi-elliptic filter always produces better stop-band performance with a sufficient number of TZs in the stop band compared to a Chebyshev filter. The design of a band pass filter with a chained-elliptic function [6], using methods of proximity coupling [7], or with the method of parallel line coupled extended structures [8, 9], is well presented without any compromise to achieve excellent stop band behavior. The in-band performances of all these filters are very good in terms of IL and RL too. In [10], a self-coupled dual-band filter is presented, where three TZs are found between the passbands, but the spurious passbands are found above the −20 dB level, which makes skirt selectivity poorer. With reference to [10] the need for suppression in the stop band is more visible as mentioned in the abstract section. A Step Impedance Resonator (SIR)-based dual passband filter is reported in [11] with excellent passband and stop band performance. A method of generating poles in passbands is employed, which in turn generates TZs in the stop bands. The combination of a Split Ring Resonator and an irregular SIR is employed in [12] to generate a dual-band filter. Both the passbands are separated by a TZ at below the −50 dB level, but the spurious passband beyond the second passband degrades the selectivity. This leads us to the design of large stop bands. The larger the stop bands with suppressed spurious bands, the greater the selectivity will be. A unique method of using a Bridge T coil is employed in [13], which not only ensures the TZs between the passbands but also produces a great degree of size miniaturization. Apart from great passband and stop band performances, size miniaturization helps us to integrate the device into wireless applications. The method of Short Circuit Coupled Lines (SCCLs) is presented in

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[14], which converts the Chebyshev filter structure with poor skirt selectivity into a quasi-elliptic structure by introducing dual TZs between passbands.

The literature survey mentioned above [1-14] establishes the fact of improving stop band performances by properly placing TZs in different innovative ways. In this article, we have designed a quad band filter with back-to-back Tri-Stage Step Impedance Resonator (TSSIR). The passband center frequencies are 2.45, 3.5, 5.4, and 8.05 GHz. The initial filter design creates TZs at 1.4 GHz (before the first passband), 9.8 GHz, and 13.45 GHz (after the fourth passband). Pairs of symmetric and asymmetric structures of Step Impedance Resonators (SIRs), coupled in vertical and diagonal directions around the TSSIR structure, are used to produce additional TZs in between all the passbands. The simultaneous vertical and diagonal coupling is a new concept that can be used by researchers in the near future to achieve controllable TZs. The SIR is used here as a Non-Resonating Node (NRN), which does not contribute to modifying the passbands but instead adds up TZs in the frequency response. The generation of all the TZs is explained through electrical equivalent analysis of the SIRs.

II. THE FILTER DESIGN METHOD

A. The Quad Band Filter

The back-to-back TSSIR structure is presented in Fig. 1a. The Z and θ values are the impedances and electrical lengths of the each sections of TSSIR. The Impedance Ratios (ratio of impedances between consecutive microstrip sections) of the structure are defined as

$$K_1 = \frac{Z_2}{Z_1}, K_2 = \frac{Z_3}{Z_2} \tag{1}$$

By adjusting the values of K_1 and K_2 four resonating modes can be generated using back-to-back TSSIR. The center frequency of each mode can be controlled by adjusting Z_1, Z_2, and Z_3. With the values $K_1 = 1.92$ and $K_2 = 1.6$, the resonant modes are found at 2.45, 3.5, 5.4, and 8.05 GHz. The choice of Z_2 is very important because it changes K_1 and K_2 in opposite directions. Both K_1 and $K_2 > 1$ and hence we have to go for unequal TSSIR sections. If all the sections of TSSIR are equal, i.e., $\theta_1 = \theta_2 = \theta_3 = \theta_0$, the total electrical length of the back-to-back TSSIR structure will be [15, 16],

$$\theta_T = 6\theta_0 = 6tan^{-1}\sqrt{\frac{K_1K_2}{K_1+K_2+1}} \tag{2}$$

On the other hand, when $\theta_1 \neq \theta_2 \neq \theta_3$, the total electrical length of the structure will be [15, 16]

$$\theta_T = 2\left(tan^{-1}\sqrt{K_1} + tan^{-1}\frac{\sqrt{K_1K_2}-1}{\sqrt{K_1}+\sqrt{K_2}} + tan^{-1}\sqrt{K_2} \right) \tag{3}$$

With $K_1 = 1.92$, $K_2 = 1.6$, θ_T from (2) is 237^0, whereas θ_Y from equation (3) is 229^0. Hence, we will go for the unequal length structure of TSSIR. The quad-band filter design parameters and its frequency response are presented in Fig. 1b and 1c. The fourth passband is wide enough compared to the others. The parallel coupled line structure at the input and output port is precisely adjusted to have three TZs [8, 9] at 1.4, 9.4, and 13.4 GHz.

