Miniaturized Wideband Bandpass Filter with Wide Stopband using Metamaterial-based Resonator and Defected Ground Structure

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Abstract. *This paper presents a miniaturized wideband bandpass filter with wide stopband performance. It is shown that the coupled metamaterial-based resonators (MBRs) incorporating with the defected ground structure (DGS) can significantly increase the coupling value to achieve wideband bandpass filter. This technique has been extended to realize wideband bandpass filter having fractional bandwidth of 63 % and low insertion loss in the passband. To further suppress the spurious harmonics and upper stopband, the combining of the zero-degree feed structure and embedded slot-loaded resonators in both input and output ports is introduced. The proposed filter has not only compact size but also good out-of-band response. The experimental results are demonstrated and discussed.*

Keywords

Wideband bandpass filter, Metamaterial-based resonator, Spurious suppression, Upper stopband, Defected ground structure.

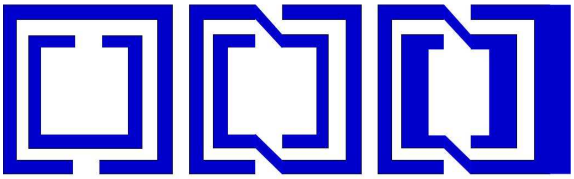
1. Introduction

Wideband and high-performance bandpass filters have gained great attention in the next generation wireless communication systems. Microstrip bandpass filters are particularly popular structures because they can be fabricated using printed circuit technology, compact size and low-cost integration. Among the diverse configurations of microstrip resonator, open loop resonator is widely used due to its advantages to produce compact filter with simple design procedure. However, coupling between resonators for designing wideband filter becomes very large and difficult to achieve. Numerous researchers have proposed various configurations for wideband bandpass filters [1]-[4]. Multimode resonators, dual-mode [1], triple-mode [2] and four-mode [3], have been proposed for wideband operation. Besides, the microstrip parallel-coupled half-wavelength resonator is one of the most commonly used wideband bandpass filters [4]. However, in these filters, critical values of the gaps between coupled lines are required to obtain very strong coupling, which leads to fabrication difficulties.

An effective way to obtain tight coupling within fabrication limit is to use defected ground structure (DGS) or aperture compensation technique, which can realize strong coupling compared with the coupled line structure [5]-[6]. This process modifies the characteristics of the transmission line such as the line capacitance and inductance. Therefore, the DGS is usually used to improve the passband and stopband characteristics. Several methods have been developed using different forms of DGSs [7].

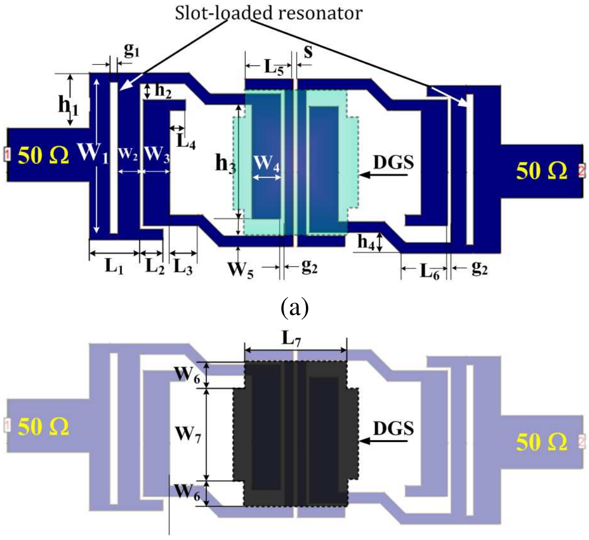
Moreover, reducing size is also the main challenge of the filter design for microstrip filters. Several types of resonators have been designed to overcome these problems, such as stepped-impedance resonator, meander resonator, and slow-wave open loop resonator. Nevertheless, miniaturized resonators lead to a reduced size of filter, but not always improve the spurious response. In recent years, several filter applications at microwave frequency have been developed by means of metamaterials (MTMs) based on subwavelength resonators such as the split-ring resonators (SRRs) [8]-[14] and different resonators [15]-[16]. Because of the small electrical size of the unit cells, the metamaterial-based resonator (MBR) offers a great solution to the design of miniaturized microwave resonator. Besides, the MBR has been used not only to design miniaturized filter but also to obtain microwave devices with enhanced bandwidth [17]. However, MBRs have usually been used for notch band [18]-[19] and narrow bandpass filters [20] and, furthermore, there is still a vast need for research on miniaturization of wideband transceiver components using MBRs.

