Progress In Electromagnetics Research, Vol. 145, 59–67, 2014

Design of Filtering Microstrip Antenna Using Filter Synthesis Approach

**Ghaith Mansour*, Michael J. Lancaster, Peter S. Hall,
Peter Gardner, and Ekasit Nugoolcharoenlap**

Abstract—Design, simulation, and measurement of a compact filtering microstrip antenna is presented. A feed line, two hairpin resonators, and a rectangular patch are integrated to form the filtering antenna. The elements together function as a third order bandpass filter with Chebyshev equal ripple response of 0.043 dB at midband frequency of 2.0 GHz. The rectangular patch acts not only as a radiating element, but also as the last resonator of the bandpass filter. The proposed filtering antenna exhibits good out-of-band gain suppression, flat in-band gain response, good selectivity at the band edges, and well-shaped radiation pattern.

1. INTRODUCTION

In wireless communication systems, the antenna and the filter are the key components. While the antenna transmits and receives signals, the bandpass filter (BPF) selects signals in the operating band and rejects spurious (out-of-band) signals. Due to the increasing trend towards simplicity and miniaturization, it is desirable to integrate the filter and the antenna into a single component that achieves filtering and radiating functions simultaneously, known as filtering antenna "filtenna". The filtenna reduces the pre-filtering requirement and improves the noise performance of the system. Many filtering antennas, in different topologies, have been designed using filter synthesis approach, in which the antenna acts as the last resonator in the filter. Filtering antennas have been implemented in different forms including rectangular patch [1], circular patch [2], patch array [3], Γ-shaped antenna [4], slot dipole [5], monopole antenna [6], inverted-L antenna [7], Yagi antenna [8], waveguide slot antenna [9], and dielectric resonator antennas [10].

In this paper, a microstrip antenna with filtering function is developed using the synthesis process of the bandpass filter. The filtering antenna consists of a feed line, two hairpin resonators, and rectangular patch. The feed line is coupled to the resonator using proximity coupling method. The proposed structure functions as a bandpass filter having a bandwidth of 58 MHz centred at a midband frequency of 2.0 GHz. A three pole Chebyshev lowpass prototype with 0.043 dB bandpass ripple was chosen. The proposed structure exhibits a well-shaped gain response with good skirt selectivity as the conventional microstrip bandpass filter. It exhibits a bandwidth of 3.5% (considering the -10 dB matching), high efficiency and reasonable realized gain of 5 dB.

2. CO-DESIGN OF ANTENNA AND FILTER

2.1. Filter Design

A microstrip bandpass filter is designed to have a fractional bandwidth of 2.94% (FBW = 0.0294) at a midband frequency $f_0 = 2.0$ GHz. A three-pole Chebychev lowpass prototype with passband ripple of

---

Received 14 January 2014, Accepted 11 February 2014, Scheduled 18 February 2014

* Corresponding author: Ghaith Mansour (frings80@yahoo.com).
The authors are with the School of Electronic, Electrical and Computer Engineering, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK.

0.043 dB is chosen. The lowpass prototype parameters, given for a normalized cut off frequency $\Omega_c = 1$, can be found in the literature [11] as follow: $g_0 = g_4 = 1.0$, $g_1 = g_3 = 0.8516$, and $g_2 = 1.1032$. Having obtained the lowpass parameters, the bandpass design parameters can be calculated by:

$$Q_{e1} = \frac{g_0 g_1}{FBW} \quad Q_{en} = \frac{g_n g_{n+1}}{FBW} \tag{1}$$

$$M_{i,i+1} = \frac{FBW}{\sqrt{g_i g_{i+1}}} \tag{2}$$

where Q_{e1} and Q_{en} are the external quality factors of the resonators at the input and the output. $M_{i,i+1}$ is the coupling coefficient between the adjacent resonators i and $i + 1$. The coupling coefficients are found to be $Q_{e1} = 29$, and $M_{i,i+1} = 0.0303$. For microstrip implementation, a dielectric substrate TRF41 from Taconic® was used. The dielectric constant of the material is 4.1 and the loss tangent is 0.0035. The dielectric thickness is $h = 3.04$ mm. The ground plane has a width of $W_g = 80$ mm, and length of $L_g = 85$ mm. The microstrip bandpass filter, shown in Figure 1, is designed to have a feed line with a characteristic impedance $Z_0 = 50\,\Omega$.

