FILTENNA DESIGN WITH SELECTIVITY ENHANCEMENT FOR MODERN COMMUNICATION SYSTEM

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Electrical Engineering)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

APRIL 2018

To God Almighty and my Beloved Mother
Mrs. Ali Jemimah Obadiah who passed on, in the
course of my research studies.

ACKNOWLEDGEMENT

In the course of my research, several persons played an important role in walking this road with me. First and foremost, I give all thanks to God almighty for his wisdom and strength through the rigours of this research. I would also like to express my profound gratitude and thanks to my Supervisor Dr. Mohamad Rijal Bin Hamid who ignited my interest in antenna design. I appreciate him for his continuous belief in my ability. Indeed his careful guidance, thorough comments, priceless support were very helpful to me in this research. My co-supervisors Prof. Dr. Mohamad Kamal A. Rahim and Dr. Noor Asniza Murad were very supportive through their critical analysis and thorough comments in helping me achieve the research objectives. Their support helped me to see my research from different perspectives. I must say it was a rare honour to have been supervised by them.

I would also like to appreciate the staff and researchers in the Advanced RF and Microwave Research Group. I do appreciate my friends who stood by me and believed in me specifically; Gyeyok A. Marcus, Richard, Andrew, Elijah Lai, Ethan, Christopher, Joshua, Moses, John, Daphne, Shagaiya, Alvin and Joel.

Finally I sincerely appreciate my parents Bldr. and Mrs Obadiah Ateasi Ali for their encouragement, guidance and support. And to my siblings; Wanderimam, Anderimam, Rimamfatem, Grace, Kukorimam and Nyantitawenarimam, thanks for your moral support, thoughtfulness, understanding throughout this process. I cherish you all.

ABSTRACT

This thesis presents filtenna design with selectivity enhancement for modern communication systems. Filtennas are designed to simplify the radio frequency (RF) front-end, reduce cost and eliminate signal losses. Two filters, (Filter A and Filter B) and two filtennas, (Filtenna A and Filtenna B) have been designed to overcome a few drawback such as decrease in the peak gain, poor selectivity, increase in feeding area and structure complexity of the existing filtennas. Filtenna A and Filtenna B are designed based on Filter A and Filter B, respectively, by using filter synthesis technique. All designed structures were simulated using Computer Simulation Technology (CST) Microwave Studio and validated through fabrication and measurement of the prototypes. Firstly, an improved technique for creating sharp selectivity of a T-shaped stub bandpass filter (Filter A) is designed. The T-shaped stub is loaded with vertical resonators to produce good selectivity at both edges of the passband at 3.6 GHz. The advantage of this filter is the potential ability to adjust the center frequency and the bandwidth to suit the system demands. Secondly, a novel and compact second order Chebyshev bandpass filter (Filter B) with sharp selectivity is designed to operate at 5.8 GHz. The sharp selectivity is obtained by using U-shaped resonators and Defected Ground Structure which are responsible for the rejection at the higher and lower band edge, respectively. The advantage of this design is size compactness. About 56% area reduction is achieved over the second order Hairpin bandpass filter. Thirdly, the T-shaped stub bandpass filter is synthesized with a microstrip patch antenna to form a T-shaped stub fed filtenna (Filtenna A) with enhanced selectivity. The advantage of this design is that it maintains the same bandwidth as the conventional patch antenna with enhanced gain and good out-of-band suppression. The fourth design involves the synthesis of the second order Chebyshev designed filter with a U-shaped patch (Filtenna B). The designed filtenna operates at 5.8 GHz and has sharp selectivity as no degradation of the peak gain. The superiority of the proposed design over the conventional patch antenna is verified by a 99 % decrease in the out-of-band suppression and a 11.86 % increase in the gain performance. The designed filtennas address the limitations faced by existing filtennas and can be used in Wireless Local Area Network (WLAN) application.

