Progress In Electromagnetics Research C, Vol. 64, 51–59, 2016

A Compact, Wideband Waveguide Bandpass Filter Using Complementary Loaded Split Ring Resonators

Amit Bage* and Sushrut Das

Abstract—This paper presents a Complementary Loaded Split Ring Resonator (CLSRR) based compact, wideband, waveguide bandpass filter. Three identical CLSRRs were fabricated and placed on the transverse plane of a standard WR-90 waveguide at a quarter wavelength distance to form the filter. The proposed filter was initially simulated using Ansoft HFSS (version 14) and then fabricated and measured. The measured result shows a fractional bandwidth of 18.80% at 10.05 GHz. Total length of the filter is only 20.33 mm which is compact enough. Detailed design procedure has been presented along with the equivalent circuit of the filter. A table has been provided to compare the performance of the proposed filter with those already available in the literatures. The table shows that the proposed filter is compact and has higher bandwidth, lower insertion loss and higher return loss.

1. INTRODUCTION

Waveguide bandpass filters are required for low-cost, low-loss and high power filtering applications in modern microwave and millimeter wave systems. To fulfill this need, several waveguide bandpass filters were developed in last few decades, generally using posts and irises. These are called direct-coupled waveguide resonator filter. A detailed theory for designing such filters has been provided by Matthaei et al. [1] and Hunter [2]. In addition to the use of post and irises, waveguide filters using Frequency Selective Surfaces [3–7], resonant window [8] and fractal shaped irises [9] were also reported.

During the last few years, as the demands for portable systems have increased, low-profile systems have drawn much interest from researchers. Therefore, several types of filter miniaturization techniques have been introduced. These include the use of evanescent mode [10–12], circular posts [13], dielectric filling [14, 15], ridge waveguide [16], fractal shaped irises [17] and ridge resonator [18].

In 1968 Veselago proposed the theoretical concept of negative permittivity and permeability, which he called left handed medium (LHM) as in such case the electric field (E), magnetic field (H) and wave vector (K) forms a left handed system [19]. Later, in 2000, Smith et al. [20] demonstrated this theory using a periodic array of interspaced conducting nonmagnetic split ring resonators and continuous wires, which put a great potential for the circuit miniaturization. It was found that the introduction of Split Ring Resonators (SRRs) can provide band stop responses [21–22]. Therefore, based on Babinet's principle [23] and duality theorem, the complementary screen of SRR is expected to provide a dual behavior, that is a bandpass response. Following this concept a few papers have been published on compact waveguide filter using CSRRs [24–26].

In addition to the filter miniaturization, many efforts also have been made to design wideband waveguide bandpass filters to accommodate more bandwidth. Different techniques like ridge waveguide [27], cavity backed inverters [28], cross-coupled K-inverters [29] and fractals [9, 17] were used.

Received 1 April 2015, Accepted 29 April 2016, Scheduled 10 May 2016
* Corresponding author: Amit Bage (bageism@gmail.com).
The authors are with the Department of Electronics Engineering, Indian School of Mines, Dhanbad, Jharkhand-826004, India.

The above literatures shows that only Olumi et al. [17] have tried to achieve both compactness and enhanced bandwidth. Since the fractals, used in this filter design, are made of metals, they are difficult to fabricate, and also make the circuit heavy.

In this paper attempt has been made to design a compact, wideband waveguide bandpass filter with 3 dB bandwidth from 9.07 GHz to 10.98 GHz and fractional bandwidth of 19.13% at 9.98 GHz using CLSRR. Three identical CLSRRs were fabricated on Roger RO4350 substrate with relative permittivity 3.66, dielectric loss tangent 0.004, substrate height 0.762 mm, copper thickness 0.035 mm and PCB cross sectional dimension same as WR-90 waveguide (22.86 mm×10.16 mm) and were placed on the transverse plane of a standard WR-90 waveguide at quarter wavelength distance. Since printed circuit board (PCB) based CLSRRs have been used instead of metal fractals, the filter has lower weight and is also easy to fabricate. The proposed filter was initially simulated using Ansoft HFSS (version 14) and then fabricated and measured. The detailed design procedure has been presented along with the necessary formulae and equivalent circuit of the filter. A table has been provided to compare the performance of the proposed filter with those already available in the literatures. The table shows that the proposed filter is compact and has higher bandwidth, lower insertion loss and higher return loss.

