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MINIATURIZED DUAL-MODE RESONATORS WITH IMPROVED DOUBLE SQUARE LOOP AND INTER-DIGITAL COUPLE FOR WLAN DUAL-BANDS

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Abstract—A novel dual-mode double square loop resonator (DMDSLR) for dual-band band-pass filter (BPF) is presented in this paper. The simple meander loop in DMDSLR is studied to improve the performance of the conventional DMDSLR. Significant size reductions over 33% are achieved. In addition, the designed meander-loop DMDSLR filter shows lower insertion loss (2.24 and 2.28 dB), higher rejection level (28/56 dB and 53/36 dB), wider bandwidth (about 8.5% and 28%) at the 2.47 and 5.47 GHz bands, respectively. Two transmission zeros are placed between the two pass-bands and result in a good isolation.

1. INTRODUCTION

The attractive features of microstrip ring resonator are its compact size, low cost, high Q and low radiation loss. In many applications, the ring resonator has been widely used to design filters, mixers, oscillators and antennas. It is well known that dual-mode first introduced by Wolff [1] can be excited on a microstrip ring resonator. This character is usually applied to realize band-pass filters in microstrip circuits. The filters have wide applications in satellite, mobile, wireless

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telecommunication, and microwave systems. It was applied to narrow band-pass filter design since bandwidth less than 10% was obtained.

Based on dual-mode ring resonator (DMRR), dual-mode double ring resonator (DMDRR) configuration and voltage/current couplings techniques were developed. This was an approach to improve the bandwidth of conventional DMRR. Meanwhile, the filters using multiple cascaded DMDRRs with high rejection band were reported for applications [2–4]. Since 30% bandwidth was obtained, those structures were applied to wideband band-pass filter design. On the other hand, DMRR was modified for enhancing filter performance with series capacitance perturbation. Miniaturizing the structure with shunt capacitance perturbation [5], with meander line [6–9], with cross-strip [10–12], with cross-slot in ground plane [13], with radial-slot ground plane [14], with open-loop resonator [15], with Hilbert-curve [17], and with multi-layer [21] was proposed. Generally, the miniaturization has been widely applied to compact band-pass filter design [5–21]. The dual-mode meander line configuration is an interesting topic for research and development [6–9].

The increasing demand for multi-band applications has required a single wireless transceiver to support multi-band operations. The dual-band BPF plays an important role in a multi-band transceiver. A coupled-serial-shunted line structure was designed for 2.4 and 5.2 GHz dual-band systems [22]. The parallel-coupled and vertical-stacked SIR configurations were used at 2.45/5.2 GHz or 2.45/5.8 GHz dual-band [23]. The compact ring dual-mode resonator with 2.4/5.2 GHz dual-band was proposed [24, 25]. The dual-mode ring resonator with periodically-loaded open stubs was presented with 2.4/5.8 GHz dual-band [26]. The dual-mode SIR was designed for WLAN applications at 2.4/5.2 GHz bands [27]. The compact dual-mode BPF with 2.4/5.8 GHz dual-band was realized with a single periodic SIR ring resonator, and the size reduction of 40% was obtained [28, 29]. Using a single stub-loaded slot ring resonator, a dual-mode BPF with 2.4/5.2 GHz dual-band was designed and fabricated [30]. However, WLAN systems combining 2.4, 5.2, and 5.8 GHz are becoming more attractive. Especially for universal applications, the BPF should be covering the whole 2.4–2.5 GHz and 5.15–5.85 GHz bands for the WLAN systems. In addition, 1.7/2.15 GHz and 1.45/2.02 GHz dual-band were also applied [31, 32]. Thus, a dual-band and wideband filter is a key component for such WLAN systems [22–32].

On the other hand, an alternative dual-mode BPF using double square-loop resonator (DMDSLR) was proposed for dual-band applications [33]. Each of the square-loop forms a dual-mode resonator with controllable passbands. The two passbands centered at 3.74 GHz and 6.30 GHz were presented. In addition, a miniaturized dual-mode ring resonator BPF was implemented by a cascade of several microwave C-sections for 2.42/4.61 GHz bands [20].