ABSTRAK

Tesis ini mempersembahkan reka bentuk *filtenna* dengan peningkatan kepilihan untuk sistem komunikasi moden. *Filtenna* ini direka untuk meringkaskan keseluruhan frekuensi radio (RF), mengurangkan kos dan menyingkirkan kehilangan isyarat. Dua penapis (Penapis A dan Penapis B) dan dua *filtenna* (*Filtenna* A dan *Filtenna* B) telah direka untuk mengatasi beberapa kekurangan seperti penurunan gandaan puncak, kepilihan yang lemah, peningkatan dalam saiz talian suapan dan kerumitan struktur *filtenna* yang sedia ada. *Filtenna* A dan *Filtenna* B direka berasaskan daripada Penapis A dan Penapis B, masing-masing, dengan menggunakan teknik sintesis penapis. Semua struktur yang direka telah disimulasikan menggunakan Studio Gelombang Mikro (CST) dan disahkan melalui fabrikasi dan pengukuran prototaip. Pertamanya, penambahbaikan teknik untuk menghasilkan kepilihan tajam bagi penapis lulus jalur berbentuk “T” (Penapis A) direka. Puntung berbentuk “T” dimuatkan dengan kepulan pengayun menegak untuk menghasilkan kepilihan yang baik pada kedua tepi jalur lulus pada 3.6 GHz. Kelebihan penapis ini adalah berpotensi untuk menyesuaikan frekuensi pusat dan lebar jalur bagi menampung permintaan sistem. Keduanya, penapis lulus jalur Chebyshev jujukan kedua yang baharu dan padat (Penapis B) dengan kepilihan tajam direka untuk beroperasi pada 5.8 GHz. Kepilihan tajam diperoleh dengan menggunakan kepulan pengayun berbentuk “U” dan *Defected Ground Structure* yang bertanggungjawab untuk penolakan di jalur luar sisi tinggi dan rendah, masing-masing. Kelebihan reka bentuk ini adalah kepilihan tinggi dan kepadatan saiz. Pengurangan keluasan saiz lebih kurang 56 % telah dicapai berbanding dengan penapis lulusjalur jujukan kedua *Hairpin*. Ketiga, penapis jalur lulus berbentuk “T” disintesiskan dengan antena tampalan mikro jalur untuk menghasilkan *filtenna* suapan talian ‘T” (*Filtenna* A) dengan kepilihan yang dipertingkatkan. Kelebihan reka bentuk ini ialah mengekalkan jalur lebar yang sama dengan antena tampalan konvensional dengan peningkatan gandaan dan penindasan luar jalur yang lebih baik . Reka bentuk keempat melibatkan sintesis penapis Chebyshev jujukan kedua dengan tampalan berbentuk “U” (*Filtenna* B). *Filtenna* yang direka beroperasi pada 5.8 GHz dan mempunyai kepilihan tajam tanpa penurunan gandaan puncak. Kelebihan terhadap rekabentuk ini ke atas antena tampalan konvensional disahkan oleh pengurangan sebanyak 99 % dalam penindasan luar jalur dan peningkatan 11.86 % pada prestasi gandaan. *Filtenna* yang direka menangani kekurangan yang dihadapi oleh *filtenna-filtenna* yang sedia ada dan boleh digunakan dalam aplikasi *Wireless Local Area Network* (WLAN).

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LIST OF ABBREVATIONS

3D	-	Three Dimensional
BER	-	Bit Error Rate
BPF	-	Bandpass Filter
CST	-	Computer Simulation Technology
DGS	-	Defected Ground Structure
FBW	-	Fractional Bandwidth
OC	-	Off Centered
RF	-	Radio Frequency
SIR	-	Stepped Impedance Resonator
SNR	-	Signal to Noise Ratio
WLAN	-	Wireless Local Area Network

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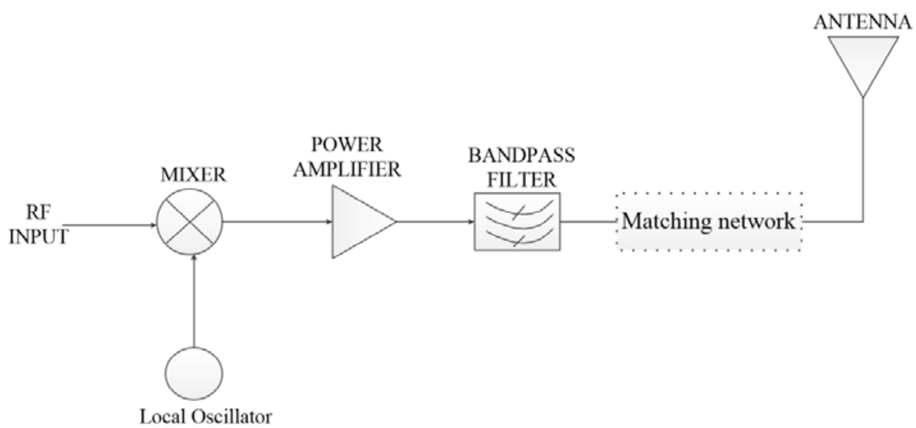
CHAPTER 1

INTRODUCTION

1.1 Introduction

The twenty-first century has experienced a significant increase in communication among all categories of people. Consequently, the rise in the use of electronic devices has become an irresistible trend that has come to stay. There is a need for supporting systems which enable communication to be more efficient and effective. The optimization of radio frequency front end circuit used to support the transmission of signals is very critical. This is because communication systems rely on RF front end circuits to deliver signals to their end users [1].

The RF front end circuit comprises of the antenna, bandpass filter, low noise/power amplifier, mixer and local oscillator [2]. It processes the incoming RF signal before it is converted to intermediate frequency and vice versa. The change in communication systems from analogue to digital communication; has made factors such as performance, cost, size and power consumption of great significance. The demand for these factors has given rise to multifunctional devices. The RF front end is therefore an integral part of any communication system. It is shown in Figure 1.1. The antenna and the bandpass filter are the key components of the RF front end circuits. The purpose of the antenna is to transmit or receive signals while the bandpass filter is used to remove unwanted signals. The antenna and bandpass filter are both individually designed with 50 Ω line impedance. However, an impedance mismatch exists between the antenna and bandpass filter when they are cascaded in the RF front end circuit. Consequently, a matching network is utilized between the antenna and bandpass filter to enhance the system performance. The matching network increases the overall system complexity and size [3, 4].