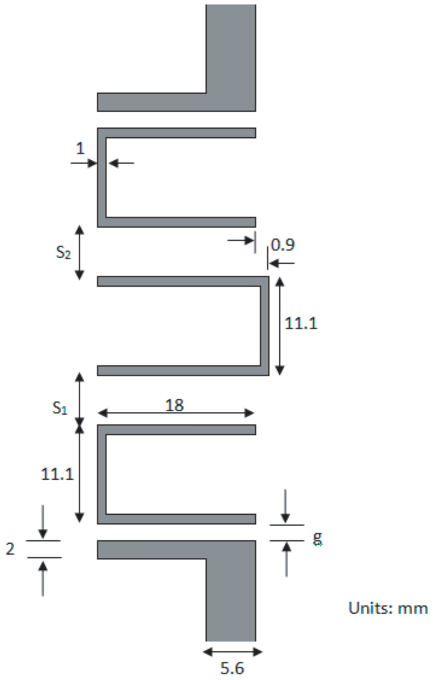


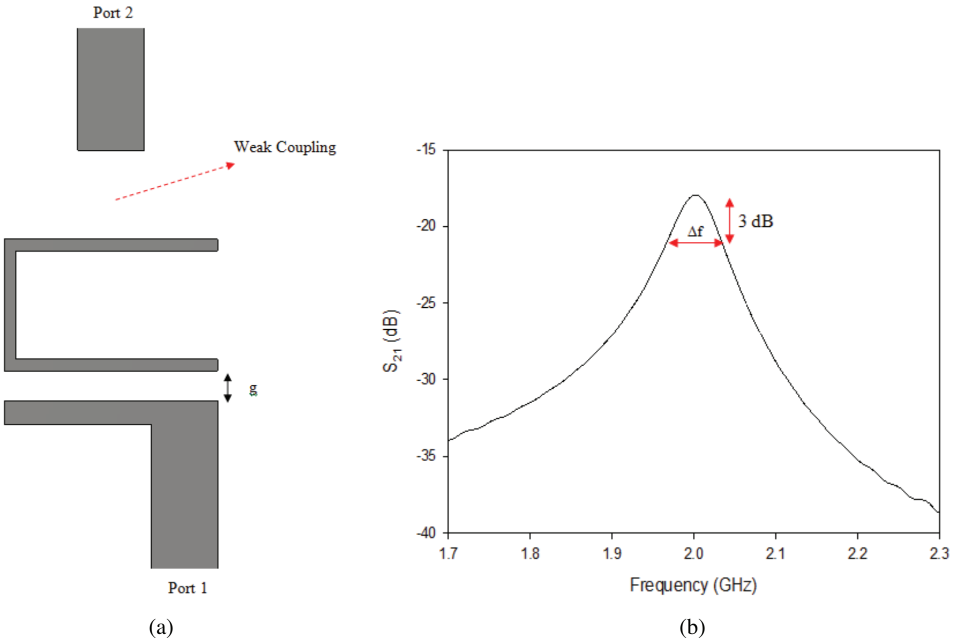
Figure 1. Layout of three-pole hairpin microstrip bandpass filter.

Full-wave electromagnetic (EM) simulations were performed to extract the desired quality factors and coupling coefficients. All simulations were performed using the 3D EM solver of CST®. Shown in Figure 2(a), an arrangement to extract the external quality factor of the input/output (I/O) resonators. The resonator, which is assumed to be lossless in the simulation, is excited at port 1 through $50\,\Omega$ coupled line. The port 2 is very weakly coupled to the resonator which implies that $Q_{e2} = \infty$. Figure 2(b) shows the simulated frequency response for the structure of Figure 2(a) for $g = 1.2$ mm. The external quality factor Q_e can be calculated directly by dividing the 3 dB bandwidth (Δf) and the centre frequency f_0 as follows:

$$Q_e = \frac{f_0}{\Delta f} \tag{3}$$

A design curve for Q_e against the gap g is shown in Figure 3. The hairpin resonators are approximately half wavelength at the midband frequency of 2.0 GHz.

The coupling between two adjacent resonators can be extracted using the arrangement of Figure 4(a). The two coupled resonators are identical. The coupling is controlled using the spacing S.



(a)
(b)

Figure 2. (a) An arrangement for extracting the external quality factor; (b) Simulated frequency response for $g = 1.2\,\text{mm}$.

