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First of all, we apologize for the lengthy review period.

Manuscript ID 14169 entitled “Multi-wideband bandpass filter using meandered stub-stepped impedance resonators for multiband application” which you submitted to our Journal “International Journal on Communications Antenna and Propagation (IRECAP)” has been reviewed. The comments of the reviewer(s) are included at the bottom of this email.

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Once again, thank you for submitting your manuscript to our Journal and I look forward to receiving your revision.

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Reviewer Responses:

In view of the feedback of the reviewer of this journal, this paper needs the following fulfillments. Below the main remarks are listed:

- The Nomenclature list should be complete with all the symbols used in the manuscript.
- More references should support the analysis of the state of the art in the review section. 50% of the references to be from 2015-2017 are expected.
- English is understandable but needs correction of grammatical errors and style. We suggest to use our service “English Language Editing”. More information can be found to http://www.praiseworthyprize.com/english_service.htm
- The authors should explain how they have chosen the design values of the multi-wideband bandpass filter structure reported at the start of paragraph III.

For any questions don't hesitate to contact us.
Best regards,
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Multi-wideband bandpass filter using meandered stub-stepped impedance resonators for multiband application

Teguh Firmansyah[1], Herudin[2], Cindy Chairunissa[3], Mudrik Alaydrus[4], Gunawan Wibisono[5]

Abstract – *This paper was proposed a multi-wideband bandpass filter (MW-BPF) using meandered stub-stepped impedance resonators (MS-SIR). This research also shows that MS-SIR resonator can generate not only five-pass bands, but also yield wide-fractional bandwidth, good transmission coefficients, ease of fabrication, and compact. The transmission line analysis was used to design and investigate the filter structure. Furthermore, this filter was fabricated on a FR4 substrate and it has a compact size of 0.08 λ_G x 0.14 λ_G, with λ_G as the wavelength at the first resonant frequency. This filter can be applied to DVB-T400, GSM800/GSM900, GPS1200, WCDMA1800, and LTE2100. The validity of the proposed design was shown by the good agreement between the simulation and measurement results.* ***Copyright © 2010 Praise Worthy Prize S.r.l. - All rights reserved.***

Keywords*: Bandpass filter, meandered, stepped impedance resonators, wideband.*

Nomenclature

θ_N	Electrical length
λ_G	Wavelength at the first resonant frequency
Z_{IN}	Characteristic impedance
h	Substrate thickness
εr	Permitivity
tan δ	Loss tan
ADS	Advanced Design System
BPF	Bandpass filter
DVB-T	Digital Video Broadcasting
MEMC	Mixed electric and magnetic coupling
MS-SIR	Meandered stub-stepped impedance resonators
MSLRR	Multiple stubs loaded ring resonator
MW-BPF	Multi-wideband bandpass filter
PCB	Printed circuit board
PMR	Penta mode resonator
GSM	Global System for Mobile communications
GPS	Global Positioning System
WCDMA	Wideband Code Division Multiple Access
LTE	Long Term Evolution

I. Introduction

A bandpass filter (BPF) is an important component in modern wireless communication systems to reduce noise and decrease signal interferences [1][2]. Planar BPFs are especially well-known filter structures that can be fabricated easily using printed circuit board (PCB) technology [3][4]. It is also suitable for commercial applications due to their low-cost integration and compact size [5][6]. In recent years, designing multi-band BPFs with multiband frequencies has become a trend to support the development of numerous types of wireless communication standards [7][8].

There are some attractive design methods to produce multiband BPF such as double-layered structure [9], tri mode stub-loaded stepped impedance resonators [10], penta mode resonator (PMR) [11], mixed electric and magnetic coupling (MEMC) [12], and multiple stubs loaded ring resonator (MSLRR) [13]. However, the multiband-BPF proposed by [5-13] still achieved narrow bandwidth, large size, and complex geometry.

