Recent Techniques in Design and Implementation of Microwave Planar Filters

R.N. BARAL, P.K. SINGHAL

[1] Dept. of Electronics, Madhav Institute of Technology and Science, Gwalior – 474 005, India

pks_65@yahoo.com, r_n_baral@yahoo.co.in

Abstract. *This paper details the techniques and initiatives made recently for improved response and simultaneous development of microwave planar filters. Although the objective of all the techniques is to design low cost filters with reduced dimensions, compact size with better frequency response, the methodological approaches are quite variant. The paper has gone through extensive analysis of all these techniques, their concept and design procedures.*

Keywords

Microstrip, Fractal, PBG (Photonic Band Gap), Defected Microstrip Structure (DMS), Defected Ground Structure (DGS).

1. Introduction

Broadband wireless access communications system is a rapidly expanding market. Such systems commonly employ filters in microwave and mm-wave transceivers as channel separators. There is an increasing demand for low cost, light weight and compact size filters. To meet such demands, the recent advances of novel materials and fabrication technologies have simulated the rapid development and use of microstrip and other filters [1]. In the meantime, advances in computer-aided design (CAD) tools such as full-wave electromagnetic simulator have revolutionized filter design. Scientists have developed a variety of approaches over the years, which can be utilized to design and develop different kinds of 'microwave planar filters', also termed as 'microstrip filters', with improved responses.

One of the principal requirements for a transmission structure to be suitable as a circuit element in microwave integrated circuits is that the structure should be 'planar' in configuration, as shown in Fig. 1. In the figure, the height of the substrate is represented by *h*, the width of the metallic surface is *W*, height of the metallic strip is *t* and *L* is the length of the microstrip line. A planar configuration implies that the characteristics of the element can be determined by the dimensions in a single plane – like adjusting width of a microstrip line to control its impedance [2].

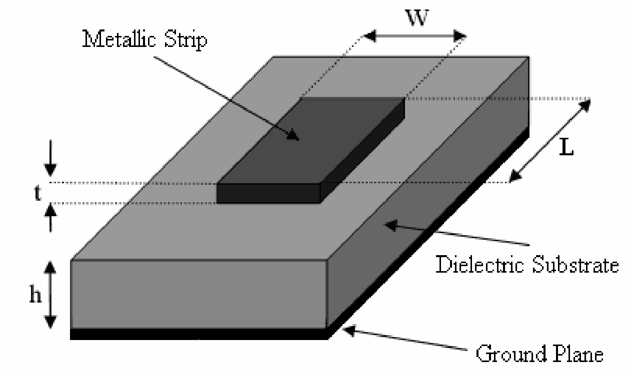

Fig. 1. Microstrip configuration.

Based on pass-band and stop-band characteristics microstrip filters can be classified as Butterworth, Chebyshev and Cauer etc. Among the primary types, the Butterworth filters don't contain ripples and develop a maximally flat characteristic, whereas Chebyshev type filters contain ripples in pass band and have a steep waveform as compared to Butterworth filters. Whereas, Cauer filters have very sharp frequency response, with ripples both in pass band and stop band [3]. These filters are used in different applications according to their requirements. For the characterization of microstrip filters lots of commercial electromagnetic (EM) simulation softwares [4-7] are available, which are very helpful for rapid research and development, in the field of RF and wireless communications. EM simulation which gives the designer the opportunity to accurately simulate passive circuit components, in particular microstrip structures, however goes far beyond the prevailing use of stand-alone EM simulators, namely, validation of designs obtained through less accurate techniques. EM simulators, although computationally intensive, are regarded as accurate at microwave frequencies, extending the validity of the models to higher frequencies, including millimeter-wave frequencies, and they cover wider parameter ranges.

The purpose of this article is to review the recent developments in the theory and design of microstrip filters. An overview of letters and papers reported so far on this field of engineering is presented here.

2. Design and Implementation of Microstrip Filters

Filter designers have different design technologies, to choose from a wide range of available unloaded quality factors (*Q*) [1]. The required filter bandwidth and the *Q* of the filter technology determine the resulting insertion loss of the filter. The microstrip, where in the fields are confined to a fairly small volume, the maximum *Q* is up to 150 and can have insertion loss less than 2 dB. The goal is to create an exact design and to fabricate filters having very tight tolerances. Of course, the real design and production environments are always slightly less than the ideal. In a microstrip filter design, the objectives always are to try achieve an exact center frequency, good bandwidth and low return losses.

2.1 Conventional Microstrip Filters

As early as in 1958, S. B. Cohn reported about parallel coupled transmission-line-resonator filters [8]. Among various circuit configurations, the parallel coupled half wavelength resonator filter is widely used. However, the size of a half-wavelength resonator filter seemed too large, as shown in Fig. 2. Also it suffered from the first spurious response at twice the center frequency. By adopting the quarter-wavelength resonators, e.g., the inter digital [9] and combline filter [10]; the circuit became smaller in size, with the first spurious response appeared at three times the center frequency.

Fig. 2. Layout of the parallel-coupled transmission-line-resonator filter.

Fig. 3. Layout of the parallel-coupled transmission-line-resonator filter.

Recently, several filter designs based on the quarter wavelength resonator have been reported [11], [12]. In which by introducing the via hole inductors, to realize the K-inverters, along with the cross-coupling effect, the filter has been much more compact with good selectivity. Nevertheless, design procedures of these filters are tedious due to their complex structures. In [13], a filter topology is proposed as shown in Fig. 3, which provides two separate electric and magnetic coupling paths. The filter has compact size and sharp roll-off rate. However, the electric coupling path of the filter was realized by the coupled gap or coupled transmission lines, which influences the center frequency of the filter considerably.

2.2 Fractal Implementation on Filters

Fractals were first defined by Benoit Mandelbrot in 1975 as a way of classifying structures whose dimensions were not whole numbers [14]. Fractal means broken or irregular fragments that possess an inherent self-similarity in their geometrical structure. Fractal have been successfully used to model complex natural objects such as galaxies, cloud boundaries, mountain ranges, coastlines, snowflakes, trees, leaves, ferns and much more. Fig. 4 shows some of the fractal structures.