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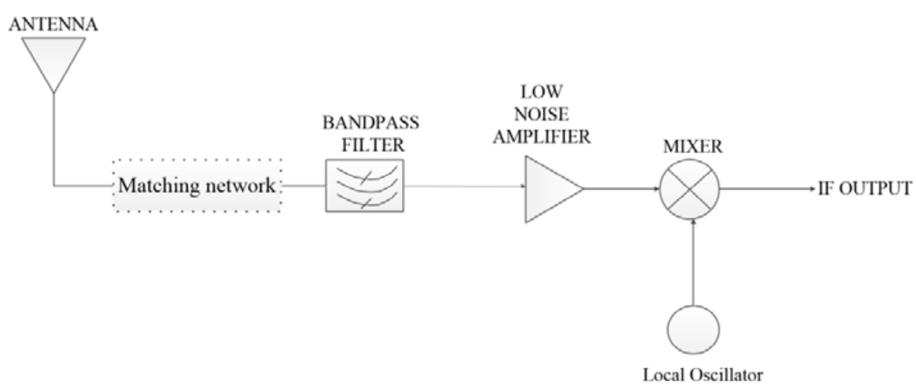
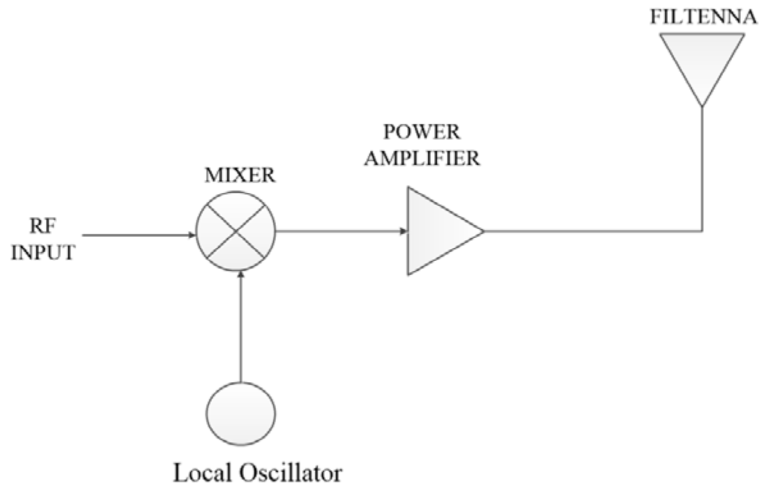


(b)

Figure 1.1 Block diagram for RF Front end (a) Transmitter circuit (b) Receiver circuit [1]

There exists external noise and transition loss between the antenna and bandpass filter. Moreover, the bandpass filter has its own insertion loss. These losses have an adverse effect on the system performance, which is quite significant in digital communication [2]. Addressing these losses is of great concern to researchers nowadays. A practicable approach used to resolve these losses is to integrate the antenna and filter into one single structure. This structure is often referred to as filtenna. This approach is not as easy as it seems because it goes beyond merely combining the filter and antenna together.

A Filtenna (*Filter+antenna*) is therefore a structure which integrates an antenna and filter into a single structure thereby reducing interference, losses, system size, complexity and improving the system noise performance [5-9]. A good filtenna structure should possess both good antenna operations (in terms of the radiation pattern, directivity, polarization) and good filter performance (i.e. high selectivity, good out-of-band rejection with sharp roll off) [2]. The filtenna design simplifies the RF front end circuit as seen in Figure 1.2 by eliminating the need for a bandpass filter and matching network. Multifunctional devices such as filtennas are therefore generating much attention by researchers due to the advantages they possess. The design of filtennas is the main motivation behind this research; more details would be further discussed in this thesis.



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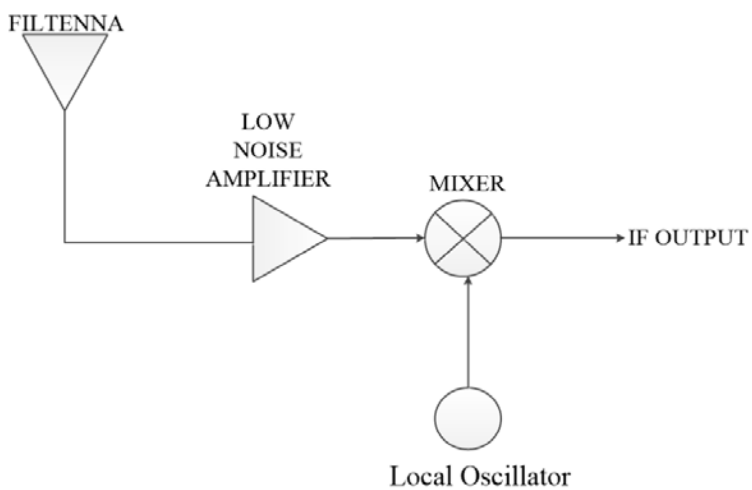

(b)

Figure 1.2 Block diagram for RF Front end with Filtenna (a) Transmitter circuit (b) Receiver circuit

1.2 Problem Statement

The RF front end affects the quality of the bit error rate (BER) performance as well as the best possible Signal to noise ratio (SNR) of the system. Therefore, the signal quality can be improved by having a properly designed RF front end. One of the measures taken to improve the RF front end is by integrating the filter and antenna in a single structure. As a result, the losses, and interference between the antenna and the bandpass filter is tackled thereby yielding a better BER and system SNR. Generally, these losses are tackled by filtenna design.

Several literatures [10-17] have implemented the filtenna design through different approach or process to yield the required performance. Filtennas are designed for fixed, multiband and reconfigurable frequencies. The approaches used in filtenna design include Stacked substrates filtennas [3, 4, 18], edge coupled filtennas [19-21] differentially designed filtenna [22-25], hairpin resonator filtennas [3, 17, 26], substrate integrated waveguide (SIW) filtennas [27-31], filtennas with Dipole [32, 33]. A filtenna which operates at both a filter and filtenna with three ports is shown in [34]. Filtenna arrays using edge coupling and power divider [35] and U-shaped hairpin resonators [36] have been designed. A number of reconfigurable filtennas have been achieved by embedding bandpass filters on the feedline of the wideband antennas [37-41]. Each of these approaches are discussed in detail in Chapter 2 of this thesis.