As a novelty, this research proposed a multi-wideband bandpass filter (MW-BPF) with meandered stub-stepped impedance resonators (MS-SIR). In order to realize the five-band bandpass filter, this research proposed to replace the conventional half-wavelength open-circuited stub single-frequency resonators with meandered stub-stepped impedance resonators (MS-SIR). Compared with conventional half-wavelength open-circuited stub single-frequency resonators, the MS-SIR resonator could generate not only the five pass-bands, but also better transmission coefficients, higher fractional bandwidth, and compact size.

To the best of our knowledge, it is the first design of five-passband BPF with wide fractional bandwidth using MS-SIR, which can significantly improve fractional bandwidth. Furthermore, a meander method also was proposed in this research to obtain significant size reduction. A meander method could reduce a filter size as reported by [14].

This filter was fabricated on a FR4 substrate with εr= 4.4, h=1.6 mm, and tan δ= 0.0265. This proposed MW-BPF was simulated by using software Advanced Design System (ADS). The design methodology was detailed in the following sections. Section 2 describes the design of

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multi-band BPF by folded MS-SIR. The transmission line analysis was used to investigate the filter structure. The simulation and measurement results of the MW-BPF are described in Section 3. Finally, Section 4 concludes this research.

II. Stub-stepped impedance resonators structure analysis

A conventional single-band microstrip band pass filter was shown in Fig 1(a). The structure of single-BPF consists of quarter-wavelength (λ/4) and open-circuit stub resonator (λ/2) [15]. The bandwidth of a single-band microstrip BPF is in principle determined by characteristic impedances of open-circuit stub resonator as shown in Fig 1(b). Further, the filter structures are commonly optimized for microstrip realization.

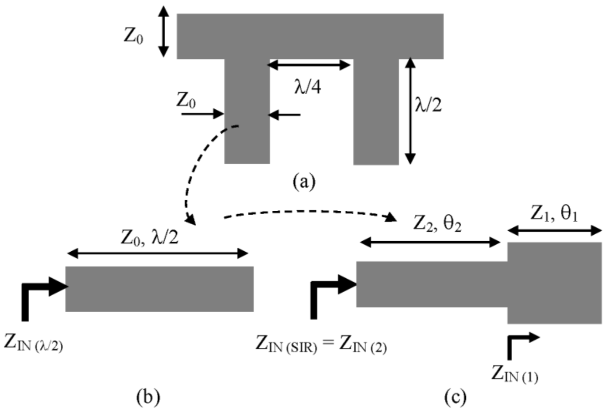


Fig 1. (a) A single band BPF based on conventional half-wavelength open stub resonator, (b) A half-wavelength open stub resonator, (c) A stub-stepped impedance resonator.

In this work, to realize the five-band operation, each open-circuit stub resonator (λ/2) is converted to open-circuit stub-stepped impedance resonators as shown in Fig 1(c). Moreover, the filter structure of MW-BPF using stub-stepped impedance resonators structure was shown in Fig 2(a), with the Z_N (N=1,2,3) and θ_N (N=1,2,3) stand for the characteristic impedance and electrical length, respectively. Furthermore, Fig 2(b) shows the even-excitation characteristic impedance of stub-stepped impedance resonators and Fig 2(c) shows the odd-excitation characteristic impedance of stub-stepped impedance resonators.

Investigating the input impedance Z_{IN} of the stub-stepped impedance resonators at the even- excitation condition as shown in Fig 2(b), the following equations can be derived:

$$Z_{IN\,(1)} = -jZ_1 \cot\theta_1 \,, \quad \text{and} \tag{1}$$

$$Z_{IN\,(SIR-even\ excitation)} = Z_2 \frac{Z_{IN(1)} + jZ_2 \tan\theta_2}{Z_2 + jZ_{IN(1)} \tan\theta_2}$$

$$= Z_2 \frac{-jZ_1 \cot\theta_1 \; + jZ_2 \tan\theta_2}{Z_2 + j(-jZ_1 \cot\theta_1 \;) \tan\theta_2} \tag{2}$$