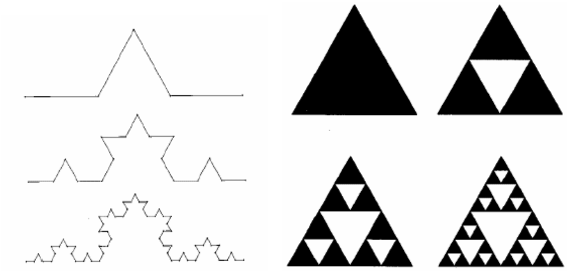

Fig. 4. Fractal configurations.

Hence, fractals are objects that posses hierarchical structure which is self-similar, i.e. repeats itself over several scales of magnitude [15]. Mathematically, constructed fractals extend the property of self-similarity down to arbitrary small or up to arbitrary large scales. The real fractals, however, do have both smallest and largest scales. The fractals have been found to be pertinent physical models for variety of natural structures and phenomena, [16]. Another line of using fractals, which proved even more fruitful, is a design and fabrication of self-similar objects for technological purposes, such as fractal element antennas [17] and microstrip fractal filters [18-20]. Fig. 5 shows fractal shaped microstrip coupled line band pass filters [21].

Traditionally, microstrip coupled line filters have been used to achieve narrow fractional bandwidth due to their relatively weak coupling [1]. However, despite advantages, this type of filter has some problems, such as a large second harmonic. This parasitic second harmonic contributes to an asymmetric pass band shape and degrades the upper band skirt properties. In addition, a large second harmonic signal can degrade the performance of other system components such as mixers.

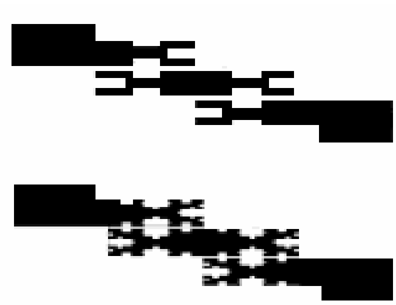

Fig. 5. Koch fractal island shaped coupled-line filter whose iteration factor is ¼ for (a) 1st iteration order, (b) 2nd iteration order.

To overcome this second harmonic problem, Koch fractal geometry has been applied to the coupled section of the filter. Another fractal filter known as Hairpin-line band pass filter is shown in Fig. 6 (a), out for suppression of harmonics. The corresponding scattering parameter plots are shown in Fig. 6 (b) and 6 (c). Conventionally, there are two methods used to solve the second harmonic problem in microstrip coupled line structures: by making the phase velocity of even and odd modes the same or by compensating the different electrical lengths of both modes by modifying the line shape. An approach where both of the above methods were used together has also been reported [22], where periodic structures used to create Bragg reflections to suppress the second harmonic [1].

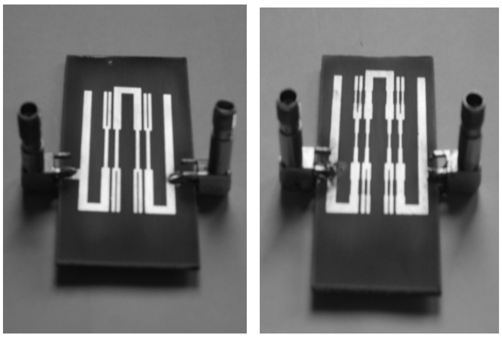

Fig. 6. **(a)** Photograph of fractal hairpin-line filters for suppression of spurious bands.

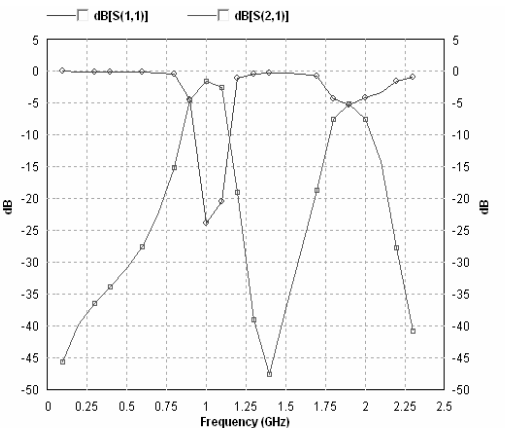

Fig. 6. **(b).** Frequency response of hairpin-line band pass filter.

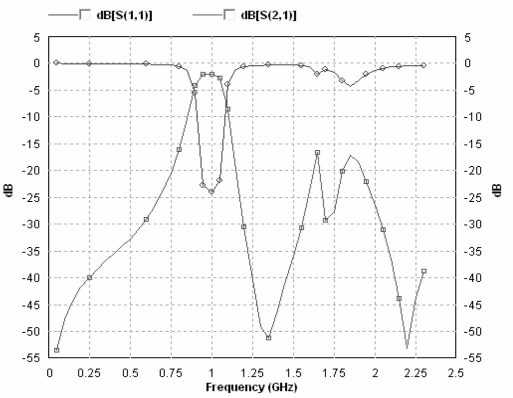

Fig. 6. **(c)** Frequency response of 1st iteration fractal hairpin line band pass filter.

Fractals also used to improve the performances of microwave devices such as superconducting resonators, for layouts of microstrip filters [23]. In the last decade, much effort has been dedicated to the fabrication and optimization of microwave resonant devices, such as filters and antennas, based on high temperature superconducting (HTS) films.

Fractal electrodynamics is the application of fractal concepts to the electromagnetic theory and in this field, fractal description of natural geometries allowed the characterization of interaction between these structures and electromagnetic waves, leading to the solution of problems such as land or ocean surfaces diffraction or random media propagation [24]. By utilizing a Hilbert pattern, as mentioned in the Fig. 7, it is possible to design very compact resistors, which minimize the parasitic inductance per unit surface, and at the same time maximize the capacitance for a fixed area in microstrip capacitors [25].