Based on the DMDSLR dual-band filter [33] and dual-mode meander line configuration [6–9], the improved T-couple consisting of one-arm couple and inter-digital feed for exciting dual-band simultaneously and modified DMDSLR structure for extending the bandwidth are presented in this paper. An alternative meander loop in DMDSLR is studied to improve the performance of the conventional DMDSLR. Besides, size reduction is obtained, and the responses are presented to achieve a lower insertion loss, higher rejection level, and wider bandwidth in 2.47 and 5.47 GHz bands. Results including surface current distributions and frequency response are presented and discussed. Frequency responses with various perturbations are also studied.

2. CONFIGURATION AND BASIS

2.1. DMDSLR Design

For a dual-mode square loop resonator (DMSLR) shown in Figure 1(a), the mean circumference of the loop is equal to an integral multiple of the guided wavelength, and the resonance is established as:

$$4L_1 = n\lambda_g, \quad n = 1, 2, 3, \ldots \tag{1}$$

where L_1 = side length of the loop and λ_g = guided wavelength.

The guided wavelength is written as:

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}} \tag{2}$$

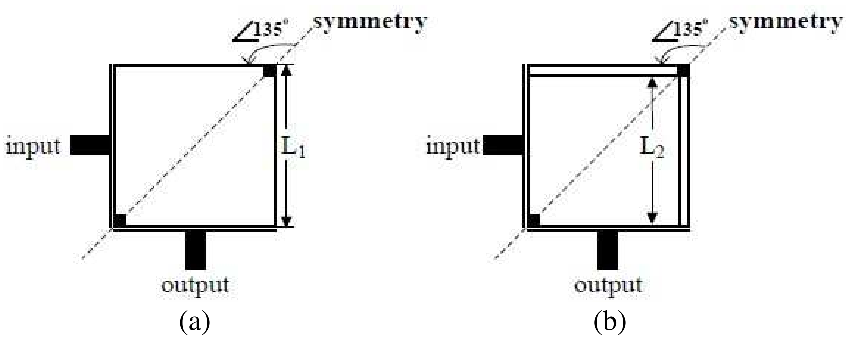

Figure 1. Dual-mode square loop resonators. (a) DMSLR. (b) MDSLR.

where λ_0 = wavelength in free space and ε_{eff} = effective dielectric constant.

The resonated frequency is expressed as:

$$f_1 = \frac{nc}{4L_1\sqrt{\varepsilon_{eff}}}, \quad n = 1, 2, 3, \ldots \tag{3}$$

Shown in Figure 1(a) is a basic DMSLR, in which the input and output ports are spatially separated 90° from each other and the perturbation located 135° from the input and output ports.

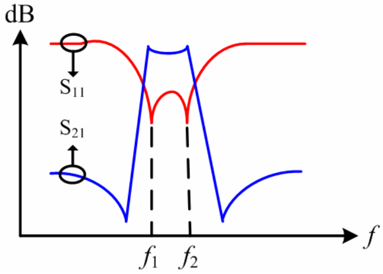

Figure 2. Wide-band response.