2. FILTER DESIGN

The objective of the design is to realize a wideband, three-section Chebyshev bandpass filter with lower cut-off frequency (f_1) 9.07 GHz, higher cut-off frequency (f_2) 10.98 GHz, center frequency (f_0) 9.98 GHz and pass band ripple 0.15 dB. To achieve the goal, we have started with a low pass filter prototype with unity source and load impedance and unit cut-off frequency and then applied impedance and frequency scaling [29]. For a three-section, 0.15 dB equiripple Chebyshev lowpass filter with unity source and load impedance and unity cut-off frequency, the element values can be found as $g_0 = 1.0000$, $g_1 = 1.1397$, $g_2 = 1.1546$, $g_3 = 1.1397$ and $g_4 = 1.0000$. If the first element of the low-pass filter is considered to be inductor, then after impedance and frequency scaling, the prototype lumped element equivalent bandpass filter will be as shown in Fig. 1, where [30]

$$L'_1 = \frac{g_1 Z_0}{\omega_0 \Delta} = 47.4741\,\mathrm{nH} \tag{1}$$

$$C'_1 = \frac{\Delta}{\omega_0 g_1 Z_0} = 0.0054\,\mathrm{pF} \tag{2}$$

$$L'_2 = \frac{\Delta Z_0}{\omega_0 g_2} = 1.3209\,\mathrm{nH} \tag{3}$$

$$C'_2 = \frac{g_2}{\omega_0 \Delta Z_0} = 0.1925\,\mathrm{pF} \tag{4}$$

$$L'_3 = \frac{g_3 Z_0}{\omega_0 \Delta} = 47.4741\,\mathrm{nH} \tag{5}$$

$$C'_3 = \frac{\Delta}{\omega_0 g_3 Z_0} = 0.0054\,\mathrm{pF} \tag{6}$$

where

$$\Delta = (f_2 - f_1)/f_0 = 0.1913 \tag{7}$$

$$Z_0 = 499.8960\,\Omega \tag{8}$$

The lumped element equivalent circuit, shown in Fig. 1, requires two different types of resonator circuit with different L and C values, which makes the filter design complicated. Therefore, to simplify the design, we have modified the series resonators into equivalent parallel resonators having L and C values same as the parallel resonator of Fig. 1 with the help of inverters on both sides of them, as shown in Fig. 2 [31]. If L_S and C_S be the inductance and capacitance of the series resonator and L_P and C_P be the inductance and capacitance of the equivalent parallel resonator then they should satisfy the following relation:

$$L_S C_S = L_P C_P = 1/\omega_0^2 \tag{9}$$

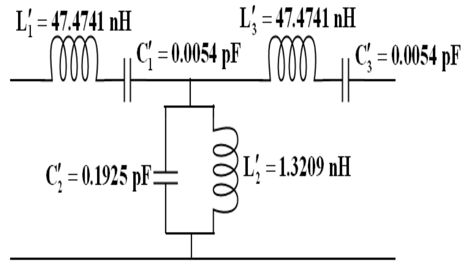

Figure 1. Lumped element equivalent circuit of the bandpass filter.

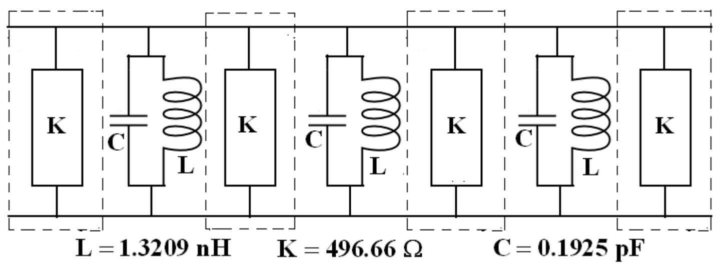

Figure 2. Lumped element equivalent circuit of the bandpass filter consisting of identical parallel tuned circuits.