One of the critical issues in the performance of a reactive component is the quality factor Q. The highest the factor Q, the better the component [26]. In filtering applications, Q is directly related to sharpness of the passband; to reject-band transition, the minimum bandwidth and to the insertion loss of the filter. The value of Q degrades by ohmic losses, but enhances with storage of reactive energy. In general terms, the performance of a small filter is related to the ability of the resonating structures of the filter in storing as much reactive energy as possible in the available volume. A good example of the energy storing capabilities of fractals is the Hilbert resonator, as shown in Fig. 8. Due to the unique space-filling properties of fractals, a very long but small resonator can be effectively packed into a same space as a conventional half-wave length resonator yet featuring a Q factor which is about 10 times larger.

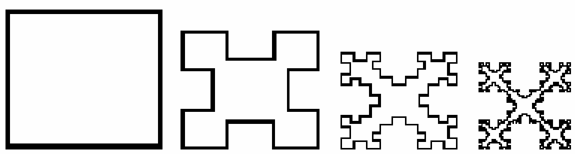

Fig. 7. Square koch island fractal for super conducting resonators.

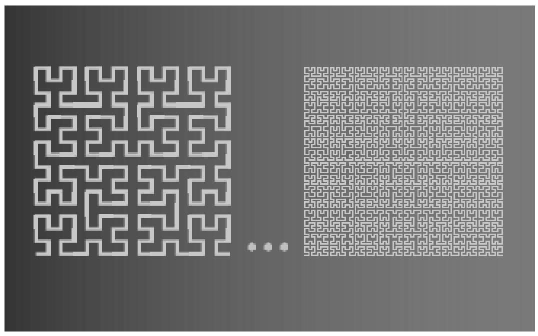

Fig. 8. Hilbert fractal curve for two different iterations.

A highly modern Hi-Lo microstrip low pass filter proposed for the first time [27], using Koch fractal shapes. The excellent pass band performance was mainly due to the gradual changes of the steps of the fractal shaped microstrip line, thus to provide weak current discontinuities.

2.3 Photonic Band Gap Filters

Initially, Photonic band gap (PBG) devices were proposed in optical applications, which have a property of preventing light from propagating in certain frequency bands [28]. Filters can be implemented with shunt stubs [1] or stepped impedance lines in microstrip circuit [3], but these techniques require large circuit and provide a narrow band, along with a spurious pass-band in stopband. PBG structures provide the alternate solution for these problems in microwave applications.

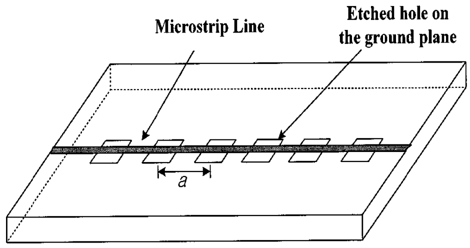

Fig. 9. Layout of a 1-D PBG Filter with square holes etched in ground plane.

Microstrip lines incorporating photonic band gap structures exhibit slow wave characteristics which can be exploited to control the size of circuit layouts and periodicity. As shown in Fig. 9, PBG structures are periodic where the propagation of waves is not allowed for some frequency bands or directions, according to Bragg condition [29]. In the figure *a* is the order of approximation or distance between periodic patterns which may be square or circular holes in the ground plane. This is quite similar to the energy band gap concept in solid-state materials, and photonic crystals – providing a mean to control propagation of electromagnetic wave.

As mentioned above, the structures having periodic arrangement of dielectric or magnetic materials that result in the formation of stop bands in the microwave frequency region are called Microwave band gap structures. In general, these structures are also called as Electromagnetic band gap (EBG) structures. The reason for such peculiar behavior is that electromagnetic waves traveling through such structures experience a periodic variation of dielectric permittivity or magnetic permeability similar to the periodic potential energy of an electron in an atomic crystal. Therefore, like the electronic state in an atomic crystal, the photonic state in a photonic crystal can be classified into bands and gaps, the frequency range over which the photons are allowed or forbidden respectively to propagate in the medium. Another explanation can be that the electromagnetic waves scattered by the materials form secondary sources. The waves from these secondary sources interfere destructively at the receiving end for certain frequency region. The application of photonic bandgap structures as substrates in microstrip circuits has been reported in [30]. A low-pass filter with a very wide high-frequency rejection bandwidth has been constructed from a serial connection of many different PBG structures, as shown in Fig. 10.

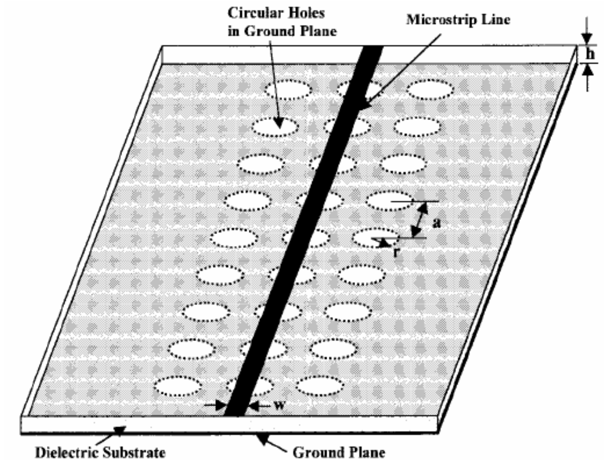

Fig. 10. Layout of circular etched holes PBG filter.

The various parameters that control the stop band in PBGs are, periodicity of the geometric arrangement, effective refractive index contrast, filling fraction and geometry of the structure. The defects are created either by removing or adding a material into the lattice, thereby disturbing the periodicity. This may result in the appearance of extra modes in the forbidden frequency range or a change in the power levels. Depending on the position of the defect and the number of defects that are created in a finite structure, the change in the power levels is either more or less. By addition of material, if a defect mode is created, then it is referred to as a donor mode and if the material is removed to form a defect mode, it is referred to as an acceptor mode [31].

Microstrip PBG structures have attracted great interest mainly due to their good performance and potential applications. In recent time, several papers dealing with one-dimensional (1-D) microstrip photonic band-gap (PBG) were presented [32-41]. Majority 1-D microstrip PBGs have holes in the substrate or etched patterns in the ground plane. Disadvantage of the mentioned structures is a packaging problem and realization of MMICs [41]. The etched ground plane must be far enough from any metal plate in order to keep etched patterns in function. Structures based on the modification of the shape of the microstrip line and without etching in the ground plane were reported in [36], [40].

