

# A Folded SIR Cross Coupled WLAN Dual-Band Filter

Zi Jian Su\*, Xi Chen, Long Li, Bian Wu, and Chang-Hong Liang

**Abstract**—A compact cross-coupled dual-band bandpass filter based on folded Stepped Impedance Resonators (SIRs) with four controllable transmission zeros is proposed in this paper. A pair of stepped impedance tapped lines is utilized to improve the dual band impedance matching, which reduces the insertion loss of the filter; meanwhile the tapped lines are also coupled with non-adjacent resonators to produce transmission zeros to improve skirt characteristics. At the end of this paper, the simulated and measured results are compared with each other, and good agreement is achieved.

## 1. INTRODUCTION

Wireless Location Area Network (WLAN) has become a standard configuration of smart mobile terminal with standards IEEE 802.11 b/g (2.4/2.45 GHz) and IEEE 802.11 a (5.2–5.8 GHz), which requires bandpass filter with both dual-band property and high selectivity. As an important part of the RF front-end, dual-band filter has become a hot research field [1–12]. Stepped Impedance Resonators (SIRs) are presented in the design of bandpass filters for its controllable spurious frequencies, simple structures and well-established design methodology [1, 2, 7, 9, 11, 13–15]. In [15] a tapped-line input/output structure was utilized to create transmission zeros, which expanded the stop band of the SIR filter. The dual-band bandpass filter design methodology was proposed by Kuo et al. [1], and two fourth-order filters were designed by the methodology. To miniaturize the filter, a pseudo-interdigital SIR structure with tapped-line output/input structure was proposed in [2]. However, the quarter wavelength tapped line did not work well due to poor impedance matching in the dual bands, which may lead to a large insert loss in the second passband. This paper utilizes stepped impedance input/output tapped feed lines to satisfy the dual band impedance matching and reduce the insertion loss effectively. Simultaneously the cross-coupling effect and tapped-line feed produce four independent transmission zeros to improve the selectivity as well as out-of-band suppression.

## 2. ANALYSIS OF THE PROPOSED DUAL-BAND BPF

This paper proposes a folded SIR dual-band bandpass filter with the specification as follows: the first band has a center frequency 2.4 GHz, bandwidth 100 MHz with 19 dB return loss; the second band has a center frequency 5.2 GHz, bandwidth 140 MHz with 20 dB return loss.

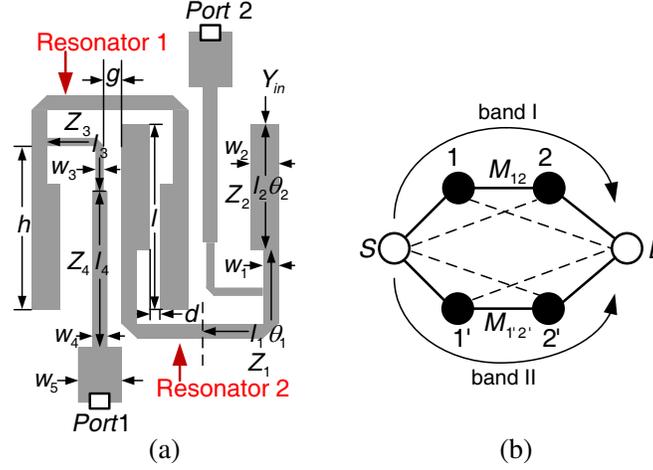
Figure 1 shows the layout and topology of the proposed filter. As depicted in Fig. 1(a), port 1 has been connected to resonator 1 directly by the feed line, which is a direct coupling as shown in Fig. 1(b) by the solid line between  $S$  and resonator  $1/1'$  in both bands. The folded SIRs are interdigitally coupled with each other by a gap  $d$ , which is also a direct coupling. Then there is a little part of energy coupling to resonator 2 from the port 1 feed line, which is a cross coupling as depicted in Fig. 1(b) by the dashed line connecting  $S$  and resonator  $2/2'$  in band I/II. When the electric lengths of two sections of half SIR