where ω_0 is the angular resonance frequency of the resonators. The value of the impedance inverter can be calculated as:

$$K = \omega_0 \sqrt{L_S L_P} = 496.66\,\Omega \tag{10}$$

Once the equivalent lumped element circuit of the proposed wideband bandpass filter has been found, the next step is to establish the inverters and resonators. The inverters can be implemented using a $\lambda_g/4$ waveguide with dominant TE_{10} mode characteristic impedance of $496.66\,\Omega$ at 9.98 GHz. This corresponds to a waveguide with width 23.06 mm. A standard WR-90 waveguide has a dimension of 22.86 mm, which is 0.2 mm less than that calculated. Since the difference is small (only 0.87%), we have tolerated this difference and used a standard WR-90 waveguide to implement the inverter.

To establish the parallel resonator, CLSRR structure embedded in a WR-90 waveguide, has been used. The schematic circuit is shown in Fig. 3. Rectangular waveguide, loaded with CSRR, was earlier reported by few researchers [24, 26, 32–35]. For an incident TE_{10} mode, the resonance frequency can be calculated using [24].

$$f_0 = \frac{1}{2\pi\sqrt{L_0 C_0}} \tag{11}$$

Schematic diagram of the CLSRR structure, used in this paper, is shown in Fig. 4 whereas its lumped equivalent circuit model is shown in Fig. 5. In the circuit model, C_C represents the capacitances formed by the semi-circular metallic patches at the middle and the ground plane at a distance $(R_1 - R_0)$, the inductor L_P represents the inductances of the metallic patches connecting the semi-circular metallic

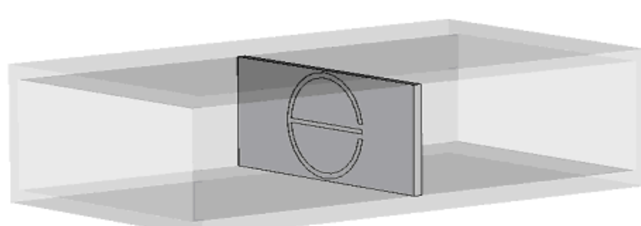

Figure 3. CLSRR inserted in a WR-90 waveguide.

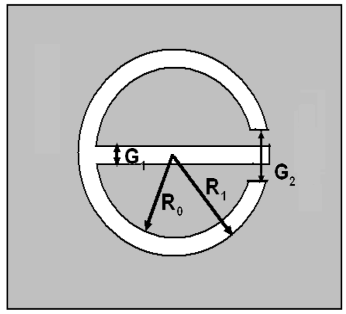

Figure 4. Typical complementary loaded split ring resonator.

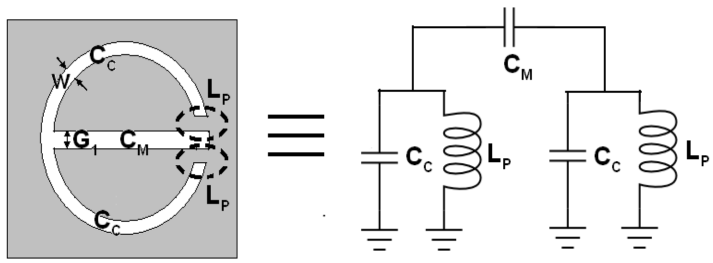

Figure 5. Equivalent lumped element circuit model of the CLSRR.

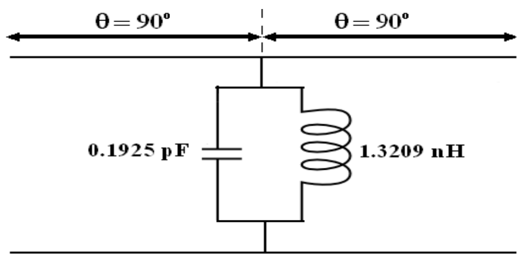

Figure 6. Equivalent lumped element circuit model of the CLSRR in waveguide (Approximate).

patches to the ground plane, and C_M represents the mutual capacitance between the two semi-circular metallic patches, separated by a distance G_1. In practice C_M has a much higher value than C_C and at the frequencies of interest it provides a very low impedance path. Therefore, to estimate the different dimensions of the CLSRR structure, shown in Fig. 4, we will temporarily neglect this capacitance and will assume the equivalent circuit of Fig. 6.