A novel 1-D microstrip PBG filter without etching in the ground plane is presented in [41]. In this case, the structure as shown in Fig. 11(a), has a sinusoidal variation of the characteristic impedance as a function of the length of the microstrip line. The corresponding simulated response is shown in Fig. 11 (b). The range of applications proposed for these PBG structures in microstrip technology has been widely used last years, based on broadband harmonic tuning in power amplifiers [42] and so on.

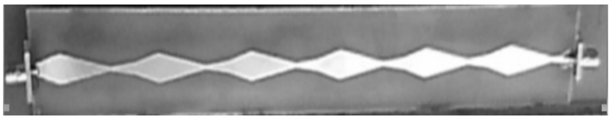

Fig. 11. (a). Configuration of one-dimensional PBG bandstop filter without etching ground plane.

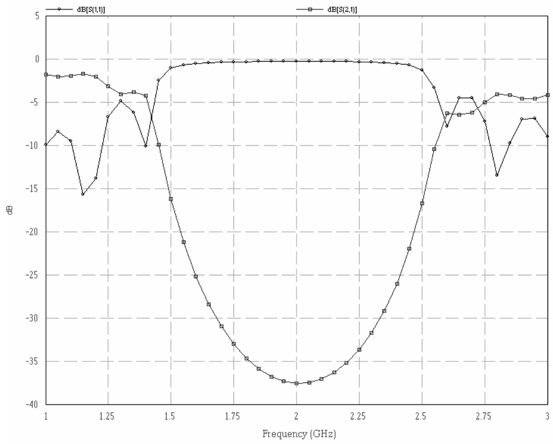

Fig. 11. (b) Simulation result of the PBG bandstop filter.

2.4 DGS and DMS Analysis

The use of discontinuities in ground planes or in microstrip lines is currently employed to improve the performance of different passive circuits such as the size reductions of amplifiers, the enhancements of filter characteristics and applications to suppress harmonics.

As shown in Fig. 12, Defected ground structure (DGS) is an etched lattice shape, which locates on the ground plane. It may be periodic or non-periodic structures and easy to represent in the form of an equivalent circuit. Currently, the DGS structure is widely employed in the behavior improvement of different RF and microwave circuits as filters [43], as well as power amplifiers [44] and patch antennas [45]. The DGS disturbs shielding fields on the ground plane, increases effective permittivity, increases effective inductance and capacitance of transmission line, and behaves as stop-band filter.

An etched defect disturbs the shield current distribution in the ground plane. This disturbance can change characteristics of a transmission line, such as line capacitance and inductance. A novel 3-pole coupled line band pass filter with DGS is proposed in [46]. The proposed DGS consists of narrow and wide etched areas in the backside metallic ground planes, which give rise to increasing the effective capacitance and inductance of a transmission line, respectively. The coupled line filter has a microstrip resonator and two DGS sections, which operate as inverters and resonators simultaneously, at in-out port. Thus, the proposed-coupled line bandpass filter provides more compact size compared to conventional coupled line bandpass filter. In addition, DGS has a self-resonance frequency. Due to this self resonance characteristic of DGS section, the proposed bandpass filter structure can provide an attenuation pole in upper stopband. In order to derive an equivalent circuit for the proposed coupled line bandpass filter, we employ equivalent circuit and extraction methods of circuit parameters for a DGS, which are described in [47].

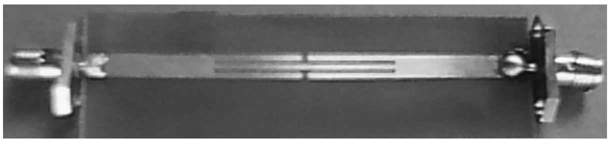

Fig. 13. (a) Photographed layout of a DMS low pass filter.

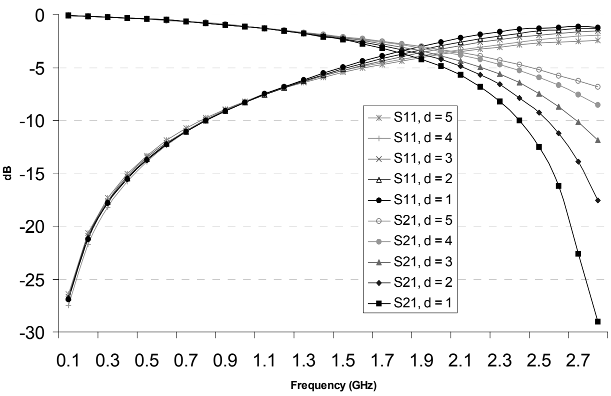

Fig. 13. (b) Frequency response with respect to slot width *d*.

Defected microstrip structure (DMS) is made by etching a little slot over the microstrip, generating a stop band as a function of slot length. The larger the slot length, the lower the stop band frequency response. The designing of specific DMS structure is independent of the microstrip length which can be very useful in the design of microstrip filters, among other different applications. In the DMS, there is no etching in the ground plane avoiding any increment of leakage through the ground plane.

As shown in Fig. 13 (a), a defected microstrip structure is made by etching a little slot over the microstrip, generating a stop band as a function of the slot length and width. As the width of the slot becomes smaller the stop band response becomes steeper and attenuation falls to lower levels. DMS presents a greater slow wave effect, since it has more discontinuities providing a longer trajectory to the electromagnetic wave [48]. The slow wave factor (SWF) of a microstrip line is raised when a discontinuity is introduced in the path of the electromagnetic wave, increasing the impedance of the line. The frequency response characteristics is shown in Fig. 13 (b). Another advantage with DMS is that harmonics can be suppressed by selecting the appropriate slot length tuned to the specific harmonics obtaining a great rejection without the necessity of using a fixed microstrip length. After introducing the unit-sell in the microstrip line, the substrate employed in the implementation presents an apparent effective dielectric constant, which is larger than the real effective dielectric constant. This apparent permittivity provides the tool to explain how the dimensions of the microstrip circuits can be reduced. Considerable reduction in circuit size makes defected microstrip structures effective not only to make filters, but to reduce the dimensions of other microwave devices such as microstrip lines, patch antennas etc.