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**Figure 1.** (a) Layout and parameters of the proposed filter, where  $Z_1 = 100 \Omega$ ,  $Z_2 = 78 \Omega$ ,  $Z_3 = 67.4 \Omega$ ,  $Z_4 = 41.2 \Omega$ ,  $w_1 = 0.8 \text{ mm}$ ,  $w_2 = 1.4 \text{ mm}$ ,  $w_3 = 0.3 \text{ mm}$ ,  $w_4 = 1.1 \text{ mm}$ ,  $w_5 = 2.7 \text{ mm}$ ,  $l_1 = 10.7 \text{ mm}$ ,  $l_2 = 10.2 \text{ mm}$ ,  $l_3 = 9.2 \text{ mm}$ ,  $l_4 = 14.5 \text{ mm}$ ,  $l = 14.4 \text{ mm}$ ,  $d = 0.7 \text{ mm}$ ,  $h = 12.9 \text{ mm}$ ,  $g = 1.9 \text{ mm}$ .  $\theta_i$  is the electric length corresponding to  $l_i$  ( $i = 1, 2$ ); (b) The topology of the proposed filter, where the solid line denotes direct coupling and the dash line denotes cross coupling.

are equal, i.e.,  $\theta_1 = \theta_2 = \theta$  and we assume  $K = Z_2/Z_1$ , the input impedance of the folded SIR can be expressed as [14]

$$Y_{in} = j \frac{1}{Z_2} \frac{2(1+K)(K - \tan^2 \theta)}{K(1 - \tan^2 \theta)^2 - 2(1+K^2)\tan^2 \theta} \quad (1)$$

According to the resonance condition  $Y_{in} = 0$ ,  $\theta = \arctan \sqrt{K} = \theta_0$  and  $\theta = \frac{\pi}{2} = \theta_{s1}$  can be obtained. The ratio of two resonance frequencies is

$$R_{s1} = \frac{f_{s1}}{f_0} = \frac{c/f_0}{c/f_{s1}} = \frac{\lambda_0}{\lambda_{s1}} = \frac{2\pi/\lambda_{s1}}{2\pi/\lambda_0} = \frac{(2\pi/\lambda_{s1}) \cdot l}{(2\pi/\lambda_0) \cdot l} = \frac{\theta_{s1}}{\theta_0} = \frac{\pi}{2 \arctan \sqrt{K}} \quad (2)$$

where  $f_0$  is the first resonance frequency,  $f_{s1}$  the second resonance frequency,  $c$  the velocity of light, and  $l$  the physical length of transmission line. According to formula (2),  $K$  is determined by  $R_{s1}$  which is the ratio of second to the first center frequency of two passbands. The filter operates at 2.4 GHz and 5.2 GHz, then  $f_0 = 2.4 \text{ GHz}$ ,  $f_{s1} = 5.2 \text{ GHz}$ ,  $R_{s1} = f_{s1}/f_0 \approx 2.17$ ,  $K \approx 0.78$  and  $\theta_0 = 41.6^\circ$ . The high impedance  $Z_1$  is assumed  $100 \Omega$ , according to  $K$ ,  $Z_2 = 78 \Omega$ . The physical dimension of high and low impedance lines can be determined by  $Z_1$ ,  $Z_2$  and  $\theta_0$ .

According to the requirement of the filter, the coupling coefficients of two respective bands can be determined by the synthesis methods in [16]. The SIR tapped feed lines have coupling with both resonators as depicted in Fig. 1(b), which results in the full source-load coupling matrix of Band 1 and Band 2 as

$$M_{Band1} = \begin{bmatrix} 0 & M_{S1} & M_{S2} & 0 \\ M_{S1} & 0 & M_{12} & M_{1L} \\ M_{S2} & M_{12} & 0 & M_{2L} \\ 0 & M_{1L} & M_{2L} & 0 \end{bmatrix} \quad (3)$$

$$M_{Band2} = \begin{bmatrix} 0 & M_{S1'} & M_{S2'} & 0 \\ M_{S1'} & 0 & M_{1'2'} & M_{1'L} \\ M_{S2'} & M_{1'2'} & 0 & M_{2'L} \\ 0 & M_{1'L} & M_{2'L} & 0 \end{bmatrix} \quad (4)$$