However, implementing filtennas has come with its challenges and limitations. Among these challenges are a degrading of peak in-band gain, low level out-of-band gain rejection and the complexity of the synthesis. The increase in the overall feeding portion which adds further size to the filtenna is also of concern to researchers. Currently the use of stacks have been utilized to compensate for the decrease in passband gain experienced, however this makes the antenna high profile and increases its complexity. Hence this research shall seek to address achieving filtenna design with compact size, low profile, high in-band gain and good selectivity as well as radiation pattern performance for modern communication systems.

1.3 Research Objectives

The aim of this thesis is to enhance the selectivity of the filtenna by employing efficient techniques. Hence, the following key objectives of this research are as listed below.

(i) To design a microstrip bandpass filter with good out-of-band rejection of > -10 dB, low insertion loss of < -3 dB and compact size.

(ii) To design filtennas by coupling the designed bandpass filters to microstrip patch antenna to achieve both good radiating and filtering requirements such as compact size, low profile structure, well-shaped radiation pattern, none degradation of passband gain and out of band rejection of > -10 dB.

(iii) To compare and verify the performance of the designed filtennas with a 'cascaded patch antenna and filter' found in a conventional RF front ends.

1.4 Scope of Research

The aim of this research work is to integrate filters and antennas within a single structure. This research shall cover a detailed review on filters and filtennas specifically as it affects the techniques and challenges faced by the filtennas design. Two microwave bandpass filters with very good selectivity and out-of-band rejection of > - 10 dB shall be designed. The harmonics suppression of the designed bandpass filters is not considered in this research. This is because the research focus is on enhancing the selectivity. To eliminate the need for bandpass filters in the RF front end, the designed filters shall be integrated with the patch antenna and known as filtenna. Two filtennas shall be designed using synthesis technique to properly extract the coupling coefficient. The desired filters and filtennas should possess a sharp selectivity without degradation of the peak gain in the passband. Computer Simulation Technology (CST) software shall be used to simulate the designs due to its accuracy. The parameters to be analysed are the S_{11}, S_{21}, gain, radiation pattern and coupling of the design. The proposed designs shall be fabricated in the laboratory with photolithography using laminate boards (FR4 and Taconic TLY5). The measurements of the designed prototype shall be done with the use of Vector Network Analyser (VNA). The gain and radiation pattern are measured in an anechoic chamber. A detailed analysis of the designed filters and filtennas shall be carried out. The designed filtennas shall be compared with a conventional patch antenna and a cascaded filter and antenna in terms of their performance.

1.5 Thesis Structure and Organization

This thesis is comprised of seven chapters. The outline of every chapter is provided below:

Chapter 1 presents the introduction to the research. A succinct introduction to RF front end and filtennas are reviewed. Furthermore, the problem statement, scope of research and the objectives of the research are presented.

In Chapter 2, the literature review is discussed. The literature review of microwave bandpass filters, filtennas, filter synthesis technique and RF front end are provided in detail from previous works done.

The methodology utilized in the research is presented in Chapter 3. The research flow chart is described. The way to synthesize the filters with a patch antenna to achieve both radiation and filtering functions is also detailed out. The key summary to use CST Microwave Studio is also explained. Fabrication and measurement techniques in the laboratory are also pointed out. These processes are all described in the chapter.

A loaded T-shaped stub loaded bandpass filter (Filter A) is presented in Chapter 4. The position of the transmission zeros of the filter can be adjusted by changing the position of the stub used in loading the resonator. The filter has a Chebyshev gain response. The filter shows good rejection of out of band gain at both the upper and lower frequency.

Chapter 5 introduces a compact second order Chebyshev bandpass filter (Filter B) for modern communication systems. The filter is made up of a pair of U-shaped resonator formed along an indirectly coupled feedline with a Defected Ground Structure (DGS). The designed filter possesses good out-of-band gain suppression.

Chapter 6 describes the integration of the earlier designed filters to a patch antenna which form a filtenna. The first filtenna (Filtenna A) has a Chebyshev type performance. The output feedline is replaced with microstrip patch antenna. The second filtenna structure is formed by making the antenna patch the second resonator of the second order Chebyshev filter (Filtenna B). The external quality of the filter resonator and patch are equivalent to each other. This gives the filtenna good radiation and filtering characteristics. The proposed filtenna provides a sharp selectivity and good out-of-band rejection.

The conclusions and areas of future works and thesis contribution are given in Chapter 7. The contributions derived from the achieved objectives are highlighted and discussed in the chapter. Further possible future works are also suggested.

REFERENCES

[1] D. M. Pozar, "Microwave Engineering 3e," *Tramsmission Lines and Waveguides,* pp. 143-149, 2005.

[2] J.-S. G. Hong and M. J. Lancaster, *Microstrip filters for RF/microwave applications*. John Wiley & Sons, 2004.

[3] J. Zuo, X. Chen, G. Han, L. Li, and W. Zhang, "An integrated approach to RF antenna-filter co-design," *IEEE Antennas and Wireless Propagation Letters,* vol. 8, pp. 141-144, 2009.

[4] X. Y. Zhang, W. Duan, and Y.-M. Pan, "High-gain filtering patch antenna without extra circuit," *IEEE Transactions on Antennas and Propagation,* vol. 63, no. 12, pp. 5883-5888, 2015.