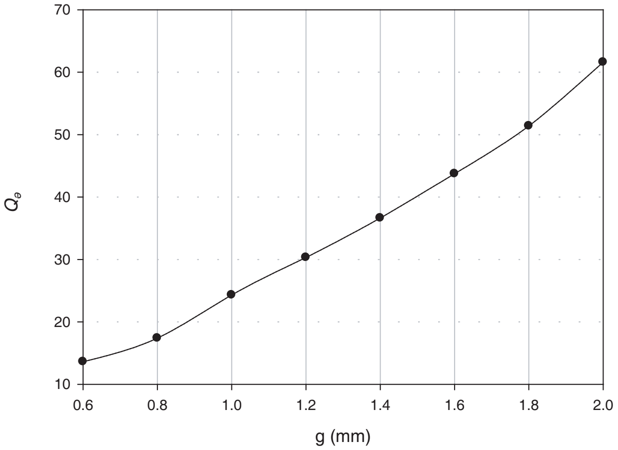
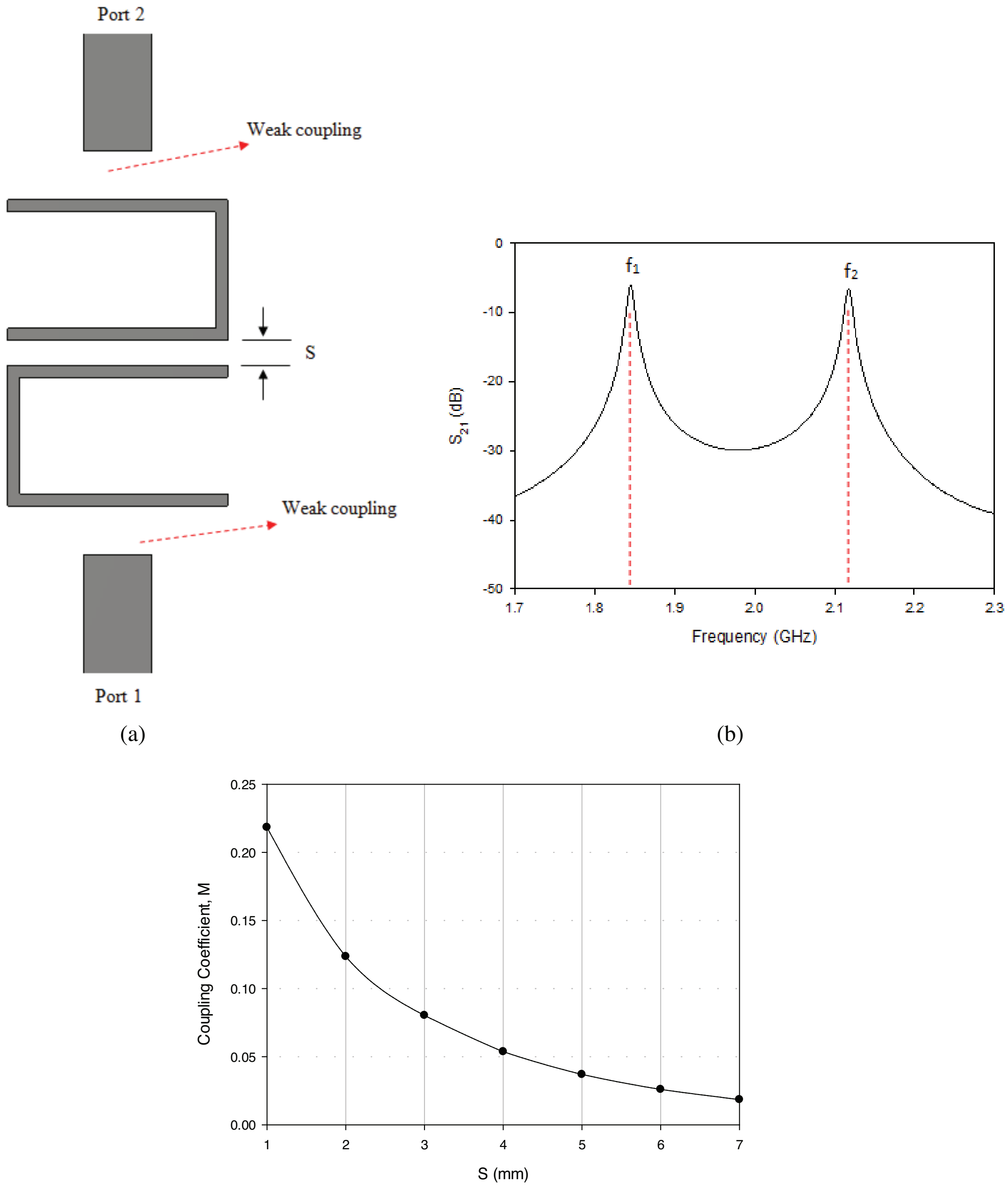


Figure 3. Design curve for the external quality factor Q_e.

