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A Novel Bandpass Filter with Controllable Transmission Zeros

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Abstract—A planar bandpass filter is proposed in this paper. Its stopband is realized by using the concept of bandstop filter. A key merit of the filter configuration is that the position of the transmission zeros can be conveniently controlled whereas the bandwidth is fixed. The bandpass filter is realized using open circuited uniform impedance resonator and stepped impedance resonators. With five reflection zeros generated in the passband, ten controllable transmission zeros are introduced to sharpen the passband skirts. Skirt selectivity can be freely controlled by tuning the impedance ratio of the stepped impedance resonators. Without coupling gaps between resonators, the structure of the filter is simple and easy to fabricate. To illustrate the concept, a bandpass filter with ten transmission zeros is designed, fabricated and measured. Simulated and measured results are found to be in good agreement with each other, with insertion loss in the passbands less than 1 dB.

1. INTRODUCTION

Planar bandpass filters with high selectivity and low insertion loss are highly desired in modern wireless communication systems. Cross coupling between nonadjacent resonators has been widely employed to design bandpass filters for improving the selectivity. Two fourth-order bandpass filters using cross-coupled single mode resonators were implemented in [1]. Transmission zeros may also be implemented with input and output or source-load coupling, which has been reported for filter applications [2, 3]. Quasi-elliptic function response can be achieved with the same principle by introducing additional pair of coupled lines to classical multiple mode resonator filters. A compact microstrip filter with two close-to-band transmission zeros has been proposed and designed using the folded multiple-mode resonator [4]. In [5], the authors proposed a compact quasi-elliptic bandpass filter with terminated anti-coupled line, and thus the stopband transmission zero occured.

However, the conventional end-to-line coupling structure suffers from high insertion loss. To reduce the insertion loss, transmission line structures based on open- or short-circuited stub were usually employed to design bandpass filter with transmission zeros. A systematic and analytical method for the exact synthesis of generalized Chebyshev hybrid ring based bandpass filters with a controllable transmission zero pair was developed in [6]. A bandpass filter composed of a shorted microstrip line fed by two open-ended side-coupled lines was presented in [7]. A cross-coupled bandpass filter developed from a standard short-circuited stub filter with additional coupled lines was proposed in [8]. Low insertion loss microstrip bandpass filters with four transmission zeros were proposed in [9]. In [10], transversal signal-interaction was introduced as an effective method to produce multiple transmission zeros. In [11], stub-loaded resonators and stepped-impedance resonators were employed in bandpass filter design. In [12], A modified wideband bandpass filter is realised using half-wavelength and one-wavelength open-circuited resonators was proposed to generate six transmission zeros. In [13], a low insertion loss bandpass filter was designed using two transmission line section and open stubs. The aforementioned bandpass filters have very good passband performance, however, the lower and upper

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stopband has room to improve, e.g., more controllable transmission zeros to enhance the stopband characteristics.

This paper presents a bandpass filter with ten controllable transmission zeros. The bandpass filter is designed using open circuited uniform impedance resonators (UIR) and stepped impedance resonators (SIR) developed from bandstop filters [14–16]. Usually very strong coupling is required in the design of a bandpass filter with a wide passband. A different approach is employed in this paper to avoid the coupling difficulty. The UIR and SIR are employed not only to form the passband characteristics but also to introduce multiple transmission zeros. Skirt selectivity of the bandpass filters can be controlled conveniently by tuning the impedance ratio of the SIR while the bandwidths are fixed. The lossless transmission line model has been used to analyze in-band and out-of-band performances of the filters. For validation, a bandpass filter is designed, fabricated and measured, with insertion loss in the passbands less than 1 dB.