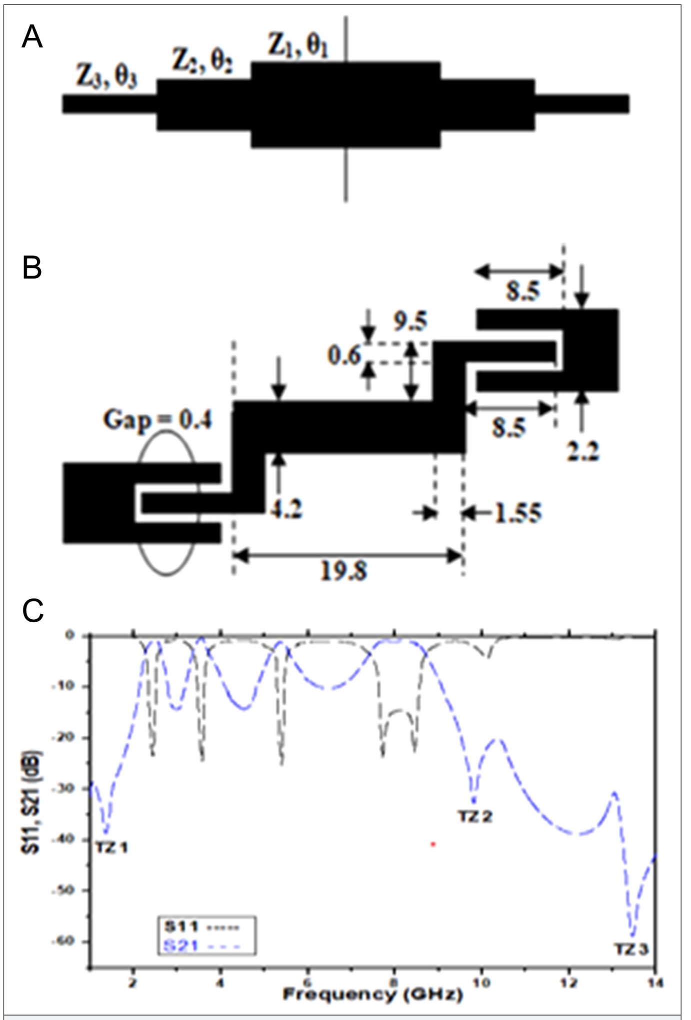

Fig. 1. (a) Back-to-back TSSIR. (b) Proposed quad band filter, dimensions (in mm). (c) Frequency response.

B. Stop Band Transmission Zeros Creation

1) Creation of Transmission Zero

The process of creating Transmission Zeros (TZs) starts with placing two shunt isolated symmetric resonators vertically on both sides of the low impedance section of TSSIR. We used conventional SIR structures which are magnetically coupled with the TSSIR. A pair of shunt SIR structures on the TSSIR can be interpreted by its equivalent LC model as in Fig. 2a.

Two SIRs are purely capacitive, and hence TZs will be contributed by the poles of the modified series reactance of the TSSIR structure. M1 and M2 are the couplings of the SIR with TSSIR, whereas M′ represents the mutual coupling between the SIRs. The resonating frequencies of the two shunt SIRs are $f_1^2 = (1/2\pi L_1C_1)^{-1/2}$ and $f_2^2 = (1/2\pi L_2C_2)^{-1/2}$. The impedance of the TSSIR structure (series branch) is modified by considering the effects of M1, M2, and M′ which is well explained in [17].