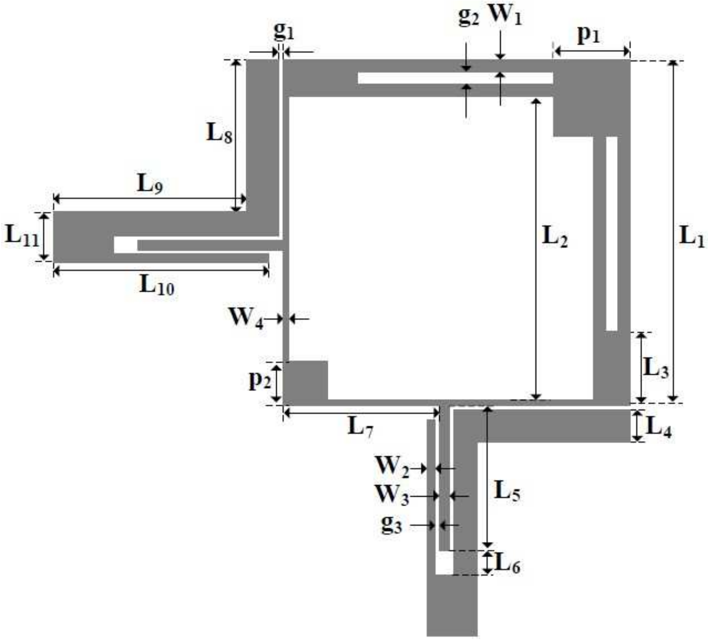

Figure 3. Dual-mode double square loop resonator.

In Figure 1(b), the modified double square loops are considered and depicted. Beside the outer loop with a side length of L_1, a inner loop with a side length of L_2 is presented. The second resonated frequency is obtained as:

$$f_2 = \frac{nc}{4L_2\sqrt{\varepsilon_{eff}}}, \quad n = 1, 2, 3, \ldots \tag{4}$$

The outer loop represents the lower resonant frequency f_1, and the inner loop determines the upper resonant frequency f_2. Thus, these two resonated frequencies with respect to these loops can be applied to determine the bandwidth of the desired wide-band response shown in Figure 2. By using the typical T-couples for input/output ports, only one band of the filter is obtained. Tuning the small square patch in the corners, the bandwidth of the response can be adjusted.

For exciting dual-band at the same time, an alternative T-couple is proposed. The improved T-couple is constructed with one-arm couple and inter-digital feed. It is designated as an inter-digital couple. The DMDSLR with an inter-digital couple is designed in Figure 3. The structural dimensions of this DMDSLR are $L_1 = 17.2$, $L_2 = 15.1$, $L_3 = 3.4$, $L_4 = 1.6$, $L_5 = 7.2$, $L_6 = 1.2$, $L_7 = L_8 = 7.55$, $L_9 = 9.6$,

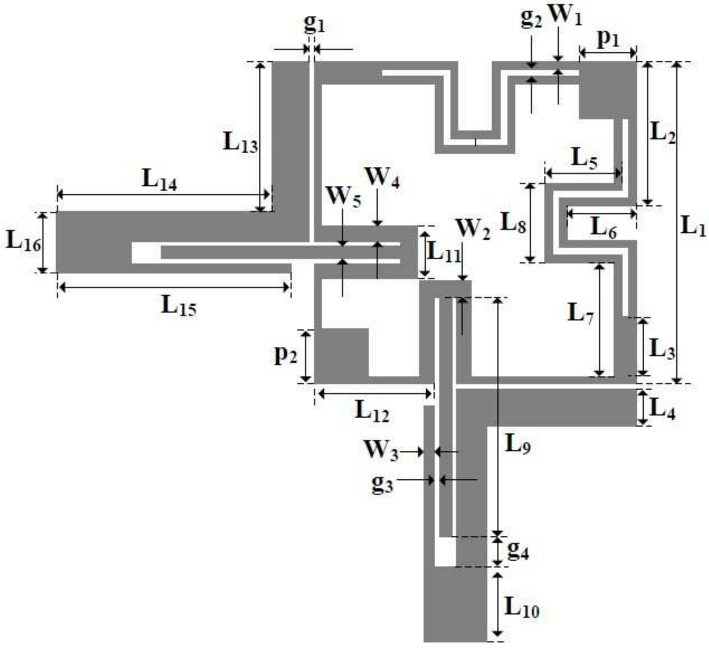

Figure 4. Meander loop DMDSLR.