2. BANDPASS FILTER WITH TEN TRANSMISSION ZEROS

Transmission line structures based on series and shunt stubs are usually used to design bandstop filters, and these structures can be also used to realize bandpass filters with multiple transmission zeros. The lossless transmission model of the proposed bandpass filter is presented in Figure 1, which consists of one open-circuited UIR (Z_1, θ_1), two open-circuited SIR (Z_3, θ_3, Z_4, θ_4, Z_5, θ_5, Z_6, θ_6) and two connecting transmission lines (Z_2, θ_2). The $ABCD$ parameters of the filter can be derived using lossless transmission line model [14] as

$$Y_{in\text{-}SIR1} = \frac{j(1+K_1)\tan\theta}{K_1 Z4(1-K_1\tan^2\theta)} \tag{1}$$

$$Y_{in\text{-}SIR2} = \frac{j(1+K_2)\tan\theta}{K_2 Z_6(1-K_2\tan^2\theta)} \tag{2}$$

$$\begin{aligned} A = &\cos 2\theta - \frac{Z_2\sin^2\theta(1+K_1)}{K_1Z_4(1-K_1\tan^2\theta)} - \frac{2Z_2\sin^2\theta(1+K_2)}{K_2Z_6(1-K_2\tan^2\theta)} \\ &+\frac{Z_2^2\sin^2\theta\tan^2\theta(1+K_1)(1+K_2)}{K_1K_2Z_4Z_6(1-K_1\tan^2\theta)(1-K_2\tan^2\theta)} \end{aligned} \tag{3}$$

$$B = jZ_2\sin 2\theta - j\frac{Z_2^2\sin^2\theta\tan\theta(1+K_1)}{K_1Z_4(1-K_1\tan^2\theta)} \tag{4}$$

$$\begin{aligned} C = &j\frac{\tan\theta\cos 2\theta}{Z_1} + j\frac{\sin 2\theta}{Z_2} + j\frac{\tan\theta(1+K_1)(Z_1\cos^2\theta - Z_2\sin^2\theta)}{K_1Z_1Z_4(1-K_1\tan^2\theta)} \\ &+j\frac{\tan\theta(1+K_2)(Z_1\cos 2\theta-2Z_2\sin^2\theta)}{K_2Z_1Z_6(1-K_2\tan^2\theta)} + j\frac{Z_2\tan^2\theta(1+K_1)(1+K_2)(2Z_2\sin^2\theta-Z_1\sin 2\theta)}{2K_1K_2Z_1Z_4Z_6(1-K_1\tan^2\theta)(1-K_2\tan^2\theta)} \end{aligned} \tag{5}$$

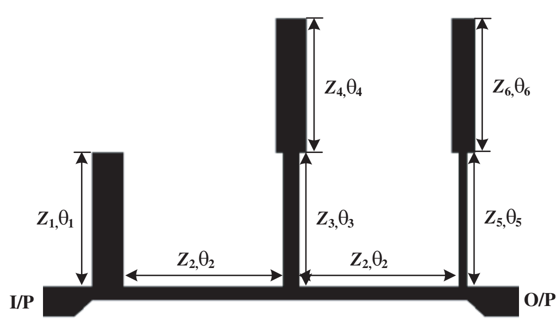


Figure 1. Configuration of the bandpass filter with ten transmission zeros.

$$D = \cos 2\theta - \frac{2Z_2 \sin^2\theta}{Z_1} + \frac{Z_2 \tan\theta(1+K_1)(2Z_2 \sin^2\theta \tan\theta - Z_1 \sin 2\theta)}{2K_1 Z_1 Z_4 (1 - K_1 \tan^2\theta)} \quad (6)$$

where $Y_{in\text{-}SIR1}$ is the input admittance of one SIR (Z_3, Z_4), $K_1 = Z_3/Z_4$, and $Y_{in\text{-}SIR2}$ is the input admittance of the other SIR (Z_5, Z_6), $K_2 = Z_5/Z_6$. The corresponding reflection and transmission coefficients of the filter is

$$S_{11} = \frac{A + B/Z_0 - CZ_0 + D}{A + B/Z_0 + CZ_0 + D} \quad (7)$$

$$S_{21} = \frac{2}{A + B/Z_0 + CZ_0 + D} \quad (8)$$

When $\theta_1 = \theta_2 = \theta_3 = \theta_4 = \theta_5 = \theta_6 = 180°$ at the center frequency (f_0) of the bandpass filter, the equivalent circuit of the structure in Figure 1 is a fifth order bandpass filter, the open-circuited UIR or SIR can be equivalent to parallel resonant circuit [17], the connecting transmission line can be equivalent to series resonant circuit, and the impedances of the resonators are determined by the bandwidth and ripple level of the bandpass filter [12].