Therefore, the input admittance is given by:

$$Y_{IN\,(SIR-even\ excitation)} = \frac{1}{Z_2} \frac{Z_2 + Z_1 \cot\theta_1 \tan\theta_2}{-jZ_1 \cot\theta_1 \; + jZ_2 \tan\theta_2} \tag{3}$$

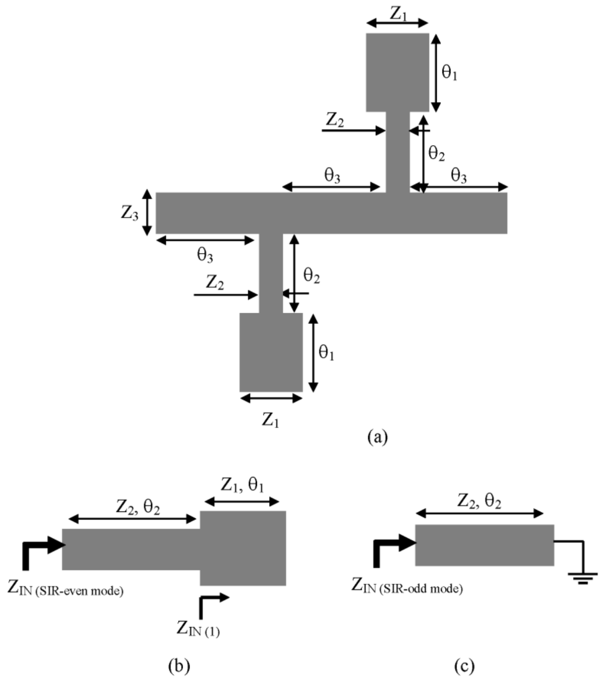


Fig 2. (a) The multi-wideband BPF with stub-stepped impedance resonators structure, (b) even- excitation stub-stepped impedance resonators structure, (c) odd- excitation stub-stepped impedance resonators structure.

The resonant frequencies can be extracted from admittance condition $Y_{in} = 0$ or impedance condition $Z_{in} = \infty$ [16][17][18]. Therefore, the resonance condition of the structure is found as follows:

$$Z_2 + Z_1 \cot\theta_1 \tan\theta_2 = 0 \tag{4}$$

This can be obtained when:

$$\tan\theta_2 = -\frac{Z_2}{Z_1} \tan\theta_1 \quad \text{, or} \tag{5}$$

$$\theta_2 = \pi - \tan^{-1}(K \tan\theta_1) \tag{6}$$

with the impedance ratio $K = Z_2/Z_1$, electrical length θ_N (N=1,2), and $\pi = 180°$. For electrical length $\theta_1 = \lambda/4$, and without frequency dispersion, the relation between resonant frequency (f_N) and fundamental resonant frequency (f_1) can be derived [14][19]:

$$\frac{f_N}{f_1} = \frac{\theta_N}{\theta_1} \quad \text{or} \tag{7}$$

$$f_N = \frac{2\theta_N}{\pi} f_1 \tag{8}$$

Therefore, the even- excitation of the proposed stub-SIR obtain three resonant frequencies, which can be extracted by:

$$f_{\text{even excitation}-1} = f_1 \qquad (9)$$

$$f_{\text{even excitation}-2} = \frac{2f_1}{\pi}\left(\pi - \tan^{-1}(K \tan\theta_1)\right) \qquad (10)$$

$$f_{\text{even excitation}-3} = \frac{2f_1}{\pi}\left(2\pi - \tan^{-1}(K \tan\theta_1)\right) \qquad (11)$$

Investigating the input impedance Z_{IN} at the odd-excitation condition as shown in Fig 2(c), the following equation can be derived:

$$Z_{IN\,(\text{SIR}-\text{odd excitation})} = jZ_2 \tan\theta_2 \qquad (12)$$

The resonant frequencies can be extracted from impedance condition $Z_{in} = \infty$ [16][17][18]. Meanwhile, the resonance condition of the structure is found as follows:

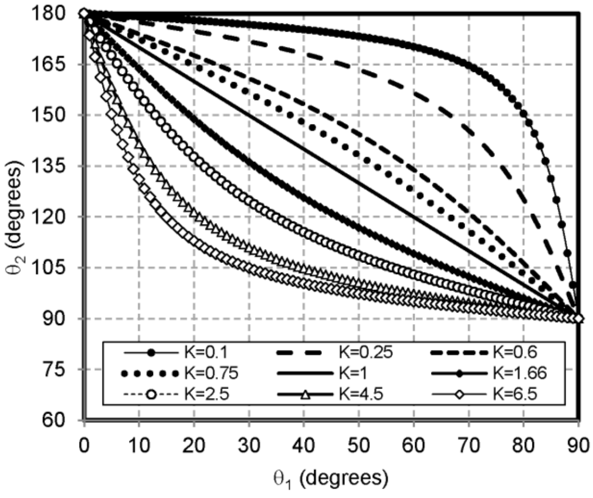
$$\tan\theta_2 = \infty$$

$$\theta_2 = \frac{(2n-1)}{2}\pi \qquad (13)$$

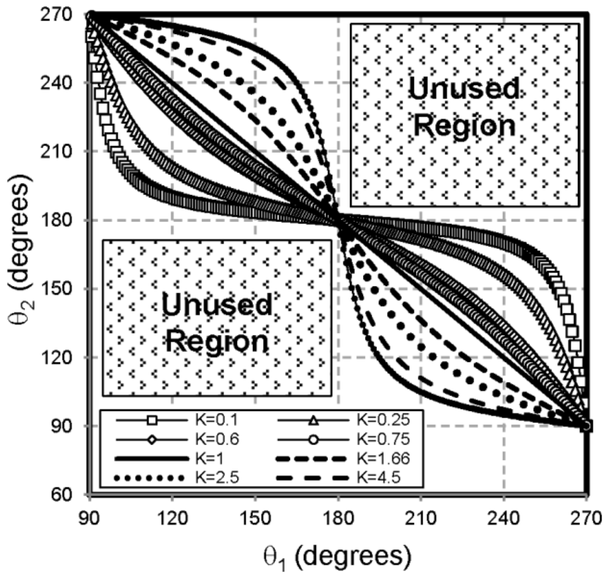
By equation 8, the odd- excitation obtain four resonant frequencies, it can be extracted by:

$$f_{\text{odd excitation}-1,2,} = (2n-1)f_1 \qquad ; n = 1, 2, \qquad (14)$$

It is notable that, the total of resonant frequencies in even- excitation and odd- excitation has provided the five pass-bands frequency. Fig 3(a) to 3(c) show a design curve of θ_2 (degrees) for different values of impedance ratio (K) and θ_1 (degrees). In this research, the following filter structure was chosen, Z_1 = 30 Ω, θ_1=10°, and Z_2 = 50 Ω, hence K = 1.66 and θ_2=163°.



(a)