The objective of this paper is to present and implement a new class of wideband metameterial-based resonator bandpass filter with wide stopband. A metameterial-based resonator of non-bianisotropic split-ring resonator (NB-SRR) structure is applied to construct the proposed wideband filter with the high coupling coefficient and compact size. In order to improve bandwidth and relax fabrication tolerance, we also used a cross-shaped DGS under coupled area be-



(a) (b) (c)

Fig. 1. Topologies for the rectangular SRR (a), conventional rectangular NB-SRR (b), and the proposed modified NB-SRR (c).



(a)

(b)

Fig. 2. The proposed wideband bandpass filter with wide stopband using metamaterial-based resonator (MBR), NB-SRRs and defected ground structure (DGS)(a) Top view and (b) Bottom view.

tween the NB-SRRs. To suppress the first and second spurious responses, the zero-degree feed structure and embedded slot-loaded resonator have been successfully applied, respectively. Bandstop filtering effect of the second spurious frequency was achieved by adding slot-loaded resonators at input and output feed lines. Moreover, a zero-degree feed structure is introduced and applied to realize additional transmission zeros at finite frequencies near the edges of passband and increased stopband rejection, resulting in improved selectivity of the filter. Finally, the proposed filter is fabricated to experimentally verify the predicted results of our design.

2. Filter Design and Stopband Performance

2.1 Wideband Bandpass Filter Design

In order to obtain a wideband bandpass filter, we combine two techniques to obtain a good wideband characteristic and relaxing for fabrication. The first technique is the use of the coupled MTM-based resonator, namely NB-SRR. The other is the use of the DGS, which is adopted to tighten the coupling of the NB-SRR in order to improve the bandpass filter's performance.

Split-ring resonators have been applied for microstrip narrow bandpass filters and notch band filters. However, coupling between SRRs (Fig. 1a) is not enough and reduction of size is required. The conventional NB-SRR structure (Fig. 1b) is a slight modification of the basic SRR topology, which shows a 180° rotation symmetry in the plane of the element. The modified NB-SRR structure (Fig. 1c), which is the stepped-impedance NB-SRR that one can reduce through the resonator length, is proposed for wideband bandpass filter. The NB-SRR structure could be seen as two open-loop microstrip resonators with a strong electromagnetic interaction between them. Therefore, overcoupling resonator behaviour is present, leading to a frequency split where two resonances appear; one below and another above the resonant frequency of isolated open-loop microstrip resonators. It seems like multi-mode resonators. The NB-SRR is developed based on concepts of designing a unit cell of MTMs. The filter design procedure uses the coupled-resonator method, as described in [21]. Fig. 2 shows the two coupled NB-SRR scheme of the proposed filter structure, where top and bottom views of the structure are shown in Fig. 2a and 2b, respectively. This is the second-order filter. The key feature for achieving wideband operation is to realize extremely tight coupling structure. The NB-SRR on the top layer is coupled together and the coupling strength is higher if the gap (S) between NB-SRR is decreased. When designing a wideband bandpass filter, the dependence of coupling coefficient with S should be considered. Fig. 3 compares the percentages of bandwidth between three different couplings of conventional open loop resonators including electric, magnetic and mixed couplings, and the proposed NB-SRR using the same substrate. It can be noticed that for the same separation S, the modified NB-SRR structure produces higher percentages of bandwidth with the same center frequency. In contrast, the electric coupling is relatively weak, therefore, it has narrow bandwidth. It means that the modified NB-SRR is suitable for wideband filter. Given the required coupling coefficients for a filter specification, one may determine the proper spacing based on Fig. 3.