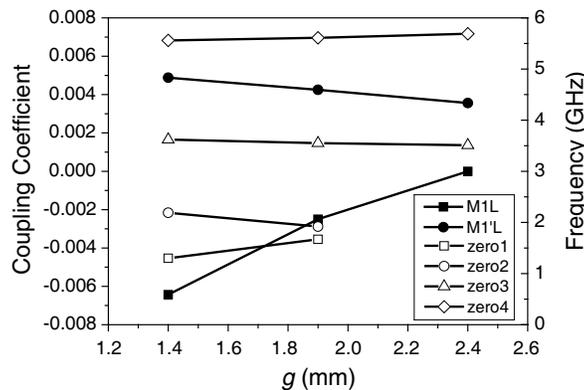
The direct external and internal couplings of the two bands can be obtained by the synthesis of conventional second-order Chebyshev bandpass filter, while the cross coupling between feed lines and non-adjacent resonator is adjusted to tune the out-of-band transmission zeros. According to

the specifications, we calculate the coupling coefficients  $M_{12} = 0.0656$ ,  $M_{S1} = M_{2L} = 0.0342$ ;  $M_{1'2'} = 0.0446$ ,  $M_{S1'} = M_{2'L} = 0.0284$ .

There are two degrees of freedom,  $l$  and  $d$ , to design the internal coupling coefficients at both bands simultaneously. When  $l = 14.2$  mm and  $d = 0.7$  mm, we have  $M_{12} = 0.0669$  for band 1 and  $M_{1'2'} = 0.0414$  for band 2, which satisfies the specification of coupling coefficients.

The following step is to adjust the tapped-line to meet the requirement of external coupling. There are two reasons for utilizing tapped-line input/output structure: first, strong external coupling can be taken without extremely narrow gap between feed line and resonator, which is convenient for fabrication; second, transmission zeros will be brought in stop band [17]. A stepped-impedance transmission line with high impedance  $Z_3 = 67.4 \Omega$  and low impedance  $Z_4 = 41.2 \Omega$  is applied rather than  $1/4\lambda_g$  ( $\lambda_g$  is the work wavelength of 2.4 GHz) transmission line, which improves the impedance matching and leads to more degrees of freedom to adjust  $M_{s1}$  and  $M_{s1'}$  simultaneously. As shown in Fig. 1(a),  $h$ ,  $l_3$ ,  $l_4$  become tunable parameters to control external coupling coefficients of two passbands. It should be noted that the parameter  $h$  not only affects  $M_{S1}$  and  $M_{S1'}$ , but also determines the positions of transmission zeros [17]. When  $l_4 = 14.5$  mm,  $l_3 = 8.6$  mm,  $h = 12.9$  mm are chosen,  $M_{S1} = 0.0332$ ,  $M_{S1'} = 0.0286$ , which meets the design targets on the whole.

