Compact Ultra-Wideband Filtering Antennas on Low Temperature Co-Fired Ceramic Substrate

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***Abstract* — In this paper, co-designs of filters and ultra-wideband (UWB) antennas are presented to reduce the overall component size on a low temperature co-fired ceramic (LTCC) substrate. In the co-design, the mutual coupling between an antenna and a filter is taken into account. Thus, in the final design, the filter becomes part of the antenna. The resulting compact component, a filtering antenna, behaves as an antenna with desired radiation performance and as a filter that suppresses undesired signals, simultaneously. Two filtering antennas are designed. The first is for the 3.1-4.85 GHz lower UWB band and the second with a notched band around the 5 GHz wireless local area network band for the full UWB band of 3.1-10.6 GHz. The proposed antennas show monopole-like radiation patterns in the desired bands and high out-of-band rejection.**

***Index Terms* — Antenna, bandpass filter, bandstop filter, monopole, low temperature co-fired ceramic substrate (LTCC), ultra wideband (UWB).**

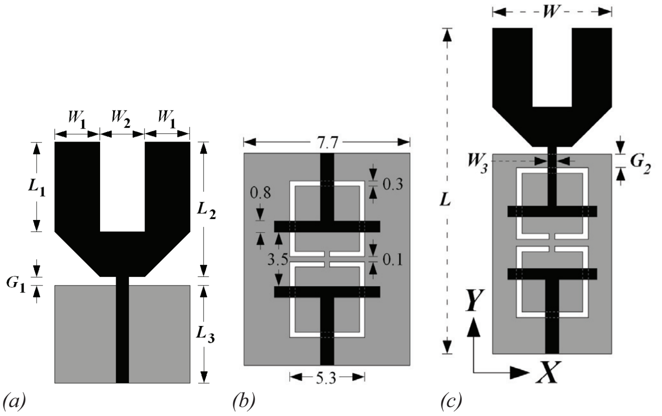

Fig. 1 Configuration of the (a) *U*-shape antenna, (b) bandpass filter and (c) the filtering antenna (all dimensions are in mm). Black and gray portions represent the top and bottom metallization, respectively.

I. Introduction

Multifunctional, multipurpose components are in great demand to satisfy today's miniaturization needs in wireless communication systems. In a communication system, both antennas and filters are usually larger components compared to other components. Thus, it will be of great interest if a single compact module can be designed to provide both the desired filtering and radiation performances. Several efforts to this topic have been reported in the literature [1-6]. In [1], metallic posts have been used as discontinuities in a horn antenna to obtain a bandpass filtering characteristics. In planar designs, a discontinuous CPW feed line with a rectangular patch antenna has been used to obtain filtering function [2]. Recently, a mutual-synthesis approach based on matching of input reflection coefficients has been presented to design a subsystem of a filter and an antenna [3]. Designs of filtering antennas on low temperature co-fired ceramic (LTCC) substrate also have been reported [4, 5]. Recently, the frequency selective surface has been positioned directly on the mouth of a horn antenna which forms a compact module with combined radiation and filtering performances [6].

However, all of the examples mentioned above are narrowband designs with operating bandwidths less than 10%. Here, two co-design examples of antenna and filter are presented for the 3.1-4.85 GHz lower UWB band and the 3.1-10.6-GHz UWB band with a notched band at the 5 GHz wireless local area networking band. The mutual coupling between the antenna and the filters are taken into account So that the integrated module provides desired radiation characteristics like a monopole and out-of-band suppression of undesired signals like a filter.

II. Design of the Filtering Antennas

In conventional RF design, a filter is often connected to an antenna in cascade. If the antenna has input impedance required to match the external quality factor Q_{ext} of the filter, the antenna can be treated as an external load of the filter. In addition, the antenna should not perturb the resonance frequencies of the resonators used in the design of the filter and vice versa. The method of mutual synthesis based on matching the input reflection coefficients of the antenna and output reflection coefficients of the filter is another approach [3]. However, both of the approaches do not consider the mutual coupling effect between the antenna and the filter.

In the proposed design, the mutual coupling effect, which is inevitable when the antenna and the filter are closely placed, is also considered. Therefore, in the co-design, both of the filter and antenna and their mutual coupling have been taken into account at the same time by using a full wave simulator. Here, Zeland's IE3D was used for this purpose.