As mentioned above, the coupling coefficient depends on the separation between resonators. There is a limitation for reducing coupling space between coupled resonators for tight coupling. When the coupling space between resonators is extremely narrow, the sensitivity depending on it can become a serious problem, and it is very difficult to implement. Hence, the DGS can be an alternative solution instead of narrow-coupling space for tight coupling. When the DGS is employed on the ground plane under the coupling area of the NB-SRRs, the coupling value between resonators and ground plane is decreased, so tighter coupling between the resonators can be achieved. Fig. 4 shows the simulated S-parameters (S_{11} and S_{21}) of the wideband bandpass filter employing with and without the DGS. In the case of the filter with the DGS, a maximum bandwidth of 2.5 GHz can

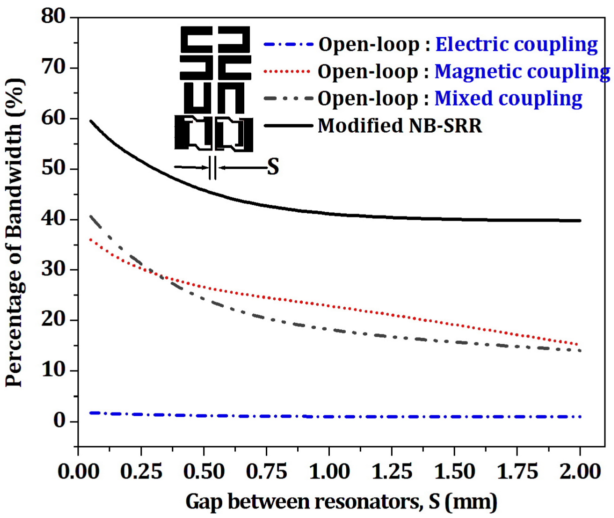


Fig. 3. Variation of percentage bandwidth with three couplings of conventional open loop resonator and the modified NB-SRR. (All of configurations used the same substrate.)

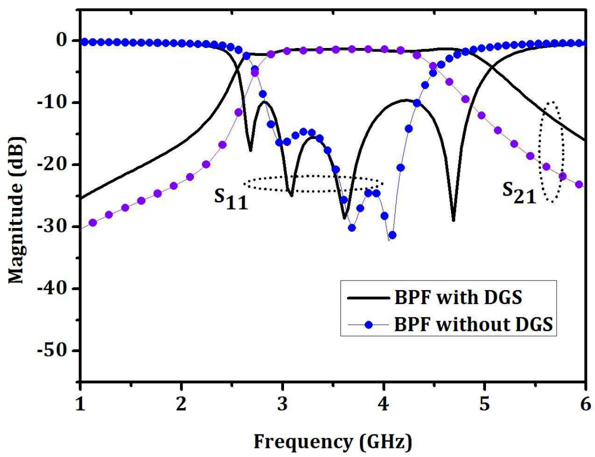


Fig. 4. Comparison of simulated S-parameter results for the wideband bandpass filter with and without the DGS.

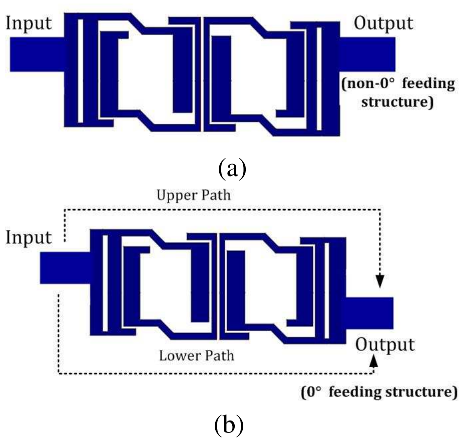


Fig. 5. (a) Non zero-degree feed structure and (b) zero-degree feed structure and the paths of the zero feed structure.

be obtained and four poles within the wideband can be observed.