2.5 Advanced Techniques in Microstrip Filter Design

As mentioned earlier, coupling factor of a resonator to an external circuit is described by the external *Q* which is an important parameter for designing microwave filters. Analytical computation of external *Q* needs exact determination of the field distribution around the coupling port. But the complexities of I/O ports in microwave/millimeter wave filters make this procedure a very complicated process. On the other hand lack of analytical solution for field distribution in some kinds of resonators such as Square Open Loop Resonators cause to increase the complexity of external *Q* computation.

A very fast and accurate fuzzy inference method to overcome this drawback is reported in [49]. In this paper fuzzy method is implemented to model the external *Q* in a vanishingly short time and good accuracy. The fuzzy modeling method is explained and a four pole Chebychev filter has been designed as an example to show the accuracy and efficiency of the introduced method. The simulated response of the designed filter is compared with an ideal four pole Chebychev one. The results found to be in a very good agreement. The capability of fuzzy inference method in solving time consuming and complicated electromagnetic problems such as microwave filter tuning [50]-[52], EMC problems [53] and also antenna modeling [54], [55] has been proved.

Developing a UWB filter can be a challenging task, and various techniques have been proposed [56]–[61]. In [56], UWB filters using microstrip rings are studied. These filters have good insertion loss and sharp rejections, but suffer from poor out-of band performance due to the strong spurious response. The concept of multimode resonators was originally proposed in [57] and developed in [58], [59] for designing UWB filters. These filters show good insertion loss and flat group delay in the pass band. However, to obtain an UWB response, small coupling gaps are required in this type of filter. In [60] and [61], transmission line filters with shunt short-circuited stubs were designed for UWB applications, which, however, suffer from strong harmonic response. Novel ultra-wideband (UWB) band pass filters are proposed based on quasi-lumped-element prototypes and implemented with multilayer liquid-crystal-polymer (LCP) technology reported in [62]. In this study, the broadside coupled microstrip radial stubs and high-impedance microstrip lines are adopted as quasi-lumped elements for realizing compact UWB bandpass filters. By introducing a short-circuited high-impedance microstrip line as a shunt inductor and suitably designing quasi-lumped-element capacitors, a compact eight-pole bandpass filter, as shown in Fig. 14, is implemented with the Federal Communications Commission (FCC) defined UWB specifications. The measured result of the fabricated eight-pole filter has an ultra-wide fractional bandwidth of 139%, and a good stopband rejection level. Such filters are attractive for UWB communications and radar systems.

The concept of Metamaterial or the left-handed medium (LHM) was first proposed by Veselago in 1968 [63]. The electric field, the magnetic field, and the wave vector of electromagnetic wave propagation in left-handed (LH) materials obey the left-hand rule (instead of the right-hand rule for usual materials). In such medium, the permittivity and permeability are negative simultaneously. Also it exhibits many unusual physical properties different from the conventional right-handed (RH) material, such as the negative refraction index, the backward Cerenkov radiation, the reversed Doppler shift, etc. Unfortunately, such a new medium does not exist in nature, which has restricted the further investigation of LHM for a long time. Recently, left-handed structure has been realized using wires and split-ring resonators (SRRs) experimentally in [64-67]. In 2004, an extended concept of composite right/left-handed transmission line was developed and demonstrated the practical application of LH structure [68 to 75]. Since then, left-handed materials become an attractive topic and an extensive study has been conducted in the new physical characteristics, experiments, and potential applications [76-80]. A novel narrow-band bandpass filter using metamaterials is proposed. The filter composed of cascaded four metamaterial unit cells. The proposed filter has provided a useful technology to design low-cost integrated filter. The performances of the device are investigated theoretically and experimentally. The novel bandpass filter has shown its low insertion loss, compactness and improved response. The performances are demonstrated by the simulation and measurement results. The device is easily integrated with microwave or millimeter wave planar circuits.

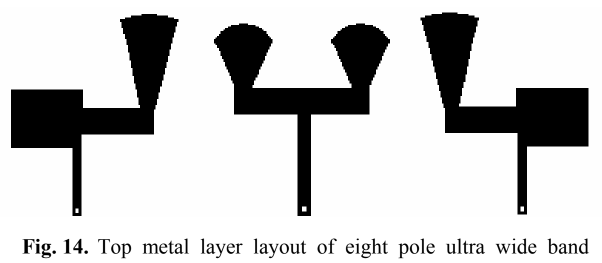

Fig. 14. Top metal layer layout of eight pole ultra wide band filter.

3. Conclusion

Applications of microstrip filters, for better responses, are becoming increasingly widespread in the field of science and engineering. This article presents a comprehensive overview of the all possible research areas around for design and implementation of microstrip filters. Included among the topics considered were – design methodologies, their applications and usefulness. The field of designing microstrip filters is still in the relatively earlier stages of development, with the anticipation of much more innovative advancement to come, over the months and years ahead.

Acknowledgement

The authors thankfully acknowledge the financial support provided by M.P. Council of Science & Technology, Bhopal, India.

References

[1] POZAR, D. M. *Microwave Engineering*. John Wiley, 2000.

[2] GUPTA, K. C., GARG, R., BAHL, I., BHARTIA, P. *Microstrip Lines and Slotlines*. London: Artech House, 1996.

[3] JIA-SHEN G. HONG, LANCASTER, M. J. *Microstrip Filters for RF/Microwave Applications*. John Wiley & Sons Inc., 2001.

[4] IE3D Software Release – 8, Developed by M/s Zeland Software Inc.

[5] Computer Simulation Technology, MICROWAVE STUDIO® (2006), AG.

[6] Applied Computational Science (ACS), Sonnet Software, Inc.

[7] HFSS, 3D Full Wave Electromagnetic Field Simulations, Ansoft Designer®.

[8] COHN, S. B. Parallel-coupled transmission-line-resonator filters. *IRE Trans. Microw. Theory Tech*., 1958, vol. MTT-6, no. 4, p. 223–231.

[9] MATTAEI, G. L. Interdigital bandpass filters. *IEEE Trans. Microw. Theory Tech.*, 1962, vol. MTT-10, no. 11, p. 479–491.