To estimate different dimensions of the CLSRR, first the ABCD parameters of the lumped element resonator circuit, shown in Fig. 6, have been calculated, assuming $\beta l = 90°$. The equation to calculate the ABCD parameter of the circuit is given by

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cos\beta l & jZ_0 \sin\beta l \\ jY_0 \sin\beta l & \cos\beta l \end{bmatrix} \begin{bmatrix} 1 & 0 \\ j\frac{\omega^2 LC-1}{\omega L} & 1 \end{bmatrix} \begin{bmatrix} \cos\beta l & jZ_0 \sin\beta l \\ jY_0 \sin\beta l & \cos\beta l \end{bmatrix} \tag{12}$$

Once the ABCD parameters have been found, corresponding $[S]$ parameters can be calculated using the formulae provided in [30]. Next the circuit, shown in Fig. 3, has been modeled in HFSS and its dimensions were optimized to achieve the same $[S]$ parameter, obtained theoretically for the lumped element resonator circuit. Doing so, the estimated dimensions of the CLSRR have been found as $R_0 = 4.4\,\text{mm}$, $R_1 = 4.9\,\text{mm}$, $G_1 = 0.425\,\text{mm}$ and $G_2 = 1.4\,\text{mm}$ respectively. The comparison of the $|S_{11}|$ of the circuits, shown in Figs. 3 and 6, is given in Fig. 7.

It may be noted that the CLSRR dimensions, obtained above, are estimated values as we have neglected the presence of C_M in Fig. 6. In the final circuit, these dimensions need slight optimization to

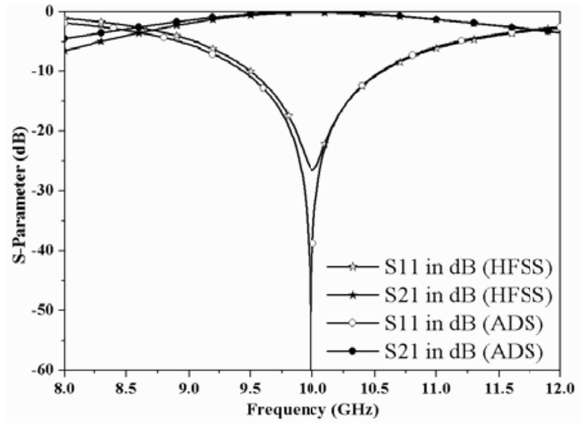

Figure 7. Comparison of the S-parameters of the CLSRR inserted in a WR-90 waveguide with its equivalent lumped element circuit model.

Table 1. Filter parameters before and after optimization.

Parameter	Before Optimization	After Optimization
R_1	4.9 mm	4.9 mm
R_0	4.4 mm	4.4 mm
G_1	0.425 mm	0.4 mm
G_2	1.4 mm	1.4 mm
Inverter Length	8.91 mm	9.78 mm

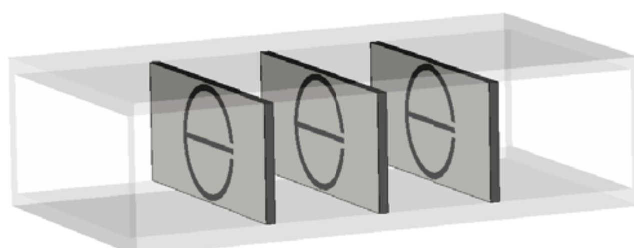

Figure 8. HFSS 3D model of the proposed wideband waveguide bandpass filter.

take into account the effect of C_M and hence to achieve a better response. Table 1 shows the comparison of different filter parameters before and after optimization. The proposed wideband bandpass filter is shown in Fig. 8. The final equivalent circuit is shown in Fig. 9.

3. RESULT AND DISCUSSION

Circuit simulator has been used to simulate the circuit model, shown in Fig. 9, whereas Ansoft HFSS has been used to simulate the 3D model of the filter, shown in Fig. 8. The HFSS, circuit model and measured data for $|S_{11}|$ and $|S_{21}|$ have been plotted and compared in Fig. 10, which shows a good agreement between them. The fabricated filter is shown in Fig. 11.