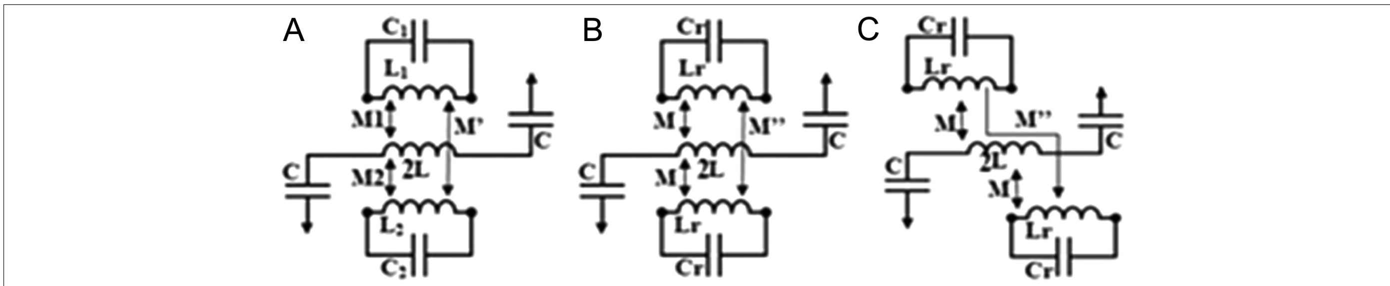

Fig. 2. (a) Circuital presentation of asymmetric vertical coupling. (b) Symmetric vertical. (c) Diagonal coupling.

$$Z(\omega) = j2\pi f\left(2L\right) + j\left(2\pi f\right)\left\{\frac{C_1 M1^2\left(1-\frac{f^2}{f_2^2}\right) + C_2 M2^2\left(1-\frac{f^2}{f_1^2}\right) + 8\pi^2 f^2 M1 M2 M' C_1 C_2}{\left(1-\frac{f^2}{f_1^2}\right)\left(1-\frac{f^2}{f_2^2}\right) - 16\pi^4 f^4 M'^2 C_1 C_2}\right\} \quad (4)$$

By forcing the denominator part to zero, the TZ frequencies are derived as

$$f_{z1},\ f_{z2} = \frac{f_1^2 + f_2^2 \pm \sqrt{\left(f_2^2 - f_1^2\right)^2 + 8\pi^4 M'^2 f_1^4 f_2^4 C_1 C_2}}{\left(1 - M'^2 f_1^2 f_2^2 C_1 C_2\right)} \quad (5)$$

It is clear that the TZ frequencies solely depend on the mutual coupling (M′) of the shunt resonators. The stronger the value of M′, the separation between two TZs will increase, i.e.,

$$f_{z1}^2 - f_{z2}^2 = \frac{\sqrt{\left(\omega_1^2 - \omega_1^2\right)^2 + 16\pi^4 M'^2 f_1^4 f_2^4 C_1 C_2}}{\left(1 - \pi^2 M'^2 f_1^2 f_2^2 C_1 C_2\right)} > f_1^2 - f_2^2 \quad (6)$$

If now the asymmetric SIR structure of Fig. 2a is converted into a symmetric structure as Fig. 2b, where $L_1 = L_2 = L_r$, $C_1 = C_2 = C_r$, $f_{z1} = f_{z2} = f_0$ and $M1 = M2 = M$, only one TZ is induced in the TSSIR frequency response. The origination of a single TZ is analyzed in [17], where it is shown that the impedance of the TSSIR section is finite for all other frequencies. The only TZ frequency is given by

$$f'_z = \frac{f_0}{\sqrt{1 + \frac{M''}{L_r}}} \quad (7)$$

The stronger the value of M′, f'_z will shift more toward the right side of the frequency axis. Now, if both the symmetric shunt resonators are shifted in opposite directions along the TSSIR axis, as presented in Fig. 2c, mutual coupling between them (M′) will surely degrade (as it is diagonal coupling) and hence f'_z shifts left. If a pair of differently oriented symmetric shunt SIR structures of resonant frequency f'_0 is now placed diagonally and reciprocally across the TSSIR in the same way, another TZ can be achieved at

$$f''_z = \frac{\omega'_0}{\sqrt{1 + \frac{M'''}{L_{r'}}}} \quad (8)$$

2) The filter Design

Where L_r, M″, and M‴ have their usual meanings. Because of the close proximity of the coupling structures, as long as M″ and M‴ ≠ 0, each of them will generate one TZ. As per the analysis from (4)–(8), a pair of TZs can be created by placing two asymmetric shunt SIR structures around the TSSIR, and by placing two pairs of symmetric SIR structures, another two TZs can be achieved. The combined

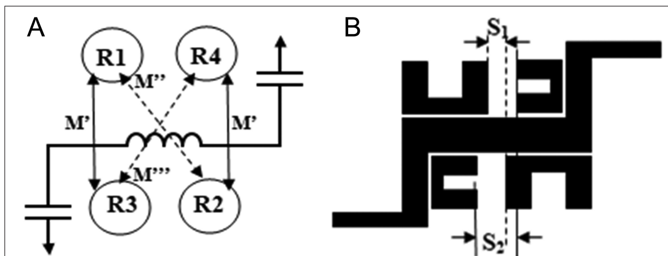

Fig. 3. (a) The coupling scheme. (b) Placement of shunt resonators.