[10] CRISTAL, E. G. Tapped-line coupled transmission lines with applications to interdigital and combline filters. *IEEE Trans. Microw. Theory Tech.*, 1975, vol. MTT-23, no. 12, p. 1007–1012.

[11] DENG, P.-H., LIN, Y.-S.,. WANG, C.-H, CHEN, C.-H. Compact microstrip bandpass filters with good selectivity and stopband rejection. *IEEE Trans. Microw. Theory Tech*., 2007, vol. 54, no. 2, p. 533–539.

[12] WU, C.-H., LIN, Y.-S.,. WANG, C.-H, CHEN, C.-H. Novel microstrip coupled line bandpass filters with shortened coupled sections for stopband extension. *IEEE Trans. Microw. Theory Tech.*, 2007, vol. 54, no. 2, p. 540–546.

[13] MA, K.-X., MA, J.-G., YEO, K.-S., DO, M.-A. A compact size coupling controllable filter with separate electric and magnetic coupling paths. *IEEE Trans. Microw. Theory Tech.*, 2006, vol. 54, no. 3, p. 1113–1119.

[14] MANDELBROT, B. B. *Fractrals: Form, Chance and Dimension*. Fhem M, Sanhciseo, USA, 1977.

[15] TCI, T., Z. Naturforch., 1988,

[16] PIETRONERO, L., TOSATTI, E., (eds.), *Fractals in Physics*. North-Holland, Amsterdam, The Netherlands, 1986.

[17] BEST, S. R. The fractal antenna: a comparison of fractal and non fractal geometries. In *Antennas and Propagation Society International Symposium*, IEEE vol. 3, 8-13 July 2001, p.146-149.

[18] ROMEU, J., RAHMAT- SAMII, Y. Fractal FSS: A Novel Dual-Band Frequency Selective Surface. *IEEE Trans. on Ant. Propag.* 2000, vol. 48, no. 7.

[19] JUNG-HYO, K., IL KWON, K., JONG- GWAN YOOK, HAN-KYU PARK, A slow-wave structure using Koch fractal slot loops. *Microw. and Opt.Technology Letters*, 2002, vol. 34, no.2, p. 87-88.

[20] LOPETEGI, T., LASO, M. A. G., FALCONE, F., MARTIN, F., BONACHE, J., GARCIA, J., PEREZ-CUEVAS, L., SOROLLA, M. GUGLIELMI, M. Microstrip "wiggly-line" and pass filters with multispurious ejection. *IEEE Microwave and Wireless Component Letters*, 2004, vol. 14, no. 11, p. 531-533.

[21] IL KWON KIM et. al. Fractal-shaped microstrip coupled-line bandpass filters for suppression of second harmonic. *IEEE Trans. on Microw. Theory Techniques*, 2005, vol. 53, no. 9, p. 2943-2948.

[22] KUO, J.-T., CHEN, S.-P., JIANG, M. Parallel-coupled microstrip filters with over-coupled end stages for suppression of spurious responses. *IEEE Microw. Wireless Compon. Lett.*, 2003, vol. 13, no. 10, p. 440–442.

[23] PRIGIOBBO, A., BARRA, M., CASSINESE, A., CIRILLO, M., MARAFIOTI, F., RUSSO, R., VAGLIO, R. Superconducting resonators for telecommunication application based on fractal layout. *Supercond. Sci. Technol.*, 2004, vol. 17, p. 427–431.

[24] JAGGARD, D. L. *On Fractal Electrodynamics: Recent Advances in Electromagnetic Theory*. Ed. Kriticos, H. N., Jaggard, D. L. New York: Springer-Verlag, 1990.

[25] 2001, *Fractal and Space-Filling Transmission Lines, Resonators, Filters and Passive Network Elements*. Patent WO 01/54221 A1.

[26] Fractus, *The technology of nature®*, S.A., Barcelona, Spain, 2001.

[27] WEN-LING CHEN, GUANG-MING WANG, YI-NA QI Fractal shaped hi-lo microstrip low pass filters with high pass band performance. *Microw. and Opt. Technology Letters*, 2007, vol. 49, no.10, p. 2577-2579.

[28] JOANNOPOULOS, J. D., et al. *Photonic Crystals: Molding the Flow of Light*. Princeton University Press, 1995.

[29] RADISIC, V., et al. Novel 2-D Photonic Band Gap structure for microstrip lines. *IEEE Microw. Guided Wave Letter*, 1998, vol. 8, no. 2, p. 69-71.

[30] RUMSEY, I.; PIKET-MAY, M.; KELLY, P. K. Photonic Bandgap structures used as filters in microstrip circuits. *IEEE Microwave and Guided Wave Letters*, 1998, vol. 8, no. 10, p. 336-338.

[31] SANTOSH BABU, G., SUBRAMANIAN, V., SIVASUBRAMANIAN, V., MURTHY, V. R. K. One-dimensional photonic band gaps at microwave frequencies for microwave filters. *Ferroelectrics*, 2005, vol. 327, p. 19-25.

[32] QIAN, Y., RADISIC, V., ITOH, T. Simulation and experiment of Photonic Band Gap structure for microstrip circuits. In *APMC'97,* 1997, p. 585-588.

[33] RUMSEY, I., PIKET-MAY, M., KELLY, P. K. Photonic Band Gap Structure used as filters in microstrip circuits. *IEEE Microwave and Guided Wave Letters,* vo1.8, no.10, 1998, p. 336-338.

[34] RADISIC, V., QIAN, Y., COCCIOLI, R., ITOH, T. Novel 2-D Photonic Band Gap structure for microwave line. *IEEE Microwave and Guided Wave Letters*, 1998, vol.8, no.2, p.69- 72.

[35] KIM, T., SEO, C. A Novel Photonic Bandgap structure for low-pass filter or wide stopband. *IEEE Microwave and Guided Wave Letters,* 2000, vol.10, no.1, p.13-15.

[36] YUN, T. Y., CHANG, K. One-dimensional Photonic Bandgap resonators and varactor tuned resonators. *IEEE MTT-S. Int. Microwave Symp. Dig.*, 1999, p. 1629-1632.