[5] Y. Quere, C. Quendo, W. El Hajj, and C. Person, "A global synthesis tool and procedure for filter-antenna co-design," in *Antenna Technology and Applied Electromagnetics (ANTEM), 2012 15th International Symposium on*, 2012, pp. 1-4: IEEE.

[6] F. Queudet, I. Pele, B. Froppier, Y. Mahe, and S. Toutain, "Integration of pass-band filters in patch antennas," in *Microwave Conference, 2002. 32nd European*, 2002, pp. 685-688: IEEE.

[7] H. Blondeaux *et al.*, "Microwave device combining filtering and radiating functions for telecommunication satellites," in *Microwave Symposium Digest, 2001 IEEE MTT-S International*, 2001, vol. 1, pp. 137-140: IEEE.

[8] T. Le Nadan, J. P. Coupez, and C. Person, "Optimization and miniaturization of a filter/antenna multi-function module using a composite ceramic-foam substrate," in *Microwave Symposium Digest, 1999 IEEE MTT-S International*, 1999, vol. 1, pp. 219-222: IEEE.

[9] X. Shang and M. J. Lancaster, "Patch antenna with integrated bandpass filter," 2013.

[10] J.-H. Yen, N.-C. Liu, K.-H. Chen, and J.-H. Tarng, "A compact planar dual-band filtering antenna," in *Computational Electromagnetics (ICCEM), 2017 IEEE International Conference on*, 2017, pp. 367-369: IEEE.

[11] T. L. Wu, Y. M. Pan, P. F. Hu, and S. Y. Zheng, "Design of a low profile and compact omnidirectional filtering patch antenna," *IEEE Access,* vol. 5, pp. 1083-1089, 2017.

[12] R. Li, C. Hua, Y. Lu, Z. Wu, and Y. Wang, "Dual-polarized aperture-coupled filtering antenna," in *Electromagnetics: Applications and Student Innovation Competition (iWEM), 2017 International Workshop on*, 2017, pp. 152-153: IEEE.

[13] S. Zuo, W.-J. Wu, and Z.-Y. Zhang, "A simple filtering-antenna with compact size for WLAN application," *Progress In Electromagnetics Research Letters,* vol. 39, pp. 17-26, 2013.

[14] S. Chen, Y. Zhao, M. Peng, and Y. Wang, "A codesigned compact dual-band filtering antenna with PIN loaded for WLAN applications," *International Journal of Antennas and Propagation,* vol. 2014, 2014.

[15] W. Y. Sam and Z. Zakaria, "A review on reconfigurable integrated filter and antenna," *Progress In Electromagnetics Research B,* vol. 63, pp. 263-273, 2015.

[16] D. Feng, H. Zhai, L. Xi, K. Zhang, and D. Yang, "A new filter antenna using improved stepped impedance hairpin resonator," *Microwave and Optical Technology Letters,* vol. 59, no. 11, pp. 2934-2938, 2017.

[17] A. Hueltes Escobar, J. A. Verdú Tirado, J. C. Collado Gómez, J. Mateu Mateu, E. Rocas Cantenys, and J. L. Valenzuela González, "Filtenna integration achieving ideal chebyshev return losses," *Radioengineering,* vol. 23, no. 1, pp. 362-368, 2014.

[18] C. Mao *et al.*, "Integrated filtering-antenna with controllable frequency bandwidth," in *Antennas and Propagation (EuCAP), 2015 9th European Conference on*, 2015, pp. 1-4: IEEE.

[19] J.-D. Zhang, L. Zhu, Q.-S. Wu, N.-W. Liu, and W. Wu, "A Compact Microstrip-Fed Patch Antenna With Enhanced Bandwidth and Harmonic Suppression," *IEEE Transactions on Antennas and Propagation,* vol. 64, no. 12, pp. 5030-5037, 2016.

[20] C.-K. Lin and S.-J. Chung, "A compact filtering microstrip antenna with quasi-elliptic broadside antenna gain response," *IEEE Antennas and wireless propagation letters,* vol. 10, pp. 381-384, 2011.

[21] C.-K. Lin and S.-J. Chung, "A compact edge-fed filtering microstrip antenna with 0.2 dB equal-ripple response," in *Microwave Conference, 2009. EuMC 2009. European*, 2009, pp. 378-380: IEEE.

[22] L. Li and G. Liu, "A differential microstrip antenna with filtering response," *IEEE Antennas and Wireless Propagation Letters,* vol. 15, pp. 1983-1986, 2016.

[23] X. Chen, F. Zhao, L. Yan, and W. Zhang, "A compact filtering antenna with flat gain response within the passband," *IEEE Antennas and Wireless Propagation Letters,* vol. 12, pp. 857-860, 2013.

[24] J. Shi *et al.*, "A compact differential filtering quasi-Yagi antenna with high frequency selectivity and low cross-polarization levels," *IEEE Antennas and Wireless Propagation Letters,* vol. 14, pp. 1573-1576, 2015.

[25] C.-Y. Hsieh, C.-H. Wu, and T.-G. Ma, "A compact dual-band filtering patch antenna using step impedance resonators," *IEEE Antennas and wireless propagation letters,* vol. 14, pp. 1056-1059, 2015.