$L_{10} = 10.7$, $L_{11} = 2.5$, $W_1 = 0.6$, $W_2 = 0.4$, $W_3 = 0.5$, $W_4 = 0.3$, $g_1 = 0.2$, $g_2 = 0.6$, $g_3 = 0.2$, $p_1 = 3.8$, and $p_2 = 2.2$, all in millimeters.

2.2. Meander Loop DMDSLR

When miniaturized DMDSLR is considered, the total length of square loop is still one guided wavelength. The meander loop is proposed in Figure 4. The dimensions are $L_1 = 13$, $L_2 = 5.8$, $L_3 = 2.4$, $L_4 = 1.5$, $L_5 = 3.1$, $L_6 = 2.8$, $L_7 = 4.6$, $L_8 = 3.2$, $L_9 = 9.65$, $L_{10} = 3$, $L_{11} = 2.1$, $L_{12} = 4.85$, $L_{13} = 6.05$, $L_{14} = 8.7$, $L_{15} = 9.5$, $L_{16} = 2.5$, $W_1 = 0.3$, $W_2 = 0.65$, $W_3 = 0.4$, $W_4 = 0.6$, $W_5 = 0.5$, $g_1 = 0.2$, $g_2 = 0.3$, $g_3 = 0.2$, $g_4 = 1.2$, $p_1 = 2.3$, and $p_2 = 2.2$, all in millimeters.

3. SIMULATIONS AND RESULTS

The simulations for DMDSLR and meander loop DMDSLR are achieved with the aid of CAD [34]. All these resonators are fabricated on FR4 substrates with $\varepsilon_r = 4.4$, $\delta = 0.0245$ and thickness $h = 1.6$. For the $50\,\Omega$ impedance, the width of the strip is 3.0, all in millimeters, effective dielectric constant $\varepsilon_{eff} = 3.38$ and guided wavelength $\lambda_g = 69.4\,\text{mm}$ at frequency $f_0 = 2.40\,\text{GHz}$. The simulated and measured S_{21} and S_{11} frequency responses of DMDSLR and meander loop DMDSLR are presented in Figure 5 and Figure 6. Obviously, both the measurements and simulations are in good agreement. The

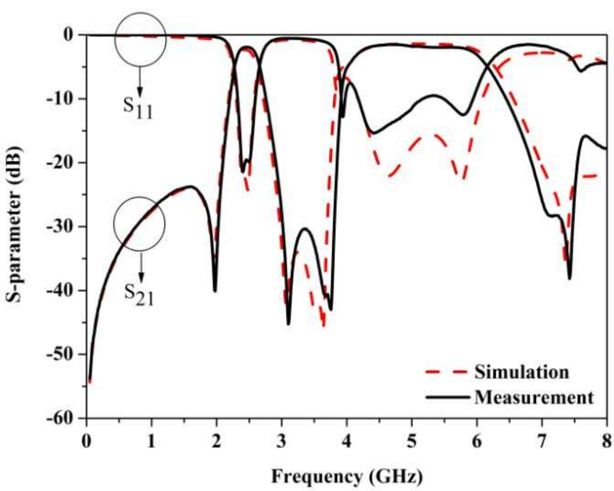

Figure 5. Frequency responses of DMDSLR.

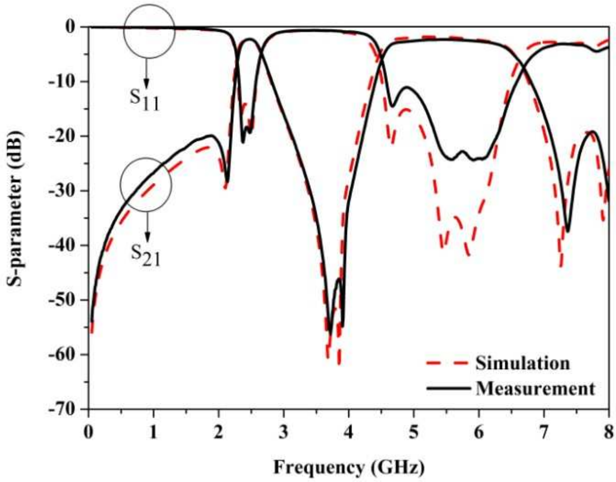

Figure 6. Frequency responses of meander loop DMDSLR.