By setting $S_{21} = 0$, when $0 < f < 2f_0$, the transmission zeros due to the UIR are obtained as

$$f_{z1} = 0.5f_0, \quad f_{z2} = 1.5f_0 \quad (9)$$

Eight additional transmission zeros due to the SIRs are obtained as

$$f_{z3} = \frac{\cot^{-1}(\sqrt{K_1})}{\pi} f_0, \quad 0 < \cot^{-1}(\sqrt{K_1}) < \frac{\pi}{2} \quad (10)$$

$$f_{z4} = \frac{\pi - \cot^{-1}(\sqrt{K_1})}{\pi} f_0 \quad (11)$$

$$f_{z5} = \frac{\pi + \cot^{-1}(\sqrt{K_1})}{\pi} f_0 \quad (12)$$

$$f_{z6} = \frac{2\pi - \cot^{-1}(\sqrt{K_1})}{\pi} f_0 \quad (13)$$

$$f_{z7} = \frac{\cot^{-1}(\sqrt{K_2})}{\pi} f_0, \quad 0 < \cot^{-1}(\sqrt{K_2}) < \frac{\pi}{2} \quad (14)$$

$$f_{z8} = \frac{\pi - \cot^{-1}(\sqrt{K_2})}{\pi} f_0 \quad (15)$$

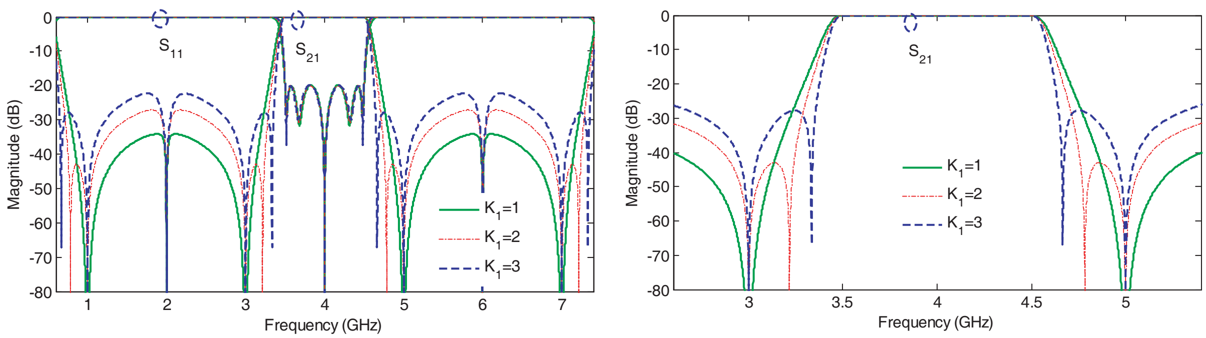
$$f_{z9} = \frac{\pi + \cot^{-1}(\sqrt{K_2})}{\pi} f_0 \quad (16)$$

$$f_{z10} = \frac{2\pi - \cot^{-1}(\sqrt{K_2})}{\pi} f_0 \quad (17)$$

From formulas (10)–(17), the transmission zeros can be adjusted freely by tuning the impedance ratio. Therefore, the selectivity of the bandpass filter can be tuned by selecting proper K_1 and K_2. Since our filter structure is realized by using transmission line technology. Thus, the filter performance exhibits periodic property. The six transmission zeros located at the position of f_{z1}, f_{z2}, f_{z4}, f_{z5}, f_{z8}, and f_{z9} are realized within one period of the transmission line structure as derived in Eqs. (9), (11), (12), (15), (16). The other four transmission zeros located at the position of f_{z7}, f_{z3}, f_{z6} and f_{z10} are produced by the transmission line structure of lower and upper period.