It may be noted that the quarter wavelength sections, shown in Fig. 8, are not completely air dielectric. A part of it is filled with the substrate RO4350 which has a relative permittivity 3.66 and thickness 0.762 mm. This substrate behaves as a dielectric filling of 0.762 mm within WR-90 waveguide. Since the guided wavelength of TE_{10} mode at 9.98 GHz with air as dielectric ($\lambda_{g,air}$) is larger than

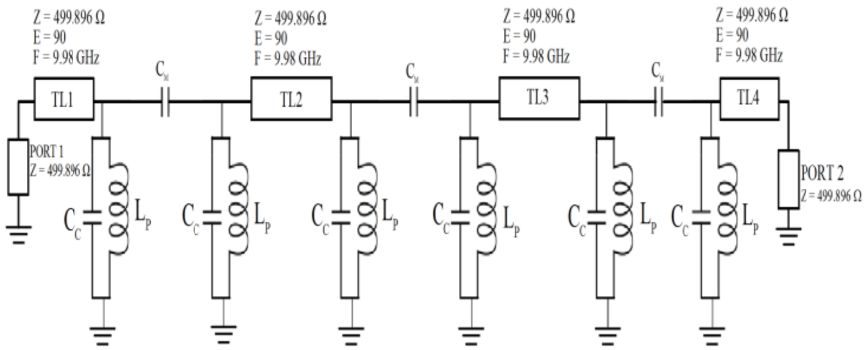

Figure 9. Final lumped element equivalent circuit of the proposed wideband waveguide bandpass filter with its elemental values $C_C = 0.10693$ pf, $L_p = 2.35$ nH and $C_M = 210.395$ pF.

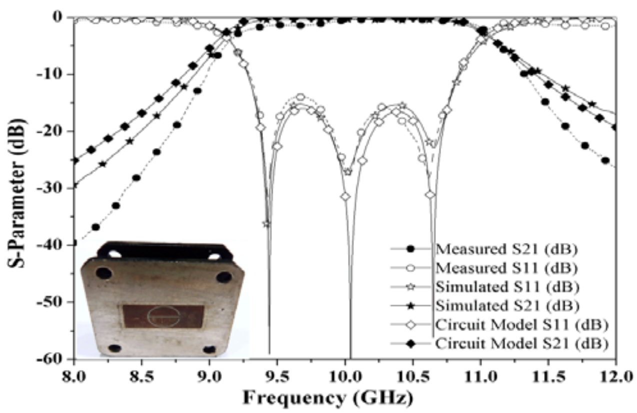

Figure 10. The comparison of the S-parameters of the proposed filter, obtained using HFSS, Circuit model and measurement.

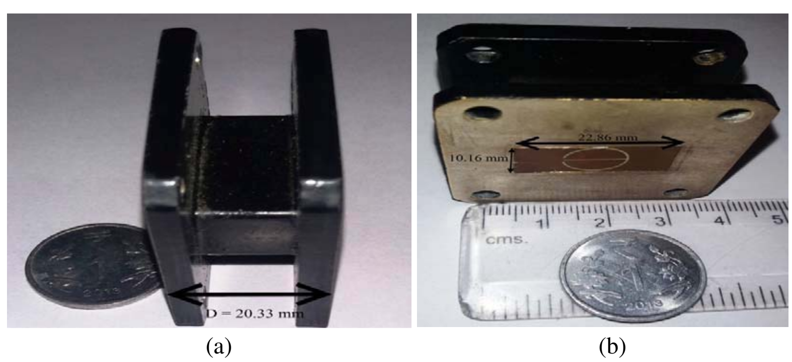

Figure 11. Photograph of the proposed fabricated filter. (a) Side view. (b) Front view.

that with the RO4350 as dielectric ($\lambda_{g,RO4350}$), the distance between two successive CLSRRs should be less than $\lambda_{g,air}/4$. It can be found that for TE_{10} mode at 9.98 GHz, $\lambda_{g,RO4350} = 16.72$ mm and $\lambda_{g,air} = 39.89$ mm. Therefore the RO4350 will contribute 16.41° to the 90° ($\lambda_g/4$) section. Rest 73.59° will be provided by the air dielectric part, which corresponds to a length 8.15 mm. Therefore the distance between two successive CLSRRs should be around 8.91 mm. In practice, fine optimization was required in the HFSS model and the distance between the CLSRRs has kept at 9.78 mm, as described in Table 1.