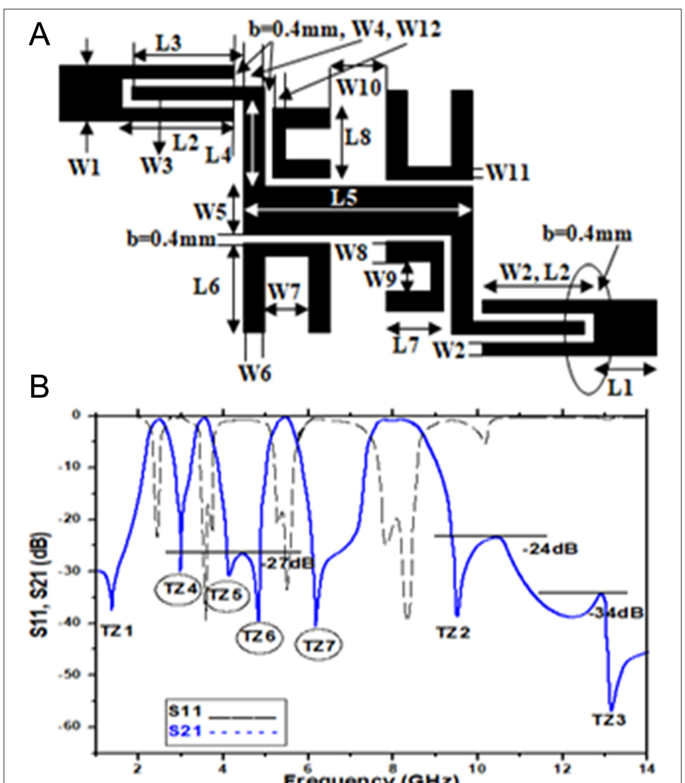

Fig. 4. (a) The final filter. (b) Frequency response.

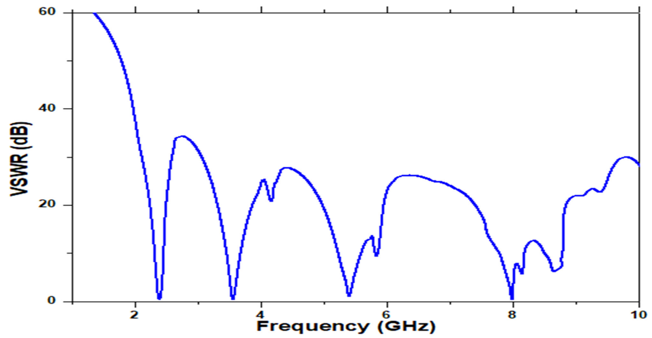

Fig. 5. Measured Voltage Standing Wave Ratio of the proposed filter.

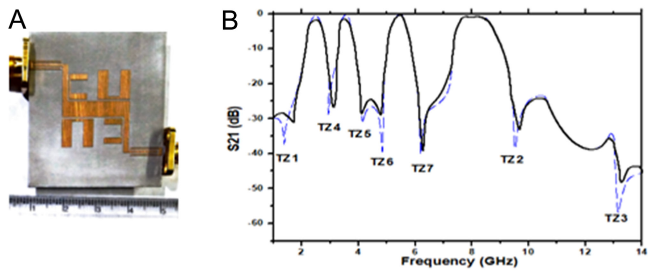

Fig. 6. (a) The fabricated prototype. (b) Comparison between simulated and measured results.

coupling scheme to achieve four TZs is presented in Fig. 3a, where R1 and R2 and R3 and R4 are coupled diagonally and R1 and R3 and R2 and R4 are coupled vertically. The design structure as per Fig. 3b depicts that the separation between R1 and R2 (S1) is smaller than the separation between R3 and R4 (S2). Therefore, the TZ created by R1 and R2 will be at a higher frequency compared to the TZ created by R3 and R4. The final filter design and its frequency response are presented in Fig. 4a and 4b. The design parametric values are (in mm) L1 = 1, L2 = 8.5, L3 = 8.5, L4 = 8.1, L5 = 19.8, L6 = 7.5, L7 = 5.35, L8 = 6.6, W1 = 2.2, W2 = 0.4, W3 = 0.6, W4 = 1.55, W5 = 4.2, W6 = 3, W7 = 3.4, W8 = 1.6, W9 = 3.4, W10 = 3.1, W11 = 0.75, W12 = 0.4. The passband center frequencies remain unaltered with additional four TZs at 2.9, 4.15, 4.85, and 6.15 GHz. The minimum passband ILs are −0.4, −0.6, −0.4, and −0.7 dB.