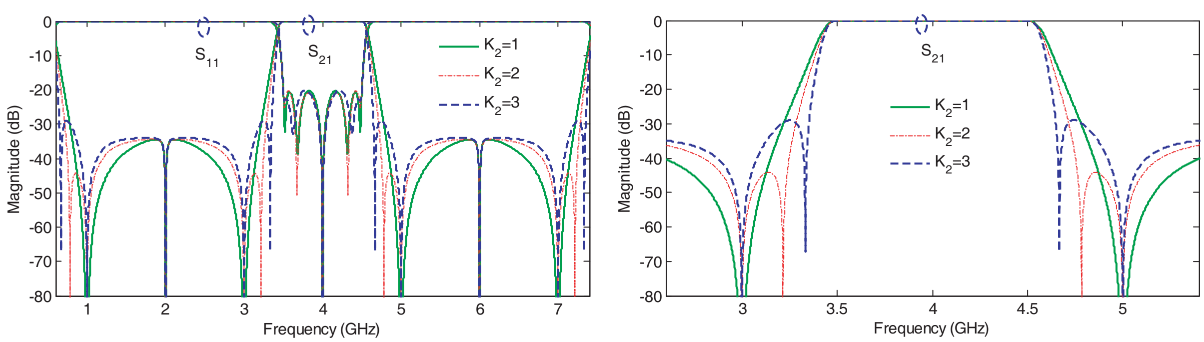
Figure 2(a) and Figure 3(a) show the simulated S_{11} and S_{21} of the proposed bandpass filter under different K_1 and K_2, respectively. Two fixed transmission zeros and eight changeable transmission zeros can be obtained between 0 and $2f_0$ ($f_0 = 4\,\text{GHz}$), while the passband bandwidth (25%) and ripple level keep fixed. Figure 2(b) and Figure 3(b) show close views of the transmission coefficients. The impedance ratio K_1 and K_2 can flexibly control the skirt selectivity of the bandpass filter.

Figure 4 shows the simulated S_{11} and S_{21} of the proposed bandpass filter under different K_1 and K_2. When $K_1 = 2$, $K_2 = 1$ or $K_1 = 1$, $K_2 = 2$, the locations of the transmission zero are the same, but the stopband attenuation levels are different. From Figure 4, $K_1 = 1$ and $K_2 > 1$ can be selected for designing bandpass filter with high selectivity and stopband attenuation.



(a) (b)

Figure 2. Simulated S-parameters of the bandpass filter with ten transmission zeros under different impedance ratio K_1. ($K_1 = 1$, $K_2 = 1$, $Z_1 = 23\,\Omega$, $Z_2 = 163\,\Omega$, $Z_3 = 26.5\,\Omega$, $Z_5 = 44.5\,\Omega$; $K_1 = 2$, $K_2 = 1$, $Z_1 = 23\,\Omega$, $Z_2 = 152\,\Omega$, $Z_3 = 47.3\,\Omega$, $Z_5 = 44.5\,\Omega$; $K_1 = 3$, $K_2 = 1$, $Z_1 = 23\,\Omega$, $Z_2 = 138.5\,\Omega$, $Z_3 = 80\,\Omega$, $Z_5 = 44.5\,\Omega$.).



(a) (b)

Figure 3. Simulated S-parameters of the bandpass filter with ten transmission zeros under different impedance ratio K_2. ($K_1 = 1$, $K_2 = 1$, $Z_1 = 23\,\Omega$, $Z_2 = 163\,\Omega$, $Z_3 = 26.5\,\Omega$, $Z_5 = 44.5\,\Omega$; $K_1 = 1$, $K_2 = 2$, $Z_1 = 23\,\Omega$, $Z_2 = 161.5\,\Omega$, $Z_3 = 26.5\,\Omega$, $Z_5 = 77\,\Omega$; $K_1 = 1$, $K_2 = 3$, $Z_1 = 23\,\Omega$, $Z_2 = 159.5\,\Omega$, $Z_3 = 26.5\,\Omega$, $Z_5 = 136\,\Omega$.).