The coupled resonators are very weakly excited by the two ports as arranged. Figure 4(b) shows the simulated frequency response of the coupled resonators, where S_{21} denotes the transmission coefficient S_{21} between the two ports. The two resonant peaks observed in the simulated response correspond to the characteristic frequencies f_1 and f_2. The coupling coefficient can be extracted using the Equation (4). Figure 4(c) shows the design curve for the coupling coefficient M against the spacing S. It can be seen that the coupling decreases as the spacing increases.

$$M_{i,i+1} = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2} \tag{4}$$

From the deign curves obtained, all physical dimensions associated with the desired design parameters, are readily determined, which are $g = 1.2\,\text{mm}$, $S_1 = S_2 = 5.2\,\text{mm}$. The I/O resonators are slightly shortened to compensate the effects of the coupled line and adjacent resonator.



(a) (b)

(c)

Figure 4. (a) An arrangement for extracting the coupling coefficient M; (b) Simulated frequency response for $S = 2\,\text{mm}$; (c) Design curve for the coupling coefficient M.

2.2. Filtering Antenna Design

The proposed filtering antenna is shown in Figure 5. The antenna is designed based on the filter synthesis process described in the last section. A rectangular patch is used as a radiating element. The patch replaces the third resonator and the output feed line. In order to preserve the filter characteristic, the radiation quality factor of the patch must be equal to the external quality factor at the input. Thus, the energy radiated by the patch (gain response) will be similar to the insertion loss response of a conventional bandpass filter with minimum insertion loss in the passband (high gain) and high suppression in the off-band (very low gain).

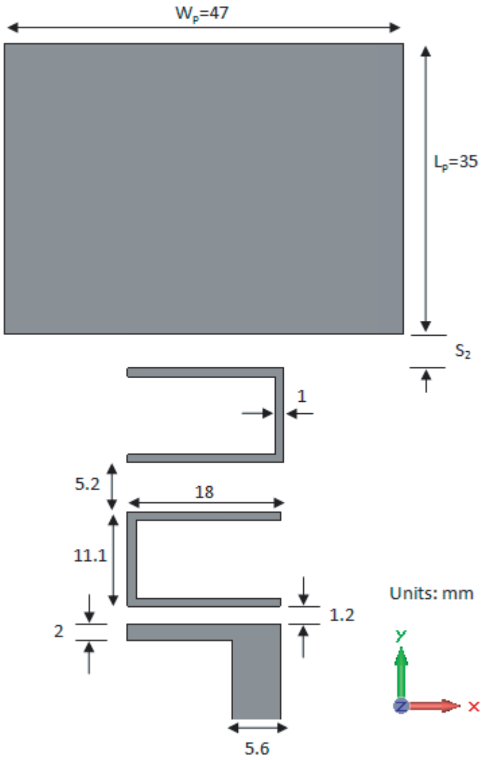
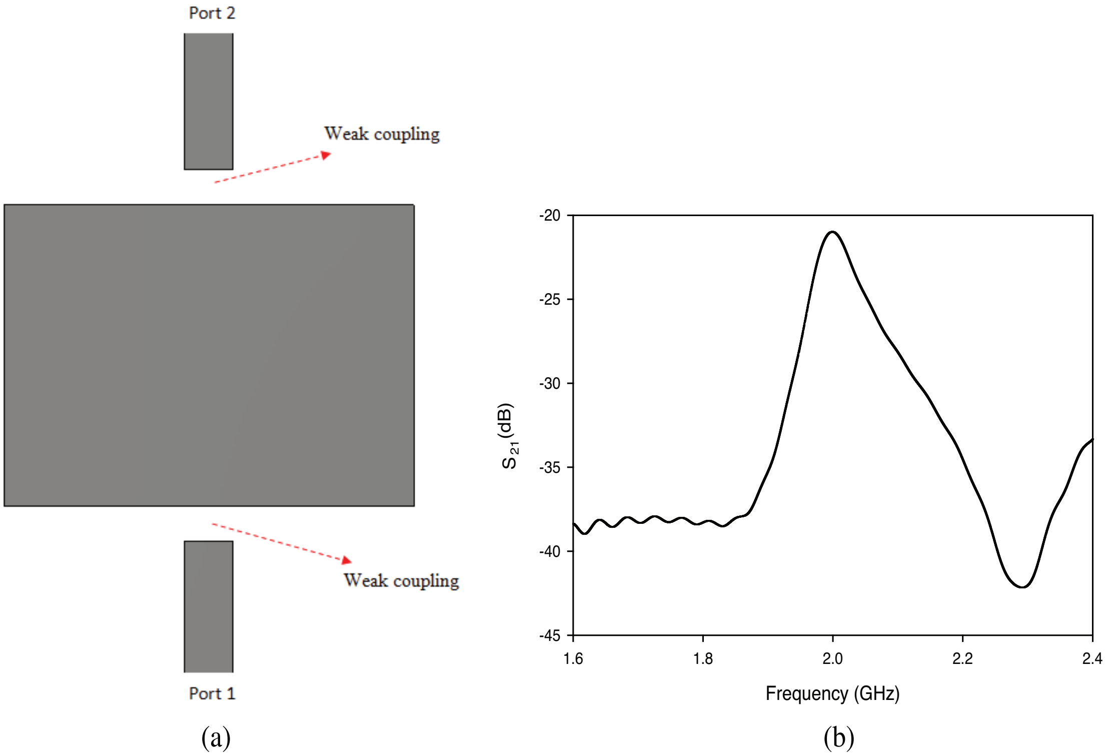