Table 1. Performances of DMDSLR and meander loop DMDSLR.

Dual-mode dual-band filters		DMDSLR		Meander loop DMDSLR	
		simulation	measurement	simulation	measurement
Central frequencies (GHz)	I	2.44	2.46	2.46	2.47
	II	5.12	5.07	5.43	5.47
−3 dB BW (MHz)	I	200	260	220	210
	II	1920	1810	1710	1530
Fractional BW (%)	I	8.1	10.5	8.9	8.5
	II	37.4	35.7	31.5	28
Maximum insertion loss (dB)	I	2.32	1.91	2.32	2.24
	II	1.4	1.81	1.83	2.28
Rejection Level (dB)	I	35, 42	40, 45	30, 60	28, 56
	II	46, 40	43, 38	63, 44	53, 36
Total size (mm^2)		28.6×28.6		23.4×23.4	

performances of the two filters are listed in Table 1. It is found that both the responses in band I and band II of the two filters are closely fitted. Because the improved T-couple excites dual-band at the same time, one more mode in band II occurs in addition to the dual-mode. These three modes could extend the bandwidth of band II. Related to DMDSLR, an improved size reduction of 33% is obtained in the meander loop DMDSLR filter.

Figure 7 and Figure 8 present the surface current distributions of the DMDSLR and meander loop DMSLR. Figures 7(b) and (c) are the surface current distributions (according to TM_{110} configuration) of the first and second resonances of the first band, at the resonant

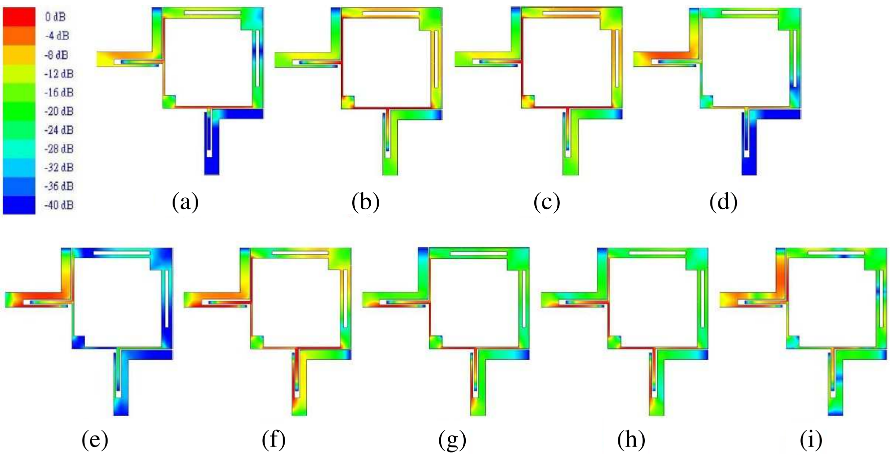

Figure 7. Current distributions of DMDSLR. (a) 1.96 GHz. (b) 2.40 GHz. (c) 2.49 GHz. (d) 3.07 GHz. (e) 3.64 GHz. (f) 3.86 GHz. (g) 4.64 GHz. (h) 5.76 GHz. (i) 7.37 GHz.