Three poles of them are due to the triple-mode NB-SRR and another is yield by the DGS. Interestingly, for filter without the DGS, the bandwidth decreases and the number of poles reduces either. Furthermore, the beginning of frequency band is also decreased when the DGS is introduced. It means that using optimal DGS size allows reducing the resonator size, obtaining maximum value of bandwidth for a specific gap between resonators.

2.2 Bandstop Characteristics for Spurious Suppression

Generally, high-performance bandpass filters are required to have wide stopband response in order to improve the system performance. Usually, spurious frequency will occur at integer of center frequency of passband for traditional microstrip $\lambda/2$ resonator bandpass filters due to the unequal even- and odd-mode phase velocities. To further suppress upper stopband and miniaturize over all size, the proposed wideband bandpass filter is constructed with (i) zero-degree feed structure and (ii) embedded slot-loaded resonators in both input and output ports.The zero-degree feed structure is used to create transmission zeros near the passband edge. A zero-degree feed structure [22] is adopted in the design of NB-SRRs in this paper. The simple explanation for the creation of transmission zeros is shown in Fig. 5. Due to the equal-magnitude and nearly 180° out-of-phase coupling through the upper and lower paths, the signal are cancelled out each other at certain frequencies. The further design of the zero-degree feed was studied and explained in [22].

The function of embedded straight slot-loaded resonators is to reject the second spurious frequency of the filter. It provides excellent bandstop characteristics and can be applied in antennas and filters. The embedded slot-loaded resonators are a simple defected structure which is realized by etching one slot on a microstrip line for filters and on the patch for antenna designs. Different configurations of slots are introduced such as U-shape [23], V-shape [24], and meander line shape [25]. For this paper, a simplest slot of straight shape is added to the input and output ports to introduce the notch band effect at around 12 GHz of the second spurious frequency. By deciding the length of the slot resonator, the spurious peak can be rejected in the stopband. The slot corresponds to a nearly half-wavelength resonator at the center frequency of the required notch band. As the first order of approximation, the required slot length (W_1 in Fig. 2) to obtain the notch frequency is given by:

$$L_{slot} \approx \frac{0.5\lambda_{0\_notch}}{\sqrt{\varepsilon_{eff\_slot}}} \quad (1)$$

where λ_{0_notch} is free space wavelength of the notch frequency and ε_{eff_slot} is the effective dielectric constant of the narrow slot structure $\varepsilon_{eff\_slot} = (\varepsilon_r + 1)/2$.

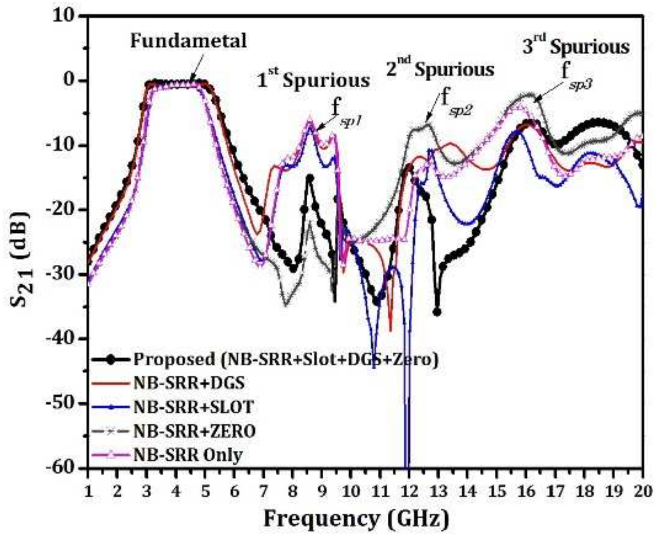


Fig. 6. Comparison of frequency responses (S_{21}) of five wideband bandpass filter configurations.