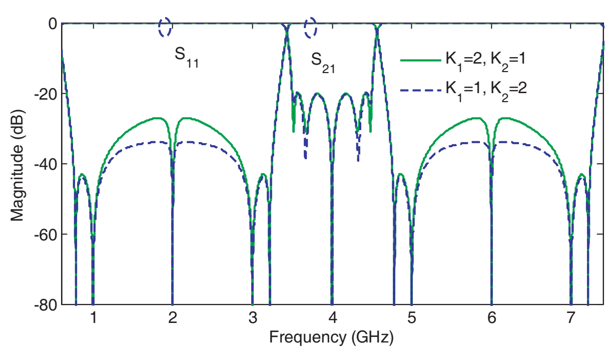


Figure 4. Simulated S-parameters of the bandpass filter with ten transmission zeros under different K_1 and K_2. ($K_1 = 2$, $K_2 = 1$, $Z_1 = 23\,\Omega$, $Z_2 = 152\,\Omega$, $Z_3 = 47.3\,\Omega$, $Z_5 = 44.5\,\Omega$; $K_1 = 1$, $K_2 = 2$, $Z_1 = 23\,\Omega$, $Z_2 = 161.5\,\Omega$, $Z3 = 26.5\,\Omega$, $Z_5 = 7\,\Omega$.).

3. EXPERIMENTAL RESULTS

A bandpass filter with a fifth-order Chebyshev frequency response and 0.01-dB ripple level is fabricated on a substrate with dielectric constant $\varepsilon_r = 2.55$, loss tangent $\delta = 0.0029$, and thickness $h = 0.8\,\text{mm}$ for validation. The central passband frequency is selected to be 4 GHz, and the relative bandwidth is chosen to be 25%. Figure 5 shows the schematic layout of the proposed bandpass filter. The connecting transmission lines are meandered to reduce the circuit size, and an open-circuited stub (L_{10}, W_6) is shunted at midpoint of the half-wavelength UIR to reduce the influence of the dispersion. The impedance ratio K_2 is selected as 3 to obtain good selectivity ($K_1 = 1$). The original design parameters of the bandpass filter are: $Z_1 = 23\,\Omega$, $Z_2 = 159.5\,\Omega$, $Z_3 = 26.5\,\Omega$, $Z_5 = 136\,\Omega$. The optimized parameters in Figure 5 are: $L_1 = 7.6\,\text{mm}$, $L_2 = 13.5\,\text{mm}$, $L_3 = 25.4\,\text{mm}$, $L_4 = 22.8\,\text{mm}$, $L_5 = 25.25\,\text{mm}$, $L_6 = 27.5\,\text{mm}$, $L_7 = 20.3\,\text{mm}$, $L_8 = 4\,\text{mm}$, $L_9 = 12.3\,\text{mm}$, $L_{10} = 3.7\,\text{mm}$, $W_1 = 5.9\,\text{mm}$, $W_2 = 0.3\,\text{mm}$, $W_3 = 5\,\text{mm}$, $W_4 = 0.3\,\text{mm}$, $W_5 = 2.6\,\text{mm}$, $W_6 = 1\,\text{mm}$. Photograph of the fabricated filter is presented in Figure 6. The total size is $69\,\text{mm} \times 29.9\,\text{mm}$, which is approximate $1.34\lambda g$ by $0.581\lambda g$, where λg is the guided wavelength on the substrate at the central passband frequency. Figures 7 and 8 show the simulated and measured results, including group delay. The measured insertion loss at central passband frequency is 0.84 dB, while the return loss is 14.8 dB. The measured 3 dB bandwidth is found to be 3.465 to 4.524 GHz, and fractional bandwidth is approximately 26.5%. The measured minimum attenuation is 20 dB from 0.67 to 3.23 GHz in the lower stopband and 4.72 to 7.15 GHz in the upper stopband. The measured group delay of the transmission coefficient is less than 2.7 ns in the passband. Table 1 shows a performance comparison between this work and three previous bandpass filters. The attenuation rate is defined as follows.

$$\text{Attenuation Rate} = \frac{20\,\text{dB} - 3\,\text{dB}}{|f_{20\,\text{dB}} - f_{3\,\text{dB}}|} \tag{18}$$