[37] LENOIR, B., BAILLARGEAT, D., VERDEYME, S., GUILLON, P. Finite Element Method for rigorous design of microwave device using Photonic Bandgap structures. *IEEE MTT-S Digest*, 1998, p.1061- 1064.

[38] LOPETEGI, T., LASO, M. A. G., ERRO, M. J., FALCONE, F., SOROLLA, M. Bandpass filter in microstrip technology using Photonic Bandgap reflectors. In *29th European Microwave Conference.* Munich (Germany), 1999, p. 337-340.

[39] LASO, M. A. G., LOPETEGI, T., ERRO, M. J., BENITO, D., GARDE, M. J., SOROLLA, M. Multiple-frequency-tuned Photonic Bandgap microstrip structures. *IEEE Microwave and Guided Wave Letters*, 2000, vol. 10, no.6, p. 220-222.

[40] XUE, Q., SHUM, K. M., CHAN, C. H. Novel 1-D microstrip PBG Cells., *IEEE Microwave and Guided Wave Letters*, 2000, vol. 10, no. 10, 2000, p. 403-405.

[41] NESIC, D., NESIC, A. Bandstop microstrip PBG filter with sinusoidal variation of the characteristic impedance and without etching in the ground plane. *Microwave and Optical Technology Letters*, 2001, vo1. 29, no. 6, p. 418-420.

[42] HANG, C. Y., RADISIC, V., QIAN, Y., ITOH, T. High efficiency power amplifier with novel PBG ground plane for harmonic tuning. In *IEEE MTT-S International Microwave Symposium.* Anaheim (CA), June 1999, p. 807-810.

[43] TSACHTSIRIS, G. F., SORAS, C. F., KARABOIKIS, M. P., MAKIOS, V. T. Analysis of a modified Sierpinski Gasket monopole antenna printed on dual band wireless devices. *IEEE Transactions on Antennas and Propagation,*2004, vol. 52, no. 10, p. 2571-2579.

[44] GONZALEZ, J. M., NAVARRO, M., PUNETE, C., ROMEU, J., AGUASCA, A. Active zone self-similarity of fractal-Sierpinski antenna verified using infra-red thermograms. *ElectronicsLetters,* 1999, vol. 35, no. 17, p.1393-1394.

[45] XIN LI, XIAO XING YIN, TIE JUN CUI, WEI HONG A new version of printed Sierpinski Multiband fractal antenna. In *Antennas and Propagation Society International Symposium.* 2004 IEEE vol. 4, 20-25 June 2004, p. 3457– 3460.

[46] JUN-SIK YUN, GEUN-YOUNG KIM, JUN-SEOK, PARK, DAL AHN, KWANG- YONG KANG, JAE-BONG LIM, A design of the novel coupled line bandpass filter using defected ground structure. *2000 IEEE MTT-S Digest*, 2000, p. 327-330.

[47] Park, J. I., Kim, C. S., Kim, J., Park, J. S., Qian, Y., Ahn, D.,Itoh, T. Modeling of photonic bandgap and its application for the low-pass filter design. In *1999 Asia-Pacific Microwave Conf dig*., Dec. 1999, vol. 2, p. 331-334.

[48] TIRADO-MENDEZ, J. A., JARDON-AGUILAR, H. Comparison of Defected Ground Structure (DGS) and Defected Microstrip Structure (DGS) behavior at High Frequencies. In *Proceeding of 1st International Conference on Electrical and Electronics Engineering, 2004*. Acapulco (Mexico), 8-10 September, 2004, p. 7-10.

[49] PAYMAN REZAEE, NASRIN NASR ESFAHANI, MAJID TAYARANI External Q computation by fuzzy inference method: Application to microstrip filter design. In *Proceedings of ICMMT2008*, p. 201-204.

[50] MIRAFTAB, V., MANSOUR, R. R. Computer-aided tuning of microwave filters using fuzzy logic. *IEEE Trans. Microwave Theory Tech.*, 2002, vol. 50, p. 2781-2788.

[51] MIRAFTAB, V., MANSOUR, R. R. A Robust fuzzy-logic technique for computer-aided diagnosis of microwave filters. *IEEE Trans. Microwave Theory Tech*., 2004, vol. 52, p. 450-456.

[52] MIRAFTAB, V., MANSOUR, R. R. EM-based design tools for microwave circuits using fuzzy logic techniques. *IEEE MTT-S*, June 2003, vol. 1, p. 8-13.

[53] MIRAFTAB, V., MANSOUR, R. R. EM-based design tools for microwave circuits using fuzzy logic techniques. *IEEE MTT-S*, June 2003, vol. 1, p. 8-13.

[54] MIRAFTAB, V., MANSOUR, R. R. EM-based design tools for microwave circuits using fuzzy logic techniques. *IEEE MTT-S*, June 2003, vol. 1, p. 8-13.

[55] TAYARANI, M., KAMI, Y. Qualitative analysis in engineering electromagnetic: An application to general transmission lines. *IEIEC Transactions on Electronics*, 2001, vol. E84-C, no.3, p. 110-113.

[56] ISHIDA, H., ARAKI, K. Design and analysis of UWB bandpass filter with ring filter. In *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2004, p. 1307–1310.

[57] ZHU, L., SUN, S., MENZEL, W. Ultra-wideband (UWB) bandpass filter using multiple-mode resonator. *IEEE Microw. Wireless Compon. Lett*., 2005, vol. 15, no. 11, p. 796–798.

[58] WANG, H., ZHU, L., MENZEL, W. Ultra-wideband (UWB) bandpass filter with hybrid microstrip/CPW structure. *IEEE Microw. Wireless Compon. Lett*., 2005, vol. 15, no. 12, p. 844–846.

[59] SUN, S., ZHU, L. Capacitive-ended interdigital coupled lines for UWB bandpass filters with improved out-ofband performances. *IEEE Microw. Wireless Compon. Lett*., 2006, vol. 16, no. 4, Aug. 2006, p. 440–442.