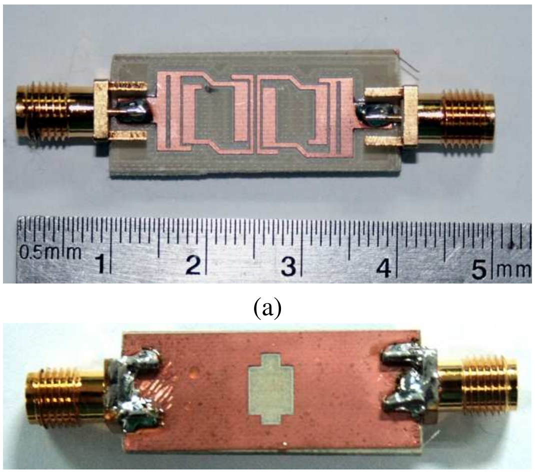
To summarize the effects of the proposed techniques including DGS, zero-degree feed and slot-loaded resonator, the performances of the proposed filter are compared and summarized in Fig. 5 and Tab. 1, respectively. Let us first consider the case of NB-SRR only without zero-degree feed, DGS, and slot-loaded. It is found that the spurious response is characterized by the presence of three modes, f_{sp1}, f_{sp2} and f_{sp3}. The position of these modes are related to the center frequency of the pass band as follows: $f_{sp1} = 2f_0$, $f_{sp2} = 3f_0$ and $f_{sp3} = 4f_0$. Concerning the performance at the passband, it is observed that the filters with DGS have wider bandwidth compared to those without DGS. Thus, wider bandwidth can be achieved by introducing DGS. In case of NB-SRR with DGS (NB-SRR+DGS), the wideband response shows good passband performance except the upper band has the spurious responses. For the case of filters with zero-degree feed, the first spurious frequency (f_{sp1} around 8.5 GHz) is mainly decreased from -4 dB to -13 dB compared without zero-feed structure. Also, there are additional transmission zeros at 9.2 and 11.8 GHz, which appears close to the first spurious. As observed in Fig. 6 for the proposed case (NB-SRR+Slot+DGS+Zero), four transmission zeros can be found at 7.8, 9.2, 10.7 and 12.8 GHz, respectively. In order to suppress the second spurious frequency (f_{sp2} around 12.5 GHz) without passband perturbation and keeping the size of filter, the embedded slot resonators are added at both input and output feed ports. From Tab. 1, it can be noticed that the filters without slot resonator (i.e. NB-SRR+Zero, NB-SRR+Zero+DGS) have high magnitude of S_{21} at 12.5 GHz while the filters with slot resonator have better stopband performance at $3f_0$ of 12.5 GHz. Thus, we can conclude that the DGS can increase the coupling between resonators and therefore increase the bandwidth. The first and second spurious responses are suppress by introducing the zero-degree feed and embedded slot-loaded resonator, respectively. Unfortunately, the third spurious frequency (f_{sp3}) of 16 GHz is still high.

3. Filter Implementation and Measured Results

To demonstrate the proposed topology usefulness, the filters are performed by a commercial full-wave electromagnetic simulator IE3D to calculate the performance of the proposed filter. Based on the above investigation, a new miniaturized wideband bandpass filter is designed, implemented and tested. The proposed filter is fabricated on an inexpensive FR-4 substrate along with dielectric constant (ε_r) of 4.4, thickness of 1.6 mm and loss tangent 0.019. For this substrate and equation (1), the slot length (W_1) is 7.30 mm (7.54 mm for fabricated prototype) corresponding with the second spurious response of 12.5 GHz. In the design, the gap g_2 and separation between the resonators S are set as 0.2 mm in order to enhance the coupling degree and relax fabrication tolerance. After slight adjustment of certain dimensions is made towards achieving the satisfactory S-parameters (S_{11} and S_{21}), a prototype of wideband bandpass filter is fabricated and measured. Photographs and dimensions of the fabricated filter are shown in Fig. 7. The proposed filter is measured by using an Agilent 8719ES vector network analyzer, which utilized the short-open-load-thru (SOLT) calibration. The measured and simulated S-parameter and group delay responses are presented and compared in Fig. 8. When compared with the simulated curve, the measured one has slightly wider bandwidth but the S_{11} is higher. Some possible reasons are the error of the fabrication tolerance and the substrate dielectric constant of inexpensive FR-4 material. The major difference occurs in the gap spacing between resonators and tolerance of size and position of DGS. The measured 3-dB fractional bandwidth is 68% from 2.76 to 5.61 GHz, whereas the in-band return loss is greater than 13 dB. The measured minimum insertion loss is 1.31 dB at 4.3 GHz. The loss is due to the circuit loss including dielectric and conductor losses. Moreover, the designed filter has