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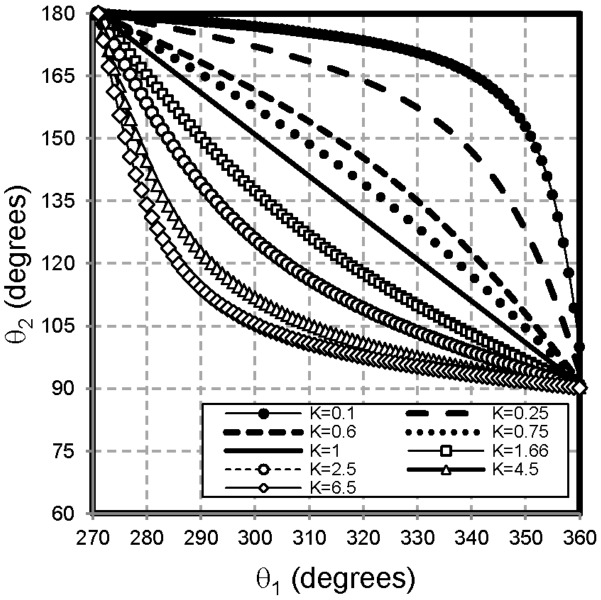
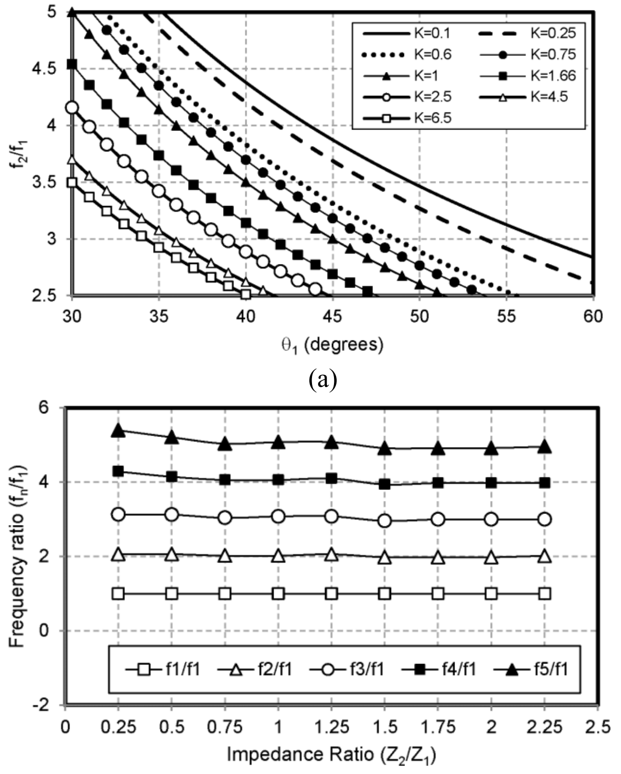


(c)

Fig 3. The curve of θ_2 (degrees) for different values of impedance ratio (K) and θ_1 (degrees). (a) with 0 < θ_1< 90 (degrees), (b) with 90 < θ_1< 270 (degrees), (b) with 270 < θ_1< 360 (degrees).

The unused-region was shown in Fig 3(b); it is also noted that K = 1 stand for uniform resonator/ without step impedance resonator. Moreover, Fig 4(a) illustrates the change of the second pass-band by the impedance ratio (K) and Fig 4(b) shows the effect of frequency ratio by the impedance ratio (K), it shows that the impedance ratio (K) has no effect to frequency ratio.



(a)

(b)

Fig 4. (a) The change of the second frequency-band by the impedance ratio (K) and length θ_1 (degrees), (b) the effect of frequency ratio by impedance ratio (K).

III. Multi-wideband bandpass filter with meandered stub SIR

Based on previously design method with $Z_0 = 50\ \Omega$, referring to Fig 3(a) to 3(c), the design of multi-wideband bandpass filter structure was proposed, $Z_1 = 30\ \Omega$, $\theta_1=10°$, $Z_2 = 50\ \Omega$, $\theta_1=163°$. This MW-BPF was simulated and optimized by using Advanced Design System (ADS). After optimization, the filter structure became $Z_1 = 36.3\ \Omega$, $\theta_1=10.9°$, $Z_2 = 50.47\ \Omega$, $\theta_1=160.4°$. The size is slightly changed compare to the original filter structure. This filter was fabricated on FR4 substrate with $\varepsilon r= 4.4$, h=1.6 mm, and tan $\delta= 0.0265$. In order to reduce filter size, a meander method was also proposed. Fig 5(a) shows layout of multi-wideband bandpass filter with meandered stub SIR (MS-SIR). The dimensions are given as follows (all in millimeters): $W_1 = 5.0$, $W_2 = 3.0$, $W_3 = 3.0$, and $L_1 = 11$, $L_{2a} = 10$, $L_{2b} = 5$, $L_{2c} = 35$, $L_{2d} = 5$, $L_{2e} = 35$, $L_{2f} = 5$, $L_{2g} = 35$, $L_{2h} = 5$, $L_{2i} = 25$, $L_{2j} =5$, and $L_3 = 14$. Moreover, Fig 5(b) shows the photograph of multi-wideband bandpass filter with meandered stub SIR (MS-SIR).