[60] HONG, J.-S., SHAMAN, H. An optimum ultra-wideband microstrip filter. *Microw. Opt. Technol. Lett.*, Nov. 2005, vol. 47, no. 3, p. 230–233.

[61] WONG, W. T., LIN, Y. S., WANG, C. H., CHEN, C. H. Highly selective microstrip bandpass filters for ultra-wideband applications. In *Proc. Asia–Pacific Microw. Conf*., Nov. 2005, p. 2850–2853.

[62] ZHANG-CHENG HAO, JIA-SHENG HONG, Ultra-wideband bandpass filter using multilayer liquid-crystal-polymer technology. *IEEE Transactions on Microwave Theory and Techniques*, 2008, vol. 56, no. 9, p. 2095-2100.

[63] VESELAGO, V. G. The electrodynamics of substrate with simultaneously negative values of ε and μ. *Sov. Phys. Usp*., 1968, vol. 10, no. 4, p. 509-514.

[64] PENDRY, J. B., HOLDEN, A. J., STEWART, W. J., YOUNGS, I. Extremely low frequency plasmons in metallic mesostructures. *Phys.Rev. Lett*., 1996, vol, 76, p. 4773.

[65] SMITH, D. R., VIER, D. C., PADILLA, W., NASSER, S. C. N., SCHULTZ, S. Loop-wire for investigating plasmons at microwave frequencies. *Phys. Lett*., 1999, vol. 75, no. 10, p. 1425-1427.

[66] SMITH, D. R., PADILLA, W., VIER, D. C., , NASSER, S. C. N., SCHULTZ, Composite medium with simultaneously negative permeability and permittivity. *Phys. Rev. Lett*., 2000, vol. 84, no. 18, p. 4184-4187.

[67] SHELBY, R. A., SMITH, D. R., SCHULTZ, S. Experimental verification of a negative index of refraction. *Science*, 2001, vol. 292, p.77-79.

[68] SANADA, A., CALOZ, C., ITOH, T. Characteristics of the composite right/left-handed transmission line. *IEEE Microwave Wireless Compon. Lett*., 2004, vol. 14, no. 2, p. 68-70.

[69] GRBIC, A., ELEFTHERIADES, G. V. Overcoming the diffraction limit with a planar left-handed transmission-line lens. *Phys. Rev. Lett.*, 2004, vol. 92, p. 117403.

[70] LIM, S., CALOZ, C., ITOH, T. A reflecto-directive system using a composite right/left-handed (CRLH) leaky-wave antenna and heterodyne mixing. *IEEE Microwave Wireless Compon. Lett.*, 2004, vol. 14, no. 4, p. 183-185.

[71] CALOZ, C., SANADA, A., ITOH, T.C. A novel composite right/lefthanded coupled-line directional coupler with arbitrary coupling level and broad bandwidth. *IEEE Trans. Microwave Theory Tech.,* 2004, vol. 52, no. 3, p. 980-992.

[72] HORII, Y., CALOZ, C., ITOH, T. Super-compact multilayered lefthanded transmission line and diplexer application. *IEEE Trans. Microwave Theory Tech*., 2005, vol. 53, no. 4, p. 1527-1534.

[73] LIN, I., DEVINCENTIS, M., CALOZ, C., ITOH, T. Arbitrary dual-band components using composite right/left-handed transmission lines. *IEEE Trans. Microwave Theory Tech*., 2004, vol. 52, no. 4, p. 1142- 1149.

[74] LAI, A., CALOZ, C., ITOH, T. Composite right/left-handed transmission line metamaterials. *IEEE Microwave Magazine*, 2004, vol. 9, p. 34-50.

[75] CALOZ, C., ITOH, T. A novel mixed conventional microstrip and composite right/left-handedbackward-wave directional coupler with broadband and tight coupling characteristics. *IEEE Microwave Wireless Compon. Lett.*, 2004, vol. 14, no. 1, p. 31-33.

[76] ENGHETA, N. An idea for thin subwavelength cavity resonators using metamaterials with negative permittivity and permeability. *IEEE Ant. Wireless Propagat. Lett.*, 2002, vol. 1, no. 1, p. 10-13.

[77] DECOOPMAN, T., VANBESIEN, O., LIPPENS, D. Demonstration of a backward wave in a single split ring resonator and wire loaded tinline. *IEEE Microwave Wireless Compon. Lett.*, 2004, vol. 14, no. 11, p. 507-509.

[78] GRBIC, A., ELEFTHERIADES, G. V. Periodic analysis of a 2-D negative refractive index transmission line structure. *IEEE Trans. on Antennas and Propag*., 2003, vol. 51, no. 10, 2003, p. 2604-2611.

[79] ZIOLKOWSKI, R. W., ENGHETA, N. Metamaterial special issue introduction. *IEEE Trans. Ant. Propag*., 2003, vol. 51, no. 10, p. 2546-2549.

[80] CUMMER, S. A. Simulated causal sub wavelength focusing by a negative refractive index slab. *Appl. Phys. Lett*., 2003, vol. 82, p. 1503.

About Authors...

R. N. BARAL was born in 1976. He received his Bachelors degree in 1998 from the Institution of Electronics and Telecommunication Engineers. He got his Masters degree in 2002 from MITS, Gwalior. Currently he is pursuing his PhD degree from RGPV, Bhopal, India, on "Design and Analysis of Microstrip Filters". Till date, he has sixteen papers at national and international level. He is a life member of the Institute of Electronics and Telecommunication Engineers (IETE), New Delhi, India.

P. K. SINGHAL was born in 1965. He received the B.E. and Ph.D. degrees in electronics engineering from Jiwaji University, Gwalior, India, in 1987 and 1997, respectively, and the M.Tech. degree in microwave electronics from the University of Delhi, Delhi, India, in 1989. Currently, he is working as Professor, in the Department of Electronics Engineering, Madhav Institute of Technology and Science, Gwalior, India. He has about 90 publications to his credit at the national and international level. His research interest includes electromagnetic, communication systems, microwave circuits and antennas. Dr. Singhal is a Life Member of the India Society for Technical Education (ISTE), the Computer Society of India (CSI), the Institution of Engineers (India), and the Institute of Electronics and Telecommunication Engineers (IETE).