The comparison of the measured and simulated results is tabulated in Table 2. The slight mismatch between the measured and HFSS results is due to the finite capacitive gap between the filter and flanges, probable misalignment of CLSRRs within the waveguide, compromise made in the inverter dimension and fabrication tolerances.

The transmission phase and group delay response of the filter have been plotted in Fig. 12 which shows that the phase varies almost linearly with frequency, and the group delay is almost flat.

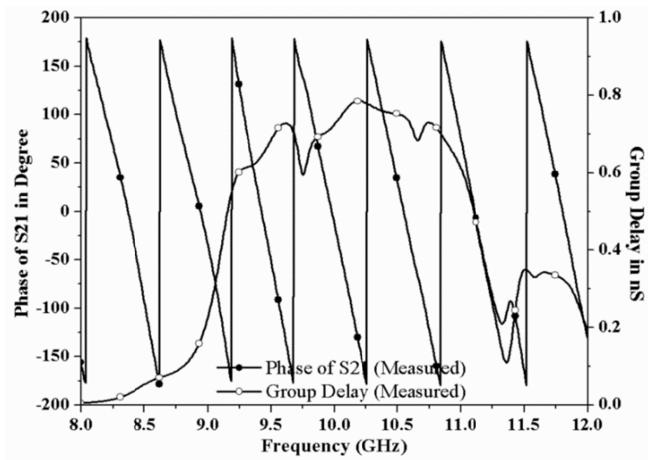

Figure 12. Measured transmission phase and group delay of the fabricated filter.

Table 2. Comparison of the measured result and simulated result.

Parameter	Measured	Simulated (HFSS)	Simulated (Circuit Model)
Lower cut-off frequency	9.15 GHz	9.14 GHz	9.11 GHz
Higher cut-off frequency	11.04 GHz	11.02 GHz	11.04 GHz
Center frequency	10.05 GHz	10.03 GHz	10.02 GHz
Bandwidth	1.89 GHz	1.88 GHz	1.93 GHz
Fractional Bandwidth	18.80%	18.74%	19.26%

Comparison of the characteristics of the proposed filter with few other CSRR filters [9, 17, 24, 31] is tabulated in Table 3.

Table 3. Comparison of characteristics of the proposed filter with few other CLSRR based waveguide bandpass filter.

Reference	Center Frequency in GHz	Bandwidth in GHz /% BW	Return Loss in dB	Insertion Loss in dB	Length in mm/electrical
[9]	9.25	1.5/16.21%	13	0.5	$92.76/2.02\lambda_g$
[17]	9.63	0.82 /8.51%	10	0.8	$133.71/3.14\lambda_g$
[24]	11.95	0.5/4.18%	10	0.5	$15.02/0.51\lambda_g$
[31]	11.95	0.5/4.18%	10	0.5	$17.42/0.56\lambda_g$
Proposed	10.03	1.88/18.74%	15.21	0.49	$20.33/0.51\lambda_g$

4. CONCLUSION

This paper presents a compact, three-section CLSRR based wideband waveguide bandpass filter. Detailed design procedure has been provided along with necessary formulae and lumped element equivalent circuits. Based on the design, a filter has been fabricated and tested. Both simulated and measured results have been presented and described.

Total length of the filter is 20.33 mm, which has a fractional bandwidth of 18.74% at 10.03 GHz, compared to only 4.18% available in the literatures. A further compactness can be obtained by modelling the inverters in terms of iris [24]. However, this will bring additional fabrication complexity. So this technique has not been incorporated in the proposed filter.

The comparison of the characteristics of different CSRR based waveguide filters with the proposed filter is presented in Table 3. The table shows that the proposed filter is compact and has higher bandwidth, lower insertion loss and higher return loss. The proposed wideband waveguide bandpass filter may find applications in aeronautical navigation (10.45–10.5 GHz), amateur satellite (10.45–10.5 GHz), radiolocation (9.37–10.55 GHz) and radio navigation (9.37–9.55 GHz) systems.