Fig 6(a) shows the extracted reflection coefficients (S_{11}) and transmission coefficients (S_{21}) with varied W_1 and L_1. It can be seen that the reflection coefficients (S_{11}) of frequency f_1, f_2, and f_3 are more stable than f_4, and f_5, by varied W_1 and L_1. However, the transmission coefficients (S_{21}) at all frequencies are still stable.

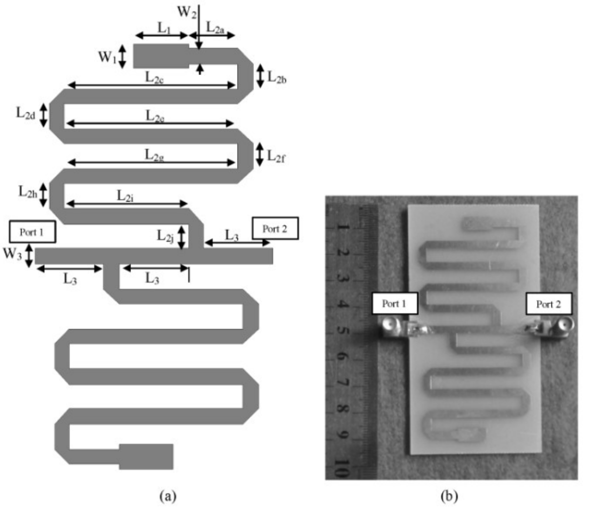
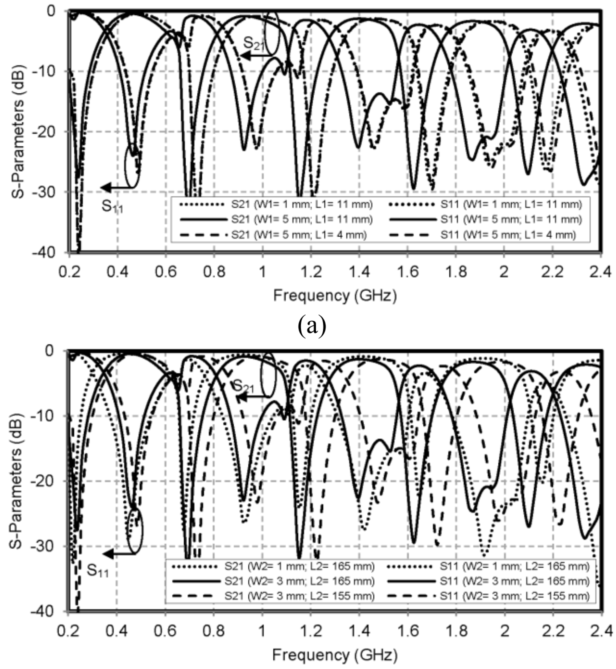


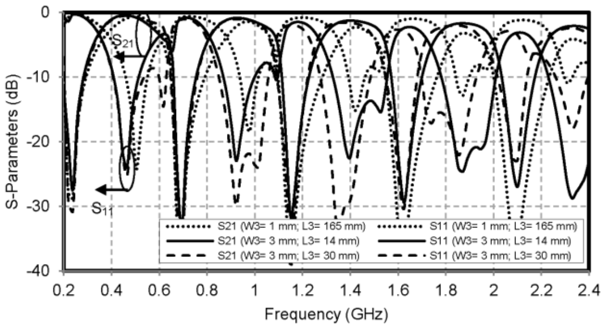
Fig 5. (a) The layout of multi-wideband bandpass filter with meandered stub SIR (MS-SIR), (b) The photograph of multi-wideband bandpass filter with meandered stub SIR (MS-SIR).

Besides that, Fig 6(b) shows the extracted reflection coefficients (S_{11}) and transmission coefficients (S_{21}) with varied W_2 and L_2. The chart shows both of reflection coefficients (S_{11}) and transmission coefficients (S_{21}) are still fairly constant at f_1, f_2, and f_3. Otherwise, at the f_4, and f_5, the reflection coefficients (S_{11}) and transmission coefficients (S_{21}) vary moderately, and it also affect the frequency shift. Furthermore, Fig 6(c) shows the extracted reflection coefficients (S_{11}) and transmission coefficients (S_{21}) with varied W_3 and L_3. It can be seen the reflection coefficients (S_{11}) decrease dramatically without resulting in frequency shift.