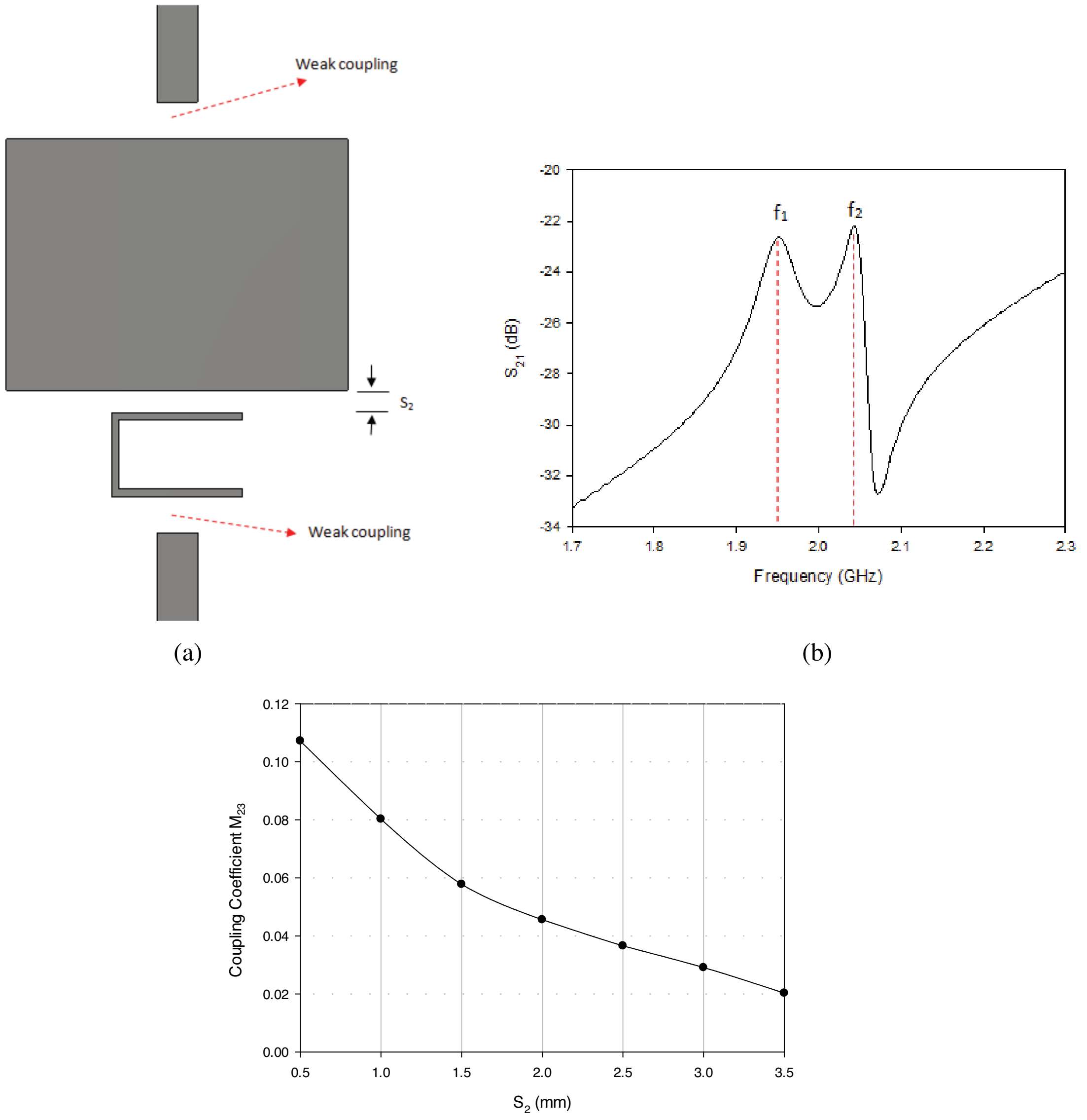
Figure 5. The layout of three-pole filtering microstrip antenna.