III. RESULTS AND DISCUSSION

The vertical and diagonal coupling of resonators R1–R4 creates four additional TZs as shown in Fig. 4b. In the present analysis, we have ignored the coupling between R1 and R4 and between R2 and R3. Minor coupling between them shifts the original TZs generated by the basic quad-band filter slightly but will not affect the positions of TZ4–TZ7. Dimensions of the shunt SIR structures are carefully adjusted to satisfy (4)–(8). As mentioned earlier, in (4)–(8), a pair of TZs can be created by placing two asymmetric shunt SIR structures around the TSSIR, and by placing two pairs of symmetric SIR structures, another two TZs can be achieved. The combined coupling scheme to achieve four TZs is presented in Fig. 3. TZ6 and TZ7 are generated by the vertical coupling of R1 and R3 (or R2 and R4). The diagonal coupling between R1 and R2 and R3 and R4 generates TZ5 and TZ4. The spurious bands are well under control as shown in the frequency response. The newly added TZs will be supported by the transmission poles, which are overlapped with the poles generated by the initial quad-band filter. The Voltage Standing Wave Ratio (VSWR) at all the passbands is measured, and it indicates excellent degree of impedance matching in Fig. 5. The existence of dual poles in the second–fourth passbands is clearly visible. To validate the simulation, a prototype is fabricated as mentioned earlier, whose measurement results are in good accordance with the simulation in Fig. 6b. The slight mismatch between the simulation and measurement results is mainly due to fabrication error and uncounted electromagnetic interferences. Comparison of the proposed design with some other contemporary designs and their design methods are presented in Table I, which establish the supiriority of our design in all mentioned aspects.

IV. CONCLUSIONS

A method of simultaneous vertical and diagonal coupling between TSSIR and conventional two-step SIR structures is introduced here to create TZs in the stop bands of a quad-band filter. The basic quad-band filter is created by back-to-back TSSIR structures and has only three TZs, whereas the introduction of vertical and diagonal coupling adds four more TZs in the stop bands. The positions of the TZs are depicted in the paper through their electrical equivalent model. Apart from the good stop band performances, minimum passband ILs of −0.4, −0.6, −0.4, and −0.7 dB and passband Fractional Band Width values 14%, 8.8%, 7.4%, and 6.7% are achieved. The size of the filter is optimized for the best possible results in terms of insertion loss, Fractional Bandwidth, and suppression of spurious bands and is found to be 0.4 $\lambda_g \times 0.36\ \lambda_g$ (i.e. 39.6 mm × 35 mm). The approach presented in this article is an experimental method and lots of permutations and combinations were done to adjust for the desired results. Other filter design methods also could be tried out to verify whether the approach presented here is applicable to all of them or not. The vertical and diagonal coupling approaches surely will play a significant role in Meander Line, Surface Wave, and Metallic Post structures.

TABLE I. COMPARISON OF THE PROPOSED DESIGN WITH SOME OTHER CONTEMPORARY DESIGNS

References	Passband Center Feq.	IL (dB)	No of TZ	Fractional Bandwidth (%)	Design Method
[18]	1.4, 1.7, 2.2, 2.7	3.5, 2.9, 2.7, 3.8	7	5, 6, 13,12	Varactor perturbed dual mode resonator
[19]	1.4, 1.6, 4.0, 6.0	1.0, 1.0, 0.8, 2.8	6	7, 9.6, 13.6, 16	Different prop. path for diff. resonators
[20]	1.2, 2.5, 3.5, 4.4	0.3, 0.7, 0.4, 0.8	7	3, 6.6, 8, 10.5	Self-coupled quad mode resonator
This Work	2.4, 3.5, 5.4, 8.0	0.4, 0.6, 0.4,0.7	7	4, 5, 9.6, 16	Vertical and diagonal coupling between TSSIR and conventional SIR

Availability of Data and Materials: The data that support the findings of this study are available on request from the corresponding author.

Peer-review: Externally peer reviewed.

Author Contributions: Concept – A.N.; Design – A.N.; Supervision – J.R.P.; Resources – S.S.; Materials – J.R.P.; Data Collection and/or Processing – A.N.; Analysis and/or Interpretation – A.N.; Literature Search – J.R.P.; Writing – A.N.; Critical Review – J.R.P., S.S.

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