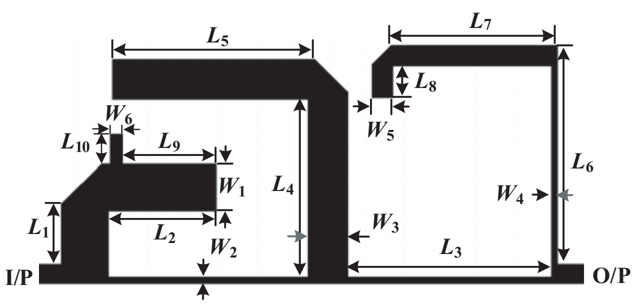


Figure 5. Layout of the proposed bandpass filter with ten transmission zeros.

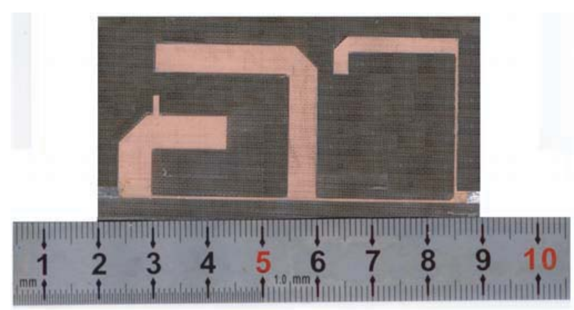


Figure 6. Photograph of the fabricated bandpass filter with ten transmission zeros.

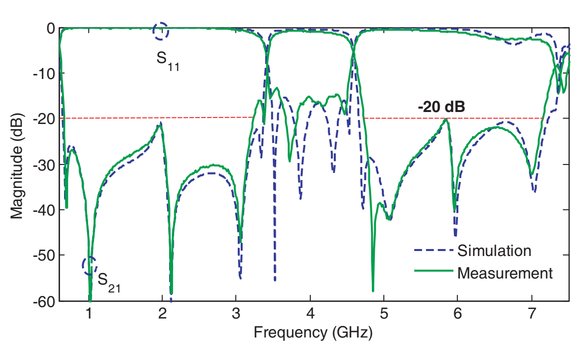


Figure 7. Simulated and measured results of the bandpass filter with ten transmission zeros.

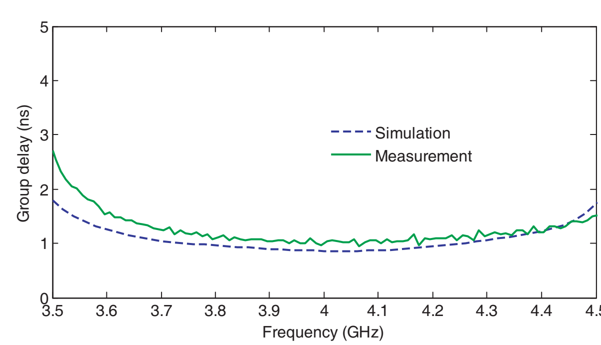


Figure 8. Simulated and measured group delay (S_{21}) of the bandpass filter with ten transmission zeros.

Table 1. Comparison between previous works and this work.

Ref.	the number of transmission zeros	Lower Attenuation Rates (dB/GHz)	Upper Attenuation Rates (dB/GHz)
[7]	3	29.3	25.3
[10]	10	68	57
[12]	6	74	61
This work	**10**	**100**	**86.7**

where $f_{20\,\mathrm{dB}}$ denotes the 20 dB frequency point of the insertion loss and $f_{3\,\mathrm{dB}}$ the 3 dB frequency point of the insertion loss. From this table we can find the filter proposed in this work has the highest number of transmission zeros and the maximum attenuation rate.

4. CONCLUSION

A modified bandpass filter is presented in this paper. The filter has ten controllable transmission zeros and good group delay performance. Sharp roll-off and improved stopband performance is achieved. The introduction of SIR makes it possible to conveniently control the skirt selectivity. Design equations and curves have been given for the suggested topology. The proposed structure has been verified through the design, implementation and measurement of the microstrip bandpass filter centered at 4 GHz with ten transmission zeros.

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