Types	Bandwidth (%, GHz)	1^{st} spurious	2^{nd} spurious	3^{rd} spurious
NB-SRR only	50%, 3.0-5.0	-4.35 dB@8.69 GHz	-11.6 dB@12.21 GHz	-5.15 dB @15.53 GHz
NB-SRR+Zero	50%,3.0-5.0	-16.3 dB@8.60 GHz	-6.40 dB@12.59 GHz	-2.19 dB @16.10 GHz
NB-SRR+DGS	61%,2.8-5.3	-4.51 dB@8.79 GHz	-10.39 dB@12.21 GHz	-8.23 dB @16.01 GHz
NB-SRR+Slot	50%,3.0-5.0	-5.5 dB@8.69 GHz	-14.10 dB@12.68 GHz	-9.95 dB @15.54 GHz
NB-SRR+Zero+Slot	50%,3.0-5.0	-13.5 dB@8.60 GHz	-19.56 dB@12.35 GHz	-3.95 dB @16.10 GHz
NB-SRR+Zero+DGS	61%,2.8-5.3	-14.8 dB@8.60 GHz	-5.83 dB@12.59 GHz	-2.92 dB @16.29 GHz
NB-SRR+Zero +Slot+DGS(Proposed)	63%, 2.8-5.4	-12.0 dB@8.60 GHz	-17.67 dB@12.11 GHz	-4.55 dB @16.20 GHz

Tab. 1. Performances of the eight wideband bandpass filter configurations.



(a)

(b)

Fig. 7. Photograph of the proposed wideband bandpass filter (a) top view, (b) bottom view L_1 = 2.47, L_2 = 1.17, L_3 = 1.43, L_4 = 0.78, L_5 = 2.34, L_6 = 2.27, L_7 = 5.0, W_1 = 7.54, W_2 = 1.08, W_2 = 1.3, W_3 = 1.43, W_4 = 0.52, W_5 = 1.3, W_6 = 4.7, h_1 = 2.76, h_2 = 0.845, h_3 = 5.72, h_4 = 1.04 and g_1 = 0.39 (unit: mm).

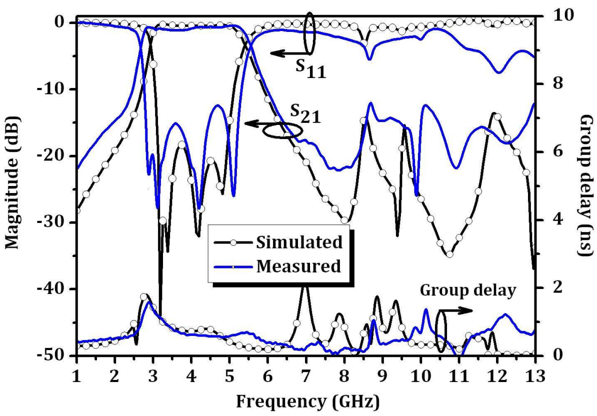


Fig. 8. Simulated and measured S-parameter and group delay results of the proposed wideband bandpass filter.

excellent stopband performance. It is observed that there is only one passband from 1.0 to 13.0 GHz. As the result, the upper rejection bandwidth is obtained from 5.6 GHz to the region beyond the measured upper scope of 13.0 GHz; all are over 15 dB band rejections. It can also be seen that the out-of-band rejection level is below 15 dB at the lower band stopband (from 1.0 to 2.5 GHz).