[26] G. Mansour, M. J. Lancaster, P. S. Hall, P. Gardner, and E. Nugoolcharoenlap, "Design of filtering microstrip antenna using filter synthesis approach," *Progress In Electromagnetics Research,* vol. 145, pp. 59-67, 2014.

[27] Y. Yusuf and X. Gong, "Compact low-loss integration of high-$ Q $3-D filters with highly efficient antennas," *IEEE Transactions on Microwave Theory and Techniques,* vol. 59, no. 4, pp. 857-865, 2011.

[28] H. Cheng, Y. Yusuf, and X. Gong, "Vertically integrated three-pole filter/antennas for array applications," *IEEE Antennas and Wireless Propagation Letters,* vol. 10, pp. 278-281, 2011.

[29] Y. Yusuf, H. Cheng, and X. Gong, "A seamless integration of 3-D vertical filters with highly efficient slot antennas," *IEEE Transactions on Antennas and Propagation,* vol. 59, no. 11, pp. 4016-4022, 2011.

[30] O. A. Nova, J. C. Bohorquez, N. M. Pena, G. E. Bridges, L. Shafai, and C. Shafai, "Filter-antenna module using substrate integrated waveguide cavities," *IEEE Antennas and Wireless Propagation Letters,* vol. 10, pp. 59-62, 2011.

[31] H. Chu, J.-X. Chen, S. Luo, and Y.-X. Guo, "A millimeter-wave filtering monopulse antenna array based on substrate integrated waveguide technology," *IEEE Transactions on Antennas and Propagation,* vol. 64, no. 1, pp. 316-321, 2016.

[32] C.-T. Chuang and S.-J. Chung, "New printed filtering antenna with selectivity enhancement," in *Microwave Conference, 2009. EuMC 2009. European*, 2009, pp. 747-750: IEEE.

[33] C.-T. Chuang and S.-J. Chung, "A compact printed filtering antenna using a ground-intruded coupled line resonator," *IEEE Transactions on Antennas and Propagation,* vol. 59, no. 10, pp. 3630-3637, 2011.

[34] Y. Sung, "Microstrip resonator doubling as a filter and as an antenna," *IEEE Antennas and Wireless Propagation Letters,* vol. 9, pp. 467-470, 2010.

[35] C.-K. Lin and S.-J. Chung, "A filtering microstrip antenna array," *IEEE Transactions on Microwave Theory and Techniques,* vol. 59, no. 11, pp. 2856-2863, 2011.

[36] W. Ahmad and D. Budimir, "Dual-band filtenna array for WLAN applications," *Microwave and Optical Technology Letters,* vol. 58, no. 2, pp. 477-481, 2016.

[37] H. A. Atallah, A. B. Abdel-Rahman, K. Yoshitomi, and R. K. Pokharel, "Compact frequency tunable filtenna with wide continuous tuning range using capacitively loaded folded arms open loop resonator for interweave cognitive

radio applications," in *Radio Science Conference (NRSC), 2016 33rd National*, 2016, pp. 87-93: IEEE.

[38] Y. Tawk, J. Costantine, and C. Christodoulou, "A varactor-based reconfigurable filtenna," *IEEE Antennas and Wireless Propagation Letters,* vol. 11, pp. 716-719, 2012.

[39] Y. Tawk, J. Costantine, and C. G. Christodoulou, "Reconfigurable filtennas and MIMO in cognitive radio applications," *IEEE Transactions on Antennas and Propagation,* vol. 62, no. 3, pp. 1074-1083, 2014.

[40] M. Soltanpour and M. Fakharian, "Compact filtering slot antenna with frequency agility for Wi-Fi/LTE mobile applications," *Electronics Letters,* vol. 52, no. 7, pp. 491-492, 2016.

[41] M. M. Fakharian, P. Rezaei, A. A. Orouji, and M. Soltanpur, "A wideband and reconfigurable filtering slot antenna," *IEEE Antennas and Wireless Propagation Letters,* vol. 15, pp. 1610-1613, 2016.

[42] S. Koley and D. Mitra, "A planar microstrip-fed tri-band filtering antenna for WLAN/WiMAX applications," *Microwave and Optical Technology Letters,* vol. 57, no. 1, pp. 233-237, 2015.

[43] T. Le Nadan, J. Coupez, S. Toutain, and C. Person, "Integration of an antenna/filter device, using a multi-layer, multi-technology process," in *Microwave Conference, 1998. 28th European*, 1998, vol. 1, pp. 672-677: IEEE.

[44] A. Abbaspour-Tamijani, J. Rizk, and G. Rebeiz, "Integration of filters and microstrip antennas," in *Antennas and Propagation Society International Symposium, 2002. IEEE*, 2002, vol. 2, pp. 874-877: IEEE.

[45] Z. H. Yao and D. Chen, "A novel filtering antenna using dual-mode resonator," *Progress In Electromagnetics Research Letters,* vol. 58, pp. 113-118, 2016.

[46] H. Zumbahlen, *Linear circuit design handbook*. Newnes, 2011.

[47] H. G. Dimopoulos, *Analog electronic filters: theory, design and synthesis*. Springer Science & Business Media, 2011.

[48] M. Makimoto and S. Yamashita, "Bandpass filters using parallel coupled stripline stepped impedance resonators," *IEEE Transactions on Microwave Theory and Techniques,* vol. 28, no. 12, pp. 1413-1417, 1980.

[49] J.-S. Park, J.-S. Yun, and D. Ahn, "A design of the novel coupled-line bandpass filter using defected ground structure with wide stopband performance," *IEEE Transactions on Microwave Theory and Techniques,* vol. 50, no. 9, pp. 2037-2043, 2002.