(a)

(b)

Figure 6. (a) An arrangement for extracting the radiation quality factor of the patch; (b) Simulated frequency response.



(a) (b)

(c)

Figure 7. (a) An arrangement for extracting the coupling coefficient M_{23}; (b) Simulated frequency response for $S_2 = 2$; (c) Design curve for the coupling coefficient M_{23}.

Figure 6(a) shows an arrangement for extracting the radiation quality factor (Q_r) of the patch. The simulated frequency response of this structure is shown in Figure 6(b), where S_{21} is the transmission coefficient between two ports that are very weakly coupled. Q_r can be calculated from the resonant frequency and the 3-dB bandwidth as given in Equation (3). Q_r is computed using this method and found to be approximately equal to 30. Thus, $Q_r = Q_{e1}$ and the filter requirement of having the same Q at the two ports is met. Design curves for calculating the radiation Q of rectangular patch were presented in [12] which gave very close result.

The coupling between the hairpin resonator and the patch can be extracted from EM simulations using the arrangement of Figure 7(a). The coupling is controlled using the spacing S between the patch and the resonator. Figure 7(b) shows the typical simulated frequency response of the coupled resonators. The coupling coefficient can be calculated using the Equation (4). Figure 7(c) shows design curve for M_{23} against the spacing S_2. From the design curve, the spacing S_2 required to achieve the desired coupling coefficient M_{23} is readily determined, which is $S_2 = 3.2\,\text{mm}$.

3. SIMULATION AND MEASUREMENT RESULTS

Simulations were performed using the commercially available 3D EM solver of CST®. The proposed structures were fabricated and measured using an HP8722D vector network analyzer. The simulated and measured frequency responses of the filter are shown in Figure 8. The measured and simulated midband frequencies are 2.03 and 2.0 GHz respectively. The simulated midband insertion loss is −0.1 dB whereas the measured one is −2.5 dB. The simulated and measured 3-dB passbands are 92 and 80 MHz respectively. The higher insertion loss is mainly due to conductor and dielectric losses. In addition, the SMA connectors introduce small loss.

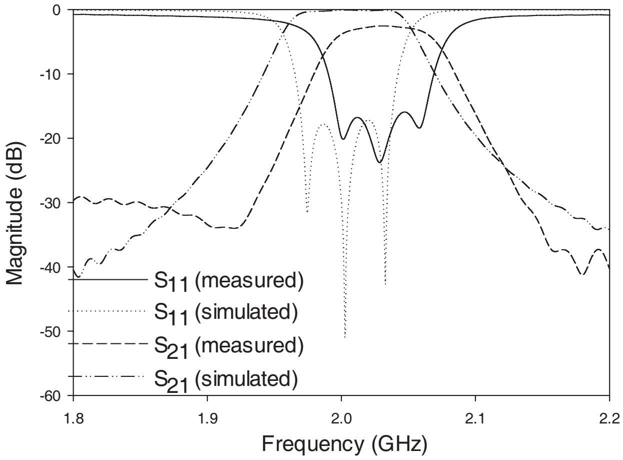


Figure 8. Simulated and measured performances of the hairpin PBF of Figure 1 with $g = 1.2\,\text{mm}$, and $S_1 = S_2 = 5.2\,\text{mm}$.