From measured results in Fig. 8, there are three transmission zeros at 7.8, 9.7 and 10.6 GHz. The first two positions of these created zeros are primarily dominated by the zero-degree feed structure. In addition, in order to suppress the second spurious frequency around 12.5 GHz, the embedded slot-loaded resonator in the input and output feed lines is applied. It is observed that the applied slot-loaded resonator will not affect the passband performance. The group delay of the proposed filter is also measured. The variation of measured group delay is from 0.62 to 0.98 nS over the frequency range of the passband.

4. Conclusion

A new miniaturized and low-cost wideband bandpass filter is successfully developed. Since the strong coupling needed for wideband filter can be obtained by using the modified NB-SRR coupled and the DGS together. By employing the DGS under the coupling area of the NB-SRRs, the coupling between coupled resonators is enhanced. The proposed wideband bandpass filter exhibits good selectivity, wide stopband and size reduction benefit. The second harmonic suppression is achieved by adding embedded slot-loaded resonators at input and output lines. Moreover, the transmission zeros are created by employing zero-feed for enhancing the rejection in the stopband and also improving the filter selectivity. This work may open the door to new design strategies for the wideband bandpass filters.

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References

[1] HSIEH, L.-H., CHANG, K. Compact, low insertion loss, sharp rejection wideband bandpass filters using dual-mode ring resonators with tuning stubs. *Electronics Letters*, 2001, vol. 37, no. 22, p. 1345 - 1347.

[2] SRISATHIT, K., WORAPISHET, A., SURAKAMPONTORN, W. Design of triple-mode ring resonator for wideband microstrip bandpass filters. *IEEE Transactions on Microwave Theory and Techniques*, 2010, vol. 58, no. 11, p. 2867 - 2877.

[3] CAI, P., MA, Z., GUAN, X., KOBAYASHI, Y., ANADA, T., HAGIWARA, G. A novel compact ultra-wideband bandpass filter using a microstrip stepped-impedance four modes resonator. In *IEEE MTT-S International Microwave Symposium Digest*. Honolulu (USA), 2007, p. 751 - 754.

[4] MANDAL, M. K., SANYAL, S. Design of wide-band, sharp rejection bandpass filters with parallel-coupled lines. *IEEE Microwave Wireless Components Letters*, 2006, vol. 16, no. 11, p. 597 - 599.

[5] ZHU, L., BU, H., WU, K. Broadband and compact multi-pole microstrip bandpass filters using ground plane aperture technique. *IEE Proceedings Microwaves, Antennas & Propagation*, 2002, vol. 149, no. 1, p. 71 - 77.

[6] PARUI, S. K., DAS, S. A new defected ground structure for different microstrip circuit applications. *Radioengineering*, 2007, vol. 16, no. 1, p. 16 - 22.

[7] PARK, J.-S., YUN, J.-S., AHN, D. A design of the novel coupled-line bandpass filter using defected ground structure with wide stopband performance. *IEEE Transactions on Microwave Theory and Techniques*, 2002, vol. 50, no. 9, p. 2037 - 2043.

[8] JANG, S.-H., Lee, J.-C. Design of novel cross-coupling elliptic function filters with the miniaturized edge-coupled split ring resonators. *Microwave and Optical Technology Letters*, 2005, vol. 45, no. 6, p. 495 - 499.

[9] BONACHE. J., MARTIN. F., GARCIA-GARCIA, J., GIL, I., MARQUES, R., SOROLLA, M. Ultra wide band pass filters (UWBPF) based on complementary split rings resonators. *Microwave and Optical Technology Letters*, 2005, vol. 46, no. 3, p. 283 - 286.

[10] GIL, M., BONACHE, J., GARCIA-GARCIA, J., MARTEL, J., MARTIN, F. Composite right/left-handed metamaterial transmission lines based on complementary split-rings resonators and their applications to very wideband and compact filter design. *IEEE Transactions on Microwave Theory and Techniques*, 2007, vol. 55, no. 6, p. 1296 - 1304.