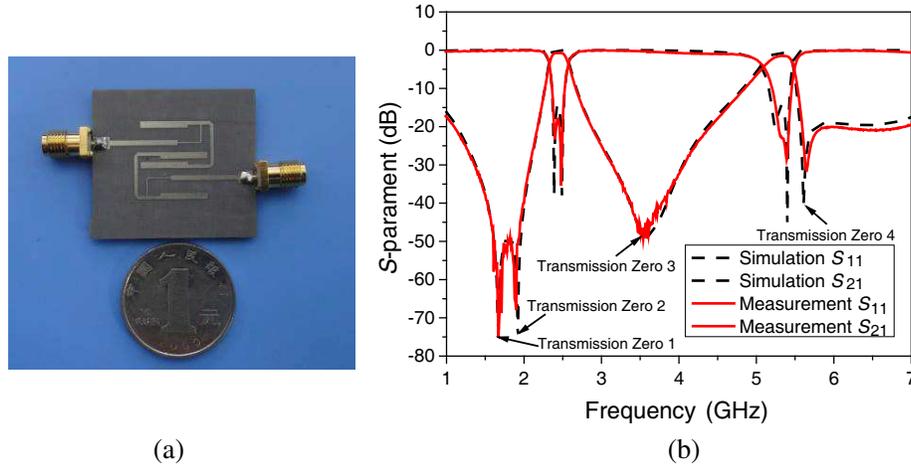
The tapped-line input/output structure and cross coupling between tapped-line and non-adjacent resonator bring four transmission zeros in stop band as shown in Fig. 2 and Fig. 3(b). The transmission zero 3 is located at about 3.55 GHz higher than the first passband, which is brought by tapped-line [17]. The transmission zeros 2 and 4 are caused by cross coupling of the tow bands. We can control  $g$  to adjust the cross-coupling coefficients  $M_{1L}/M_{S2}$  and  $M_{1'L}/M_{S2'}$  but affect  $M_{S1}$  and  $M_{S1'}$  little. When  $g = 2.4$  mm,  $M_{1L} = M_{S2} = 0$ , there is no cross coupling between tapped-line and non-adjacent resonator in the first band, and transmission zero 2 does not appear. However,  $M_{1'L} = M_{S2'} = 0.00356$ , and transmission zero 4 is at 5.69 GHz. When  $g = 1.4$  mm,  $M_{1L} = M_{S2} = -0.0025$ , which means that the coupling is induction coupling, and transmission zero 2 is at 1.92 GHz, while  $M_{1'L} = M_{S2'} = 0.00425$ , and transmission zero 4 is at 5.61 GHz. When  $g = 0.9$  mm,  $M_{1L} = M_{S2} = -0.00643$ , and transmission zero 2 is at 2.19 GHz while  $M_{1'L} = M_{S2'} = 0.00488$ , and transmission zero 4 is at 5.56 GHz, which both get closer to the passband with the stronger coupling. The transmission zero 1 is caused by multipath propagation mode of the first band and also affected by the parameter  $g$ .



**Figure 2.** The variation of cross coupling coefficients and transmission zeros with different  $g$ .

### 3. FILTER SIMULATION AND MEASUREMENT

The sample filter was fabricated on a substrate with  $\epsilon_r = 2.65$  and  $t = 1$  mm, as shown in Fig. 1(a) and Fig. 3(a). The whole size is  $0.46\lambda_g * 0.22\lambda_g$  (35.0 mm \* 17.2 mm) which is only half of traditional SIR filters and is up to 80% reduction compared to [2] in electric length. The filter is measured by Agilent 8719ES network analyzer, and the measured data are compared with simulated results in Fig. 3(b). The fractional bandwidth of the first passband is 5.1% and second passband 2.8%. The measured insertion loss of first passband is 0.751 dB and second passband 1.482 dB, which is very low and meets the target



**Figure 3.** (a) Photo of the filter; (b) Comparison between simulated and measured  $S$ -parameters, there are four transmission zeros in the stop band.

of design. It should be noted that the transmission zeros 1 and 2 appear at 1.66 GHz and 1.92 GHz and achieve nearly  $-75$  dB isolation, which efficiently isolate the operating bands of WCDMA and GSM1800. The slight difference between simulated and measured results might be caused by fabrication error.

#### 4. CONCLUSION

This paper proposes a folded SIR cross-coupled dual-band filter for WLAN application. The stepped impedance input/output tapped line is utilized to improve the impedance matching for dual-band requirement. Four transmission zeros are introduced by the tapped-line feeding and cross coupling between feed line and non-adjacent resonator to improve out-of-band suppression. The coupling mechanism and design procedure of this compact dual-band filter with multiple transmission zeros are presented and validated by both simulation and measurement.

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