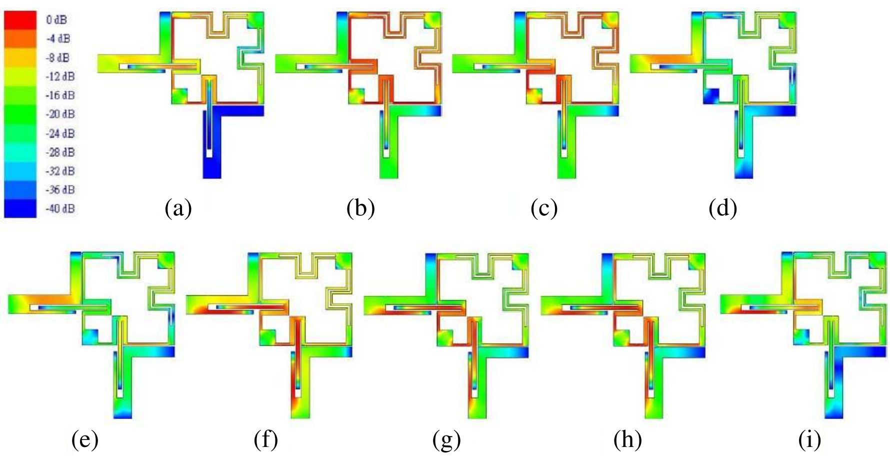

Figure 8. Current distribution of meander loop DMDSLR. (a) 2.11 GHz. (b) 2.34 GHz. (c)2.50 GHz. (d) 3.69 GHz. (e) 3.85 GHz. (f) 4.65 GHz. (g)5.46 GHz. (h) 5.85 GHz. (i) 7.25 GHz.

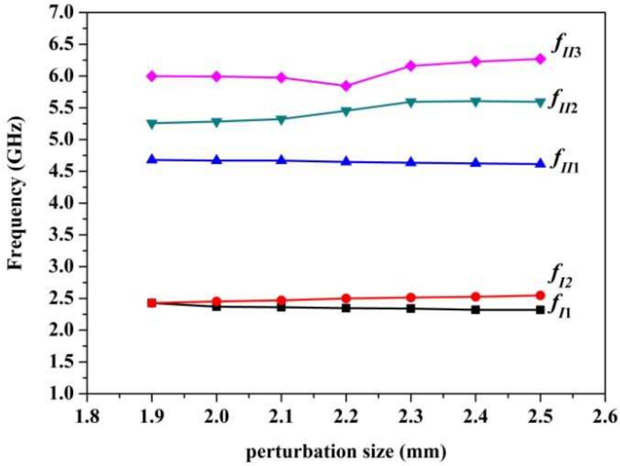

Figure 9. Frequency shift and bandwidth of meander loop DMDSLR related to perturbation size.

frequencies 2.40 and 2.49 GHz, respectively. Figures 7(a) and (d) show the surface current distributions at the transmissions zeros (1.96 GHz and 3.07 GHz) of band I. Figures 7(f), (g) and (h) are the surface current distributions (according to TM_{210} configuration) of the second band respectively, at the resonant frequencies 3.86, 4.64 and 5.76 GHz, respectively. Figures 7(e) and (i) present the surface current distributions at the transmission zeros (3.64 GHz and 7.37 GHz) of band II. These illustrations provide a physical insight into the structures of the resonators.

Similarly, Figures 8(b) and (c) express the surface current distributions of the first and second resonances of the first band respectively, at the resonant frequencies 2.34 and 2.50 GHz, respectively. Figures 8(a) and (d) present the surface current distributions at the transmission zeros (2.11 GHz and 3.69 GHz) of band I. Figures 8(f), (g) and (h) depict the surface current distributions of the second band respectively, at the resonant frequencies 4.65, 5.46 and 5.85 GHz, respectively. Figures 8(e) and (i) show the surface current distributions at the transmission zeros (3.85 GHz and 7.25 GHz) of band II. Though the meander structures are applied, the current distributions of meander loop DMSLR are similar to those of DMSLR.

Frequency split with various perturbation sizes are shown in Figure 9. f_{I1} is the first resonance and f_{I2} the second resonance of dual-mode in band I. f_{II1} is the first resonance, f_{II2} the second resonance,

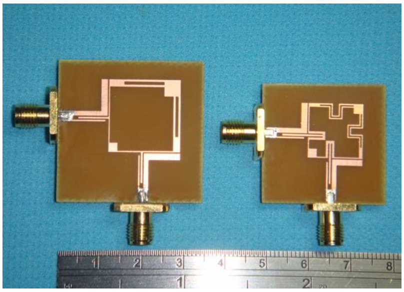

Figure 10. Photographs of DMDSLR and meander loop DMDSLR.