(a)

(b)



(c)

Fig 6. Reflection coefficients (S_{11}) and transmission coefficients (S_{21}) (a) Response with varied W_1 and L_1. (b) Response with varied W_2 and L_2. (c) Response with varied W_3 and L_3.

Fig 7(a)-7(g) show the surface current distribution on multi-wideband bandpass filter with meandered stub SIR. The surface current distribution at the first frequency band (f_1= 0.44 GHz) was flowed at the center area and slightly at the upper resonator area as shown in Fig 7(a). At the second frequency band (f_2= 0.88 GHz), the surface current distribution was flowed only at the upper resonator, as shown in Fig 7(b). Furthermore, at the third frequency band (f_3= 1.30 GHz), surface current distribution was flowed at the upper resonator, with slight distribution at the lower resonator, as shown in Fig 7(c). Moreover, both the fourth frequency band (f_4= 1.77 GHz) and the fiveth frequency band (f_4= 3.03 GHz) show that the surface current mostly flows in the lower resonator, with a little surface current in the upper resonator as shown in Fig 7(d) and Fig 7(g), respectively. Finally, either the fifth frequency band (f_5= 2.15 GHz) the surface current was flowed only at the lower resonator, as shown in Fig 7(e).

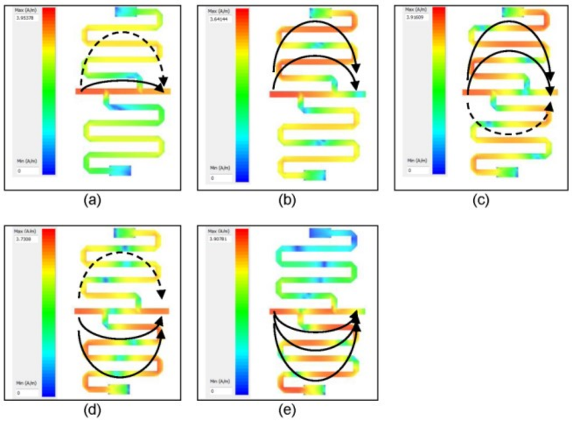
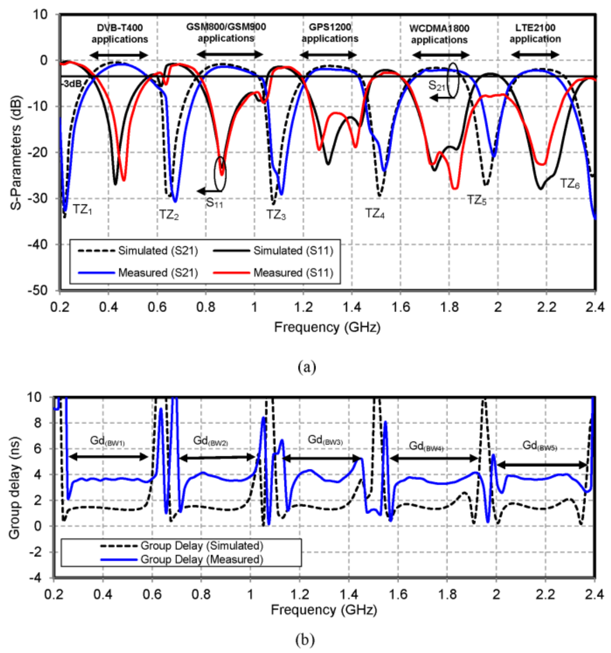


Fig 7. Surface current distribution on multi-wideband bandpass filter with meandered stub SIR, (a) 0.44 GHz, (b) 0.88 GHz, (c) 1.30 GHz, (d) 1.77 GHz, and (e) 2.15 GHz