[50] J.-T. Kuo, S.-P. Chen, and M. Jiang, "Parallel-coupled microstrip filters with over-coupled end stages for suppression of spurious responses," *IEEE Microwave and Wireless Components Letters,* vol. 13, no. 10, pp. 440-442, 2003.

[51] P. Cheong, S.-W. Fok, and K.-W. Tam, "Miniaturized parallel coupled-line bandpass filter with spurious-response suppression," *IEEE transactions on microwave theory and techniques,* vol. 53, no. 5, pp. 1810-1816, 2005.

[52] J.-S. Hong and M. J. Lancaster, "Cross-coupled microstrip hairpin-resonator filters," *IEEE Transactions on Microwave theory and techniques,* vol. 46, no. 1, pp. 118-122, 1998.

[53] G. Matthaei, N. Fenzi, R. Forse, and S. Rohlfing, "Narrow-band hairpin-comb filters for HTS and other applications," in *Microwave Symposium Digest, 1996., IEEE MTT-S International*, 1996, vol. 2, pp. 457-460: IEEE.

[54] J.-T. Kuo, M.-J. Maa, and P.-H. Lu, "Microstrip elliptic function filters with compact miniaturized hairpin resonators," in *Microwave Conference, 1999 Asia Pacific*, 1999, vol. 3, pp. 860-864: IEEE.

[55] S.-Y. Lee and C.-M. Tsai, "New cross-coupled filter design using improved hairpin resonators," *IEEE Transactions on Microwave theory and Techniques,* vol. 48, no. 12, pp. 2482-2490, 2000.

[56] C.-M. Tsai, S.-Y. Lee, and C.-C. Tsai, "Hairpin filters with tunable transmission zeros," in *Microwave Symposium Digest, 2001 IEEE MTT-S International*, 2001, vol. 3, pp. 2175-2178: IEEE.

[57] L.-H. Hsieh and K. Chang, "Tunable microstrip bandpass filters with two transmission zeros," *IEEE Transactions on Microwave Theory and Techniques,* vol. 51, no. 2, pp. 520-525, 2003.

[58] A. Sulaiman *et al.*, "Design of hairpin band pass filters for k-band application," in *RF and Microwave Conference, 2008. RFM 2008. IEEE International*, 2008, pp. 23-26: IEEE.

[59] Y.-L. Lu, S. Wang, T. Gu, P. Cao, and K. Li, "A miniaturize bandpass filter with harmonic suppression using meandered quarter-wavelength resonators," *International Journal of Antennas and Propagation,* vol. 2014, 2014.

[60] X. Y. Zhang and Q. Xue, "High-selectivity tunable bandpass filters with harmonic suppression," *IEEE Transactions on Microwave Theory and Techniques,* vol. 58, no. 4, pp. 964-969, 2010.

[61] X. Y. Zhang and Q. Xue, "Harmonic-suppressed bandpass filter based on discriminating coupling," *IEEE Microwave and Wireless Components Letters,* vol. 19, no. 11, pp. 695-697, 2009.

[62] J.-N. Lee, K.-O. Song, S.-S. Lee, K.-D. Lee, and J.-K. Park, "Design of band-pass filter with harmonics suppression using open stub," in *Microwave Conference Proceedings (APMC), 2011 Asia-Pacific*, 2011, pp. 418-420: IEEE.

[63] J.-R. Lee, J.-H. Cho, and S.-W. Yun, "New compact bandpass filter using microstrip/spl lambda//4 resonators with open stub inverter," *IEEE Microwave and Guided Wave Letters,* vol. 10, no. 12, pp. 526-527, 2000.

[64] L. Zhu and W. Menzel, "Compact microstrip bandpass filter with two transmission zeros using a stub-tapped half-wavelength line resonator," *IEEE Microwave and Wireless Components Letters,* vol. 13, no. 1, pp. 16-18, 2003.

[65] H. Zhang and K. J. Chen, "Bandpass filters with reconfigurable transmission zeros using varactor-tuned tapped stubs," *IEEE Microwave and wireless components letters,* vol. 16, no. 5, pp. 249-251, 2006.

[66] R. Zhou, I. Mandal, and H. Zhang, "Microwave bandpass filters with tunable center frequencies and reconfigurable transmission zeros," *Microwave and Optical Technology Letters,* vol. 55, no. 7, pp. 1526-1531, 2013.

[67] C. Jianxin, Y. Mengxia, X. Jun, and X. Quan, "Compact microstrip bandpass filter with two transmission zeros," *Electronics Letters,* vol. 40, no. 5, pp. 311-313, 2004.

[68] L. Gao, X. Y. Zhang, B.-J. Hu, and Q. Xue, "Novel multi-stub loaded resonators and their applications to various bandpass filters," *IEEE Transactions on Microwave Theory and Techniques,* vol. 62, no. 5, pp. 1162-1172, 2014.

[69] X. Y. Zhang and Q. Xue, "Novel centrally loaded resonators and their applications to bandpass filters," *IEEE Transactions on Microwave Theory and Techniques,* vol. 56, no. 4, pp. 913-921, 2008.

[70] W.-H. Tu, "Compact low-loss reconfigurable bandpass filter with switchable bandwidth," *IEEE Microwave and Wireless Components Letters,* vol. 20, no. 4, pp. 208-210, 2010.