[11] VELEZ, A., AZNAR, F., BONACHE, J., VELAZQUEZ-AHUMADA, M. C., MARTEL, J., MARTIN, F. Open complementary split ring resonators (OCSRRs) and their application to wideband cpw band pass filters. *IEEE Microwave and Wireless Components Letters*, 2009, vol. 19, no. 4, p. 197 - 199.

[12] MARQUES, R., BAENA, J. D., MARTEL, J., MEDINA, F., FALCONE, F., SOROLLA, M., MARTIN, F. Novel small resonant electromagnetic particles for metamaterial and filter design. In *Proceedings of International Conference on Electromagnetics in Advanced Applications, ICEAA'03*. Torino (Italy), 2003, p. 439 - 442.

[13] MARQUES, R., MEDINA, F., RAFII-EL-IDRISSI, R. Role of bianisotropy in negative permeability and left handed metamaterials. *Physical Review B*, 2002, vol. 65, paper 144440.

[14] SHAMONIN, M., SHAMONINA, E., KALININ, V., SOLYMAR, L. Resonant frequencies of a split-ring resonator: analytical solutions and numerical simulations. *Microwave and Optical Technology Letters*, 2005, vol. 44, no. 2, p. 133 - 136.

[15] AZNAR, F., GARCIA-GARCIA, J., GIL, M., BONACHE, J., MARTIN, F. Strategies for the miniaturization of metamaterial resonators. *Microwave and Optical Technology Letters*, 2008, vol. 50, no. 5, p. 1263 - 1270.

[16] GARCIA-GARCIA, J., BONACHE, J., GIL, I., MARTIN, F., VELAZQUEZ-AHUMADA, MD. C., MARTEL, J., Miniaturized microstrip and CPW filters using coupled metamaterial resonators. *IEEE Transactions on Microwave Theory and Techniques*, 2006, vol. 54, no. 6, p. 2628 - 2635.

[17] SISO, G., GIL, M., ARANDA, M., BONACHE, J., MARTIN, F. Miniaturization of planar microwave devices by means of complementary spiral resonators (CSRs): design of quadrature phase shifters. *Radioengineering*, 2009, vol. 18, no. 2, p. 144 - 148.

[18] LI, Q., LI, Z.-J., LIANG, C.-H., WU, B. UWB bandpass filter with notched band using DSRR. *Electronics Letters*, 2010, vol. 46, no. 10, p. 692 - 693.

[19] ALI, A., ZHIRUN HU Metamaterial resonator based wave propagation notch for Ultrawideband filter applications. *IEEE Antennas and Wireless Propagation Letters*, 2008, vol. 7, p. 210 - 212.

[20] DE PACO, P., MENENDEZ, O., MARIN, J. Dual-band filter using non-bianisotropic split-ring resonators. *Progress In Electromagnetics Research Letters*, 2010, vol. 13, p. 51 - 58.

[21] HONG, J. -S. LANCASTER, M. J. Microstrip filters for RF/microwave applications. New York (USA): *Wiley*, 2001.

[22] TSAI, C. M., LEE, S. Y., TSAI., C. C. Performance of a planar filter using a 0° feed structure. *IEEE Transactions on Microwave Theory and Techniques*, 2002, vol. 50, no. 10, p. 2362 -2367.

[23] MEELOON, M., CHAIMOOL, S., AKKARAEKTHALIN, P. A broadband bandpass filter with a notch-band using step-impedance resonator and embedded slots . *IEEE Asia Pacific Microwave Conference, APMC*. Singapore, 2009, p. 1446 - 1449.

[24] AHAMADI, B., FARAJI-DANA, R. A miniaturised monopole antenna for ultrawide band applications with band-notch filter. *IET Microwaves, Antennas & Propagation*, 2009, vol. 3, no. 8, p. 1224 - 1231.

[25] YANG, G.-M., JIN, R., VITTORIA, C., HARRIS, V. G., SUN, N. X. Small ultra-wideband (UWB) bandpass filter with notched band. *IEEE Microwave and Wireless Componenets Letters*, 2008, vol. 18, no. 3, p. 176 - 178.

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