REFERENCES

1. Matthaei, G. L., L. Young, and E. M. T. Jones, *Microwave Filters, Impedance Matching Networks and Coupling Structures*, Vol. 1, Artech House, Norwood, MA, 1963.
2. Hunter, I., "Theory and design of Microwave filters," *IET Electromag. Waves*, Vol. 48, 2001.
3. Ohira, M., H. Deguchi, M. Tsuji, and H. Shigesawa, "A new dual-behavior FSS resonator for waveguide filter with multiple attenuation poles," *Proc. Eur. Microw. Conf.*, Vol. 1, Oct. 2005.
4. Amjadi, S. M. and M. Soleimani, "Design of band-pass waveguide filter using frequency selective surfaces loaded with surface Mount capacitors based on split-field update FDTD method," *Progress In Electromagnetics Research B*, Vol. 3, 271–281, 2008.
5. Ohira, M., Z. Ma, H. Deguchi, and M. Tsuji, "A novel coaxial-excited FSS-loaded waveguide filter with multiple transmission zeros," *Proc. Asia-Pacific Microw. Conf. (APMC)*, 1720–1723, Dec. 2010.
6. Tsuji, M., H. Deguchi, and M. Ohira, "A new frequency selective window for constructing waveguide bandpass filters with multiple attenuation poles," *Progress In Electromagnetics Research C*, Vol. 20, 139–153, 2011.
7. Yang, Y., H. Zhou, Q. Li, and H. Li, "Waveguide filter using frequency selective surface with miniaturized element," *Progress In Electromagnetics Research Letters*, Vol. 37, 83–90, 2013.
8. Ohira, M., H. Deguchi, and M. Tsuji, "A novel resonant window having dual-behavior resonance for pseudo-elliptic waveguide filter," *Proc. 36th European Microw. Conf.*, 1083–1086, Sep. 2006.
9. Lotfi-Neyestanak, A. A., S. M. Seyed-Momeni, and M. R. Haraty, "Improved bandwidth waveguide bandpass filter using Sierpinski fractal shaped irises," *Progress In Electromagnetics Research Letters*, Vol. 36, 113–120, 2013.
10. Shen, T. and K. A. Zaki, "length reduction of evanescent-mode ridge waveguide bandpass filters," *Progress In Electromagnetics Research*, Vol. 40, 71–90, 2003.
11. Zhang, X., Q. Wang, H. Li, and R. Liu, "Evanescent mode compact waveguide filter," *Proc. Int. Conf. on Microw. and Millim. Wave Tech.*, Vol. 1, 323–325, Apr. 2008.
12. Ohira, M., T. Matsumoto, Z. Ma, H. Deguchi, and M. Tsuji, "A new type of compact evanescent-mode waveguide bandpass filter using planar dual-behavior resonators," *Proc. Asia-Pacific Microw. Conf.*, 1023–1026, 2011.
13. Li, H., Q. Wang, R. Liu, and X. Zhang, "Economical compact waveguide band-pass filter with circular posts," *Proc. Int. Conf. on Microw. and Millim. Wave Tech.*, Vol. 1, 318–319, 2008.
14. Ghorbaninejad, H. and M. K. Amirhosseini, "Compact band-pass filters utilizing dielectric filled waveguides," *Progress In Electromagnetics Research B*, Vol. 7, 105–115, 2008.
15. Mohottige, N., D. Budimir, and Z. Golubicic, "Compact dielectric-filled waveguide filters and diplexers," *Proc. IEEE Antennas and Propag. Society Int. Symp.*, 1–2, Jul. 2012.