[71] Y. Wang, Q.-X. Chu, F.-C. Chen, and J.-M. Qiu, "Low insertion loss bandpass filter with controllable transmission zeros using stepped impedance resonator," in *Wireless Symposium (IWS), 2015 IEEE International*, 2015, pp. 1-4: IEEE.

[72] M. K. Khandelwal, B. K. Kanaujia, and S. Kumar, "Defected Ground Structure: Fundamentals, Analysis, and Applications in Modern Wireless Trends," *International Journal of Antennas and Propagation,* vol. 2017, 2017.

[73] A. Boutejdar, A. Omar, M. Al Sharkawy, and A. Darwish, "A simple transformation of improved WLAN band pass to low pass filter using defected ground structure (DGS), defected microstrip structure (DMS) and multilayer-technique," *Journal of Microwaves, Optoelectronics and Electromagnetic Applications,* vol. 12, no. 1, pp. 111-130, 2013.

[74] L. H. Weng, Y.-C. Guo, X.-W. Shi, and X.-Q. Chen, "An overview on defected ground structure," *Progress In Electromagnetics Research B,* vol. 7, pp. 173-189, 2008.

[75] D. Ahn, J.-S. Park, C.-S. Kim, J. Kim, Y. Qian, and T. Itoh, "A design of the low-pass filter using the novel microstrip defected ground structure," *IEEE transactions on microwave theory and techniques,* vol. 49, no. 1, pp. 86-93, 2001.

[76] Q. Chen and J. Xu, "DGS resonator with two transmission zeros and its application to lowpass filter design," *Electronics letters,* vol. 46, no. 21, pp. 1447-1449, 2010.

[77] C.-S. Kim, J.-S. Park, D. Ahn, and J.-B. Lim, "A novel 1-D periodic defected ground structure for planar circuits," *IEEE Microwave and guided wave letters,* vol. 10, no. 4, pp. 131-133, 2000.

[78] F. Y. Zulkifli, E. T. Rahardjo, and D. Hartanto, "Mutual coupling reduction using dumbbell defected ground structure for multiband microstrip antenna array," *Progress In Electromagnetics Research Letters,* vol. 13, pp. 29-40, 2010.

[79] D.-J. Woo, T.-K. Lee, J.-W. Lee, C.-S. Pyo, and W.-K. Choi, "Novel U-slot and V-slot DGSs for bandstop filter with improved Q factor," *IEEE Transactions on Microwave Theory and Techniques,* vol. 54, no. 6, pp. 2840-2847, 2006.

[80] H.-J. Chen *et al.*, "A novel cross-shape DGS applied to design ultra-wide stopband low-pass filters," *IEEE Microwave and Wireless Components Letters,* vol. 16, no. 5, pp. 252-254, 2006.

[81] H. W. Liu, Z. F. Li, and X. W. Sun, "A novel fractal defected ground structure and its application to the low-pass filter," *Microwave and Optical Technology Letters,* vol. 39, no. 6, pp. 453-456, 2003.

[82] M. Kufa and Z. Raida, "Lowpass filter with reduced fractal defected ground structure," *Electronics Letters,* vol. 49, no. 3, pp. 199-201, 2013.

[83] C.-S. Kim, J.-S. Lim, S. Nam, K.-Y. Kang, and D. Ahn, "Equivalent circuit modelling of spiral defected ground structure for microstrip line," *Electronics Letters,* vol. 38, no. 19, pp. 1109-1110, 2002.

[84] J.-S. Lim, C.-S. Kim, Y.-T. Lee, D. Ahn, and S. Nam, "A spiral-shaped defected ground structure for coplanar waveguide," *IEEE Microwave and Wireless Components Letters,* vol. 12, no. 9, pp. 330-332, 2002.

[85] A. Boutejdar, A. Ramadan, M. Makkey, and A. Omar, "Design of compact Microstrip lowpass filters using a U-shaped defected ground structure and compensated microstrip line," in *Microwave Conference, 2006. 36th European*, 2006, pp. 267-270: IEEE.

[86] J.-K. Xiao and Y.-F. Zhu, "New U-shaped DGS bandstop filters," *Progress In Electromagnetics Research C,* vol. 25, pp. 179-191, 2012.

[87] G.-H. Sun, S.-W. Wong, L. Zhu, and Q.-X. Chu, "A compact printed filtering antenna with good suppression of upper harmonic band," *IEEE Antennas and Wireless Propagation Letters,* vol. 15, pp. 1349-1352, 2016.

[88] H. Chu, C. Jin, J.-X. Chen, and Y.-X. Guo, "A 3-D millimeter-wave filtering antenna with high selectivity and low cross-polarization," *IEEE Transactions on Antennas and Propagation,* vol. 63, no. 5, pp. 2375-2380, 2015.

[89] S. Oda, S. Sakaguchi, H. Kanaya, R. Pokharel, and K. Yoshida, "Electrically small superconducting antennas with bandpass filters," *IEEE Transactions on Applied Superconductivity,* vol. 17, no. 2, pp. 878-881, 2007.

[90] I. T. U. (ITU), "Chapter two- Frequencies," *Radio Regulation Article* pp. 33-179, 2012.

[91] V. Rodriguez, "Basic Rules for Anechoic Chamber Design, Part One: RF Absorber Approximations," *Precision Antenna Measurement Guide,* p. 4, 2017.

[92] L. H. Hemming, *Electromagnetic anechoic chambers: a fundamental design and specification guide*. Wiley Interscience, 2002.