First, as shown in Fig. 1(a), a *U*-shape antenna is designed for the whole UWB band on a 12 layer thick Heraeus HL2000 LTCC substrate. Each of the layers is 3.6 mil thick and has dielectric constant $_r$ = 7.3 and *tan* = 0.0026. For simplicity of the design, the arm width W_1 and the arm spacing W_2 are taken as equal. The arms are connected by a

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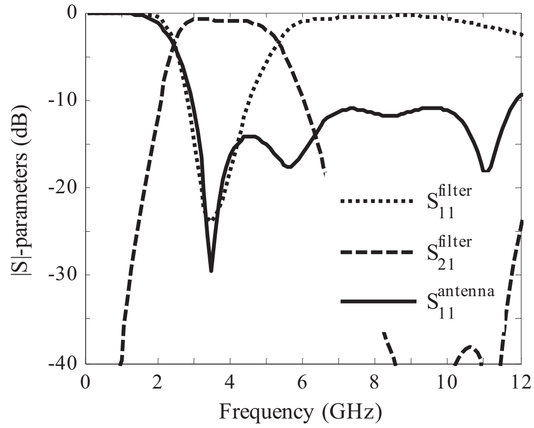


Fig. 2. Simulated *S*-parameters of the isolated bandpass filter and the antenna.

45^0 metered bend to the lower section of width L_1-L_2 = W_1. The lower cutoff frequency is mainly determined by the length L_1. Impedance matching is obtained by tuning the gap G_1 and the widths W_1. For the antenna dimensions, $W_1 = W_2 =$ 5.0 mm, L_1 = 11 mm, L_2 = 16 mm, L_3 = 10 mm and G_1 = 1.0 mm, the simulated response in Fig. 2 shows that it has a -10dB matching level from 3.0 to at least up to 12GHz. In the following sections, this antenna is used for the co-designs.

A. Filtering antenna for the lower UWB band:

The bandpass filter of [7], shown in Fig. 1(b), is redesigned for the lower UWB band on LTCC substrate. Here, a -10dB matching bandwidth is considered for the filter. Its simulated *S*-parameters are shown in Fig. 2.

Next, as shown in Fig. 1(c), the filter is placed between the feeding point and the radiator (upper portion of the antenna) with a spacing of G_2. Their dimensions remain unchanged. The feed line on the top layer has a width 1.4 mm that provides a characteristic impedance of 50 . Assume that there is no electromagnetic coupling between the antenna and the filter, then the overall return loss $|S_{11}|$ of the module is

$$S_{11} = S_{11}^{\ filt} + \left(\frac{S_{12}^{\ filt} S_{21}^{\ filt} S_{11}^{\ ant}}{1 - S_{22}^{\ filt} S_{11}^{\ ant}} \right) \quad . \qquad (1)$$

The overall return loss calculated from (1) is shown in Fig. 3, where the *S*-parameters shown in Fig. 2 are used. The full wave simulated overall return losses for three different spacing G_2, where the mutual coupling between the filter and the radiator is taken into account, is also compared in the figure. These results differ significantly. From the average current distributions, it is seen that the antenna has a strong ground plane current near the upper radiating edge of the ground plane that interacts with the filter ground current. Due to the mutual coupling between the antenna and the filter, the *S*-parameters of individual elements change in cascaded connection. The coupling remains significant even if the separation between the radiator and the filter is increased to

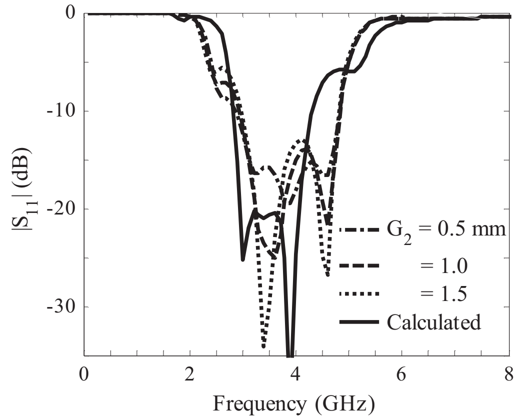


Fig. 3. Effect of varying spacing G_2 on the impedance matching.