16. Fahmi, M., J. A. Ruiz-Cruz, R. R. Mansour, and K. A. Zaki, "Compact ridge waveguide filters using non-resonating nodes," *Proc. IEEE MTT-S Int. Microw. Symp.*, 1337–1340, 2009.
17. Oloumi, D., A. Kordzadeh, and A. A. Lotfi Neyestanak, "Size reduction and bandwidth enhancement of a waveguide bandpass filter using fractal-shaped irises," *IEEE Antennas Wireless Propag. Lett.*, Vol. 8, 1214–1217, 2009.
18. Sorrentinol, R. and S. Bastioli, "Innovative solutions for compact waveguide filters," *Proc. of the Asia-Pacific Micro. Conf.*, 235–238, 2010.
19. Veselago, V. G., "The electrodynamics of substances with simultaneously negative values of ε and μ," *Soviet Phys Uspekhi*, Vol. 10, 509–514, 1968.
20. Smith, D. R., W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, "Composite medium with simultaneously negative permeability and permittivity," *Phys. Rev. Lett.*, Vol. 84, 4184–4187, 2000.
21. Jitha, B., C. S. Nimisha, C. K. Aanandan, P. Mohanan, and K. Vasudevan, "SRR loaded waveguide band rejection filter with adjustable bandwidth," *Microw. Opt. Technol. Lett.*, Vol. 48, No. 7, 1427–1429, Jul. 2006.
22. Fallahzadeh, S., H. Bahrami, and M. Tayarani, "A novel dual-band bandstop waveguide filter using split ring resonator," *Progress In Electromagnetics Research Letters*, Vol. 12, 133–139, 2009.
23. Ortiz, N., J. D. Baena, M. Beruete, F. Falcone, M. A. G. Laso, T. Lopetegi, R. Marque, F. Martín, J. García-García, and M. Sorolla, "Complementary split-ring resonator for compact waveguide filter design," *Microw. Opt. Technol. Lett.*, Vol. 46, No. 1, 88–92, 5 Jul. 2005.
24. Bahrami, H., M. Hakkak, and Pirhadi, "Analysis and design of highly compact bandpass waveguide filter utilizing complementary split ring resonators (CSRR)," *Progress In Electromagnetics Research*, Vol. 80, 107–122, 2008.
25. Bage, A. and S. Das, "studies of some non conventional split ring and complementary split ring resonators for waveguide band stop & band pass filter application," *Int. Conf. Microw. and Photonics (ICMAP)*, 1–5, Dec. 2013.
26. Bage, A. and S. Das, "Wideband waveguide band-pass filter based on broad side complementary split ring resonator," *Int. conf. microw. and photonics (ICMAP)*, 1–2, Dec. 2015.
27. Liu, Z. M., J. A. Ruiz-Cruz, C. Wang, and K. A. Zaki, "An extremely wideband ridge waveguide filter," *Proc. IEEE MTT-S Int. Microw. Symp.*, 615–618, 2004.
28. Zhang, Q. and Y. Lu, "Design of wide-band pseudo-elliptic waveguide filters with cavity-backed inverters," *IEEE Microw. and Wireless Compon. Lett.*, Vol. 20, No. 11, 604–606, Nov. 2010.
29. Zhang, Q. and Y. Lu, "Dimensional synthesis of symmetric wideband waveguide cross-coupled filters without global full-wave optimization," *IEEE Trans. Microw. Theory Tech.*, Vol. 58, No. 12, 3742–3748, Dec. 2010.
30. Pozar, D. M., *Microwave Engineering*, 2nd Edition, Wiley, New York, 1998.
31. Collin, R. E., *Foundations for Microwave Engineering*, McGraw-Hill International edition, 1992.
32. Potrebic, M. M., D. V. Tosic, Z. Z. Cvetkovic, and N. Radosavljevic, "WIPL-D modeling and results for waveguide filters with printed-circuit inserts," *Proc. 28th Int. Conf. Microelectronics*, 309–312, May 2012.
33. Stefanovski, S., D. Mirkovic, M. Potrebic, and D. Tosic, "Novel design of H-plane bandpass waveguide filters using complementary split ring resonators," *PIERS Proceedings*, 1963–1968, Guangzhou, Aug. 25–28, 2014.
34. Pulido-Mancera, L. M. and J. D. Baena, "Waveguide bandpass filters made of thick complementary small resonators," *Proc. 8th Int. Congr. Advanced Electromag. Materials in Microwa. and Optics-Metamaterials*, Aug. 2014.
35. Snezana, S., P. Milka, S. Zoran and T. Dejan, "A novel compact dual-band bandpass waveguide filter," *Int. Sym. on Design and Diagnostics of Electronic Circuits* & *Systems*, 51–56, 2015.