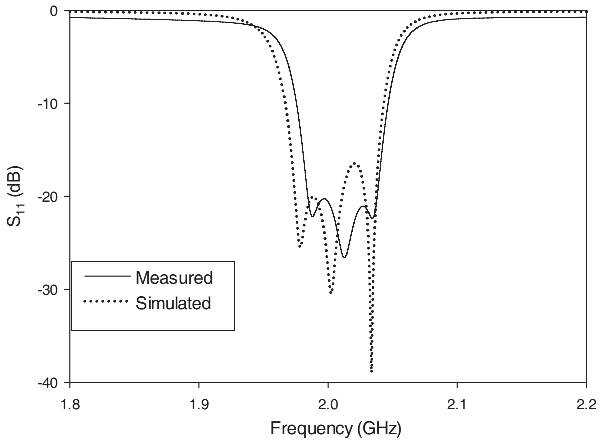
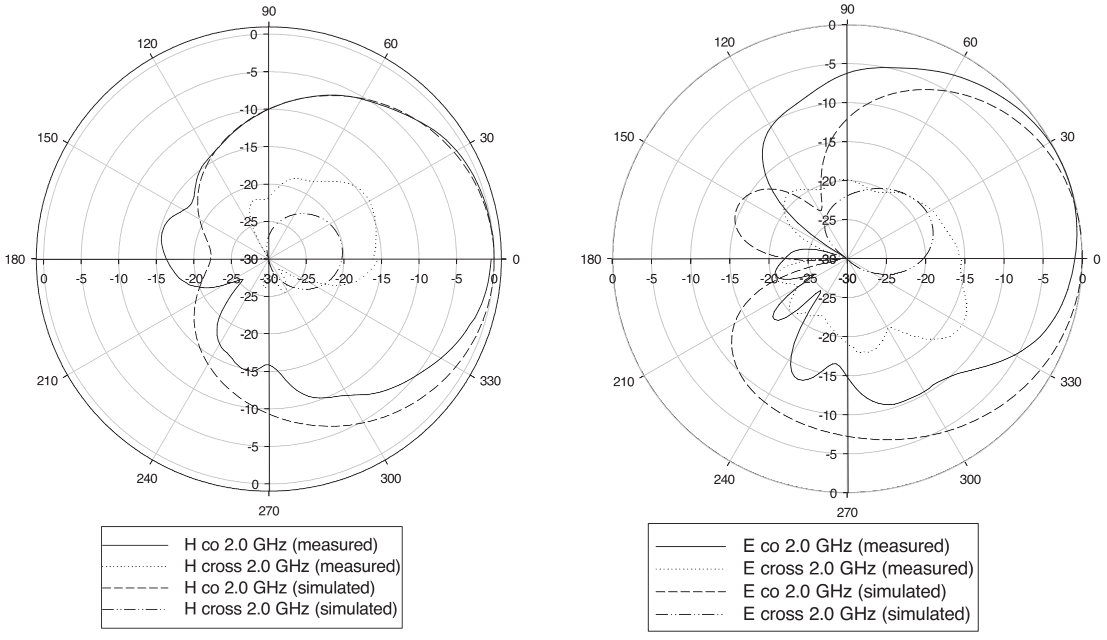


Figure 9. EM simulated and measured performance of the filtering antenna of Figure 4 with $S_2 = 3.2\,\text{mm}$.



(a) (b)

Figure 10. The normalized simulated and measured radiation pattern: (a) H (xz) plane; (b) E (yz) plane.

The simulated and measured reflection coefficient of the filtering antenna is shown in Figure 9. The proposed structure exhibits filter-like frequency response with three reflection zeros observed in the S_{11} result. The measured and simulated midband frequencies are 2.03 and 2.0 GHz respectively. The frequency shift is due to the dielectric constant of the material which has a tolerance of ±0.15. The simulated -10 dB bandwidth is 3.64% whereas the measured one is 3.5%.

The simulated and measured radiation pattern of the proposed filtering antenna are shown in Figure 10. The antenna exhibits well-shaped radiation pattern with cross polarization levels below -15 dB. The antenna maintains the same radiation pattern within the operating bandwidth with a maximum directivity in the broadside direction $(+Z)$.

Figure 11 shows the simulated and measured realized gain of the proposed antenna in the broadside direction $(+Z)$. In order to demonstrate the filtering capabilities of the proposed antenna, its performance is compared with a conventional patch antenna printed on the same substrate. It can be seen that the proposed antenna exhibits filtering functions with suppressed out-of-band gain, flat in-band gain, and good skirt selectivity at the band edges. The proposed antenna has slightly less in-band gain due to the losses associated with the coupled resonators. The fabricated prototype is shown in Figure 12.

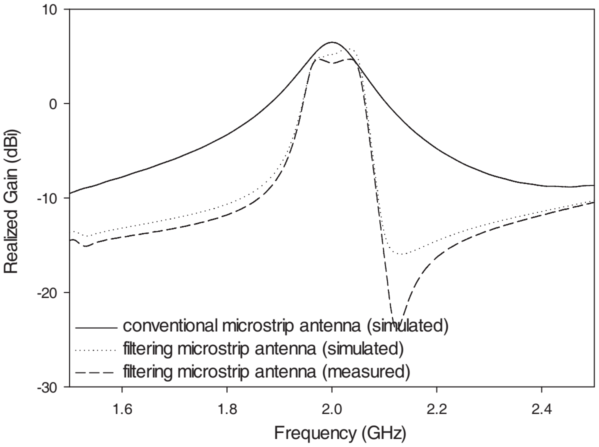


Figure 11. The simulated and measured realized gain of the proposed antenna vs conventional antenna.