Fig 8(a) shows comparison between simulation and measurement results achieved by the MW-BPF. A Rhode Schwarz ZVA VNA was used to test the fabricated prototype the MW-BPF. Both simulated and measured results of the multi-wideband bandpass filter with meandered stub SIR have accomplished the five passbands' requirements. The MW-BPF achieves transmission coefficients/fractional bandwidth of -0.84 dB / 42.5 %, -1.36 dB / 21.49 %, -1.85 dB / 14.95 %, -2.12 dB / 10.69 %, and -2.11 dB / 6.02%, at 0.44 GHz, 0.88 GHz, 1.30 GHz, 1.77 GHz, and 2.15 GHz, respectively.



(a)

(b)

Fig 8. (a) Simulation and measurement results of the proposed MW-BPF, (b) Simulated and measured results of group delay of the proposed MW-BPF.

Moreover, both simulated and measured group delays (GDs) of all pass-bands below 6 ns are also depicted in Fig 8(b). Table 1 summarizes the comparison of the proposed MW-BPF.

TABLE I
SUMMARY OF THE PROPOSED BPF COMPARISON

Ref	**Method**	**Band**	**Center Freq (GHz)**	**Trans. coef (dB)**	**-3dB FBW (%)**
[9]	Double-layered structure	5	1.50 / 2.50 / 3.50 / 4.50 / 5.80	-1.50 / -1.80 / -0.90 / -1.20 / -2.50	4.50 / 4.50 / 3.60 / 4.50 / 2.70
[10]	Trimode stub-loaded stepped impedance resonators	5	0.60 / 0.90 / 1.20 / 1.50 / 1.80	-2.80 / -2.90 / -2.90 / -2.60 / -2.30	5.80 / 5.20 / 5.80 / 8.20 / 8.00
[11]	Penta mode resonator (PMR)	5	0.63 / 1.2 / 1.8 / 2.49 / 3.46	-0.43 / -0.86 / -1.10 / -1.98 / 2.55	28.50 / 10.00 / 13.60 / 4.80 / 4.20
[12]	Mixed electric and magnetic coupling (MEMC)	5	2.10 / 3.00 / 4.00 / 4.70 / 7.20	-0.98 / -1.76 / -1.22 / -1.77 / -2.39	13.70 / 5.60 / 10.50 / 5.10 / 2.90
This Work **Multi-wideband**	Meandered Stub-SIR (MS-SIR)	5	0.44 / 0.88/ 1.30 / 1.77 / 2.15	-0.84 / -1.36 / -1.85 / -2.12 / -2.11	**42.5 /** **21.49 /** **14.59 /** **10.69 /** **6.02**

This filter can be applied to DVB-T400, GSM800, GPS1200, WCDMA1800, and LTE2100. This filter has a compact size of 0.08 λ_G x 0.14 λ_G, with λ_G is wavelength at the first frequency. Furthermore, the MW-BPF achieves transmission zeros of -32.1 dB, -30.7 dB, -29.0 dB, -23.9 dB, -20.8 dB, and -34.2 dB, at 0.22 GHz, 0.68 GHz, 1.11 GHz, 1.53 GHz, 1.99 GHz, and 2.40 GHz, respectively. Finally, the validity of the proposed design was shown by the good agreement between simulation and measurement results.

IV. Conclusion

The MS-SIR resonator could generate not only the five pass-bands, but also high fractional bandwidth.. This MW-BPF has a compact size of 0.08 λ_G x 0.14 λ_G, with λ_G is wavelength at the first frequency. This filter can be applied to DVB-T400, GSM800/GSM900, GPS1200, WCDMA1800, and LTE2100. Both the simulation and measurement results of the multi-wideband bandpass filter with meandered stub SIR have accomplished the five passbands with wide fractional bandwidth. A good agreement can be observed between the simulated and measured results which demonstrated the validity of the design.

Acknowledgements

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[IRECAP] Editor Decision

2 pesan

Editorial Staff <editorialstaff@praiseworthyprize.org> 26 April 2018 pukul 16.02
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