Table 2. Dual-mode dual-band filters for comparison.

Dual-mode dual-band filters		Proposed filter	[24]	[26]	[29]	[30]
Central frequencies (GHz)	I	2.47	2.4	2.4	2.47	2.4
	II	5.47	5.2	5.8	5.83	5.2
-3 dB BW (MHz)	I	210	145	210	133	350
	II	1530	310	250	380	980
Fractional BW (%)	I	8.5	6.0	8.7	5.39	14.6
	II	28	6.0	4.3	7.07	18.8
Maximum insertion loss (dB)	I	2.24	2.5	1.4	1.6	1.78
	II	2.28	3.2	3.2	2.18	1.9
Rejection Level (dB)	I	28, 56	43, 43	26, 14	47, 49	50, 17
	II	53, 36	43, 33	42, 53	49, 29	29, 26
Total size (mm^2)		23.4 ×23.4	17.5 ×17.5	28.4 ×28.4	12.4 ×12.4	29.5 ×16.5

and f_{II3} the third resonance of tri-mode in band II. As perturbation increases, $1.9\,\text{mm} \leq p2 \leq 2.5\,\text{mm}$, the dual-mode deviation in band I increases, and tri-mode in band II increases. The photographs of DMDSLR and meander loop DMDSLR are shown in Figure 10. The size reduction is presented.

Compared with the previous works and evaluating the proposed filter, four dual-mode dual-band filters are listed in Table 2. Though [24] and [29] have smaller size than the presented work, the proposed filter performs wider fractional bandwidth in band II, covering the whole 5.15–5.85 GHz bands for the WLAN systems. The wider bandwidth in band II, moderately compact size, two transmission zeros between the two pass-bands, resulting in good isolation, are presented in this proposed filter.

The effective design procedure is provided:

1. According to the central frequency and bandwidth of the desired band I, the circumferences of the loops equate to the guided wavelength basically, and the dimensions of the loops are determined by (1) to (4).
2. Increasing the perturbation size and splitting the dual-mode, the bandwidth is tuned.
3. Designing the available inter-digital coupling, the band II is excited, and the dual-band BPF is achieved.

Calculation by (1) to (4) in both dimensions of DMDSLR and meander loop DMDSLR, the tolerances (less than 3%) in band I related to the measurement are achieved. This demonstrates that the design equations are useful for determining the DMDSLR.

4. CONCLUSION

Miniaturized DMDSLR for wide-band and dual-band responses is presented in this paper. The novel configuration of DMDSLR with meander loop is constructed to reduce the size of conventional DMDSLR. Using the improved square loop resonator to increase the bandwidth and the inter-digital couple to excite the dual-band can be applied to dual-mode dual-band filters. The improved T-couple consisting of one-arm couple and inter-digital feed is an available method for exciting dual-band. The resonant frequency equations are available and useful for designing dual-band BPF.

For the dual-band applications, at the first band of 2.47 GHz, wide bandwidth of 2.36–2.57 GHz (3-dB fractional bandwidth, FBW = 8.5%), low insertion loss of 2.24 dB, and deep transmission zeros of 28 and 56 dB are achieved. For the second band of 5.47 GHz, wide bandwidth of 4.7–6.23 GHz (3-dB fractional bandwidth, FBW = 28%), low insertion loss of 2.28 dB, and deep transmission zeros of 53 and 36 dB are presented. Two transmission zeros (3.69 GHz and 3.85 GHz) are placed between the two pass-bands and result in a 46 dB isolation. The compact size is $23.4 \times 23.4\,\text{mm}^2$, and the size reduction is 33%. It can be applied to the WLAN 802.11a/b/g systems.

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