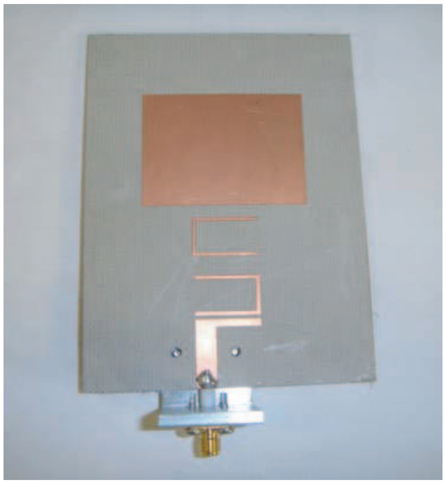


Figure 12. The proposed filtering antenna.

4. CONCLUSION

A novel filtering microstrip antenna is proposed. The design process is based on filter synthesis approach. A microstrip filter is developed into an antenna by replacing the last resonator with a radiating patch. Thus, the structure combines filtering and radiating functions simultaneously. The proposed structure exhibits good out-of-band gain suppression, flat in-band gain, and good skirt selectivity at the band edges. The proposed structure can help to reduce the size and cost of the communication system by combining two components into one.

ACKNOWLEDGMENT

The authors would like to thank their colleagues in the Antenna and Applied Electromagnetics Laboratory (AAEL) at the University of Birmingham for their valuable contributions and support.

REFERENCES

1. Queudet, F., I. Pele, B. Froppier, Y. Mahe, and S. Toutain, "Integration of pass-band filters in patch antennas," *Proc. 32nd Eur. Microw. Conf.*, 685–688, 2002.
2. Abunjaileh, A. I., I. C. Hunter, and A. H. Kemp, "A circuit-theoretic approach to the design of quadruple-mode broadband microstrip antennas," *IEEE Trans. Microw. Theory Tech.*, Vol. 56, No. 4, 896–900, Apr. 2008.
3. Lin, C.-K. and S.-J. Chung, "A filtering microstrip antenna array," *IEEE Trans. Microw. Theory Tech.*, Vol. 59, No. 11, 2856–2863, Nov. 2011.
4. Wu, W.-J., Y.-Z. Yin, S.-L. Zuo, Z.-Y. Zhang, and J.-J. Xie, "A new compact filter-antenna for modern wireless communication systems," *IEEE Antennas and Wireless Propagation Letters*, Vol. 10, 1131–1134, 2011.
5. Oda, S., S. Sakaguchi, H. Kanaya, R. Pokharel, and K. Yoshida, "Electrically small superconducting antennas with bandpass filters," *IEEE Trans. Appl. Supercond.*, Vol. 17, No. 2, 878–881, Jun. 2007.
6. Chuang, C. T. and S. J. Chung, "New printed filtering antenna with selectivity enhancement," *Proc. 39th Eur. Microw. Conf.*, Vol. 9, 747–750, 2009.
7. Chuang, C.-T. and S.-J. Chung, "Synthesis and design of a new printed filtering antenna," *IEEE Trans. Antennas Propag.*, Vol. 59, No. 3, 1036–1042, Mar. 2011.
8. Wang, Z. P., P. S. Hall, and P. Gardner, "Yagi antenna with frequency domain filtering performance," *IEEE Antennas and Propagation Society International Symposium APSURSI*, 1–2, Jul. 2012.
9. Yang, Y. and M. J. Lancaster, "Waveguide slot antenna with integrated filters," *32 European Space Agency Workshop*, 2010.
10. Lim, E. H. and K. W. Leung, "Use of the dielectric resonator antenna as a filter resonator," *IEEE Trans. Antennas Propag.,* Vol. 56, No. 1, 5–10, Jan. 2008.
11. Hong, J.-S. and M. J. Lancaster, *Microstrip Filters for RF/Microwave Applications*, John Wiley & Sons, New York, USA, 2001.
12. James, J. R., P. S. Hall, and C. Wood, *Microstrip Antenna: Theory and Design*, Peter Pereginus, London, 1981.