G_2 = 5.0 mm. Therefore, the mutual coupling between the antenna and the filter should be taken into consideration for these types of small antennas instead of a simply cascaded connection of one filter and one antenna. From full wave simulations, it is found that the mutual coupling between the radiator and the filter is mainly controlled by the separation G_2 and the characteristic impedance of the line segment between the filter and the antenna *i.e.* the width W_3. For example, Fig. 4 shows the input matching for W_3 = 0.2, 1.0 and 1.4 mm, where the other dimensions are kept fixed as before with L = 34 mm and G_2 = 0.5 mm. From the above observations, the design steps of a filtering antenna can be generalized as below.

1) Design the UWB antenna and the filter on the selected dielectric substrate with desired performance separately.
2) Integrate the filter onto the bottom portion of the antenna.
3) Optimize the dimensions W_3 and G_2 of the connecting segment between the upper radiator and the filter.

Following the above procedure, the final dimensions of the connecting section for the lower UWB band are W_3 = 0.2 mm and G_2 = 0.5 mm. Other dimensions of the configuration remain as before.

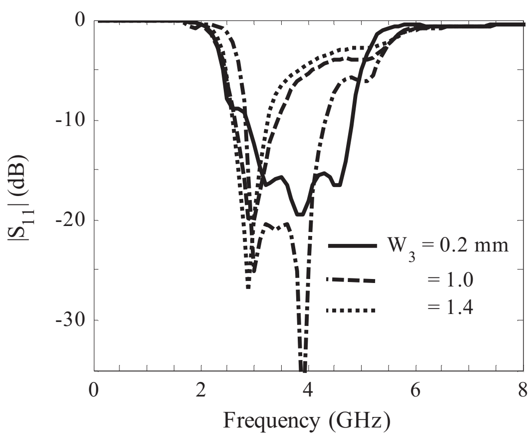
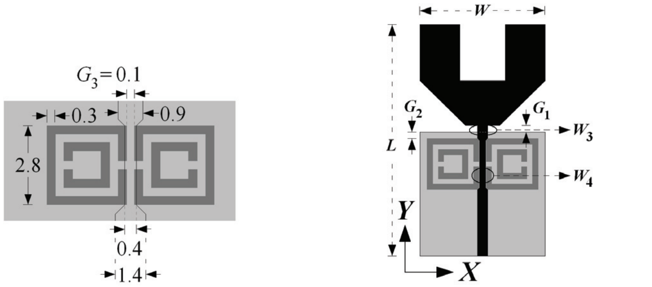


Fig. 4. Effect of varying line width W_3 on the impedance matching.



(a) (b)

Fig. 5 Configuration of the (a) band stop filter and (b) notched band antenna.

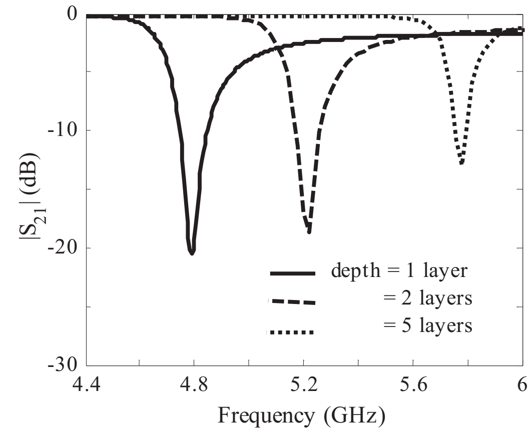


Fig. 6. Variation of the stopband depth with the number of separating layers between the microstrip and SRR. Thickness of each layer is 3.6 mil.

B. Notched band filtering antenna for the whole UWB band:

To design the notched band antenna, as shown in Fig. 5(a), a band stop filter is first designed by using two split ring resonators (SRR). The stopband center frequency is determined by the SRR resonance frequency. The SRRs are placed in a middle layer sandwiched between the top plane microstrip and the bottom plane ground. The bandwidth of the bandstop filter can be controlled by the coupling between the SRR *i.e.* the SRR separation G_3. Bandwidth increases with decreasing G_3. The depth of the stopband depends on the coupling between the SRR and the microstrip line. The stopband depth increases as the coupling increases. In LTCC substrate, we can easily change the microstrip to SRR coupling by changing the number of layers between these two components. Fig. 6 shows the simulated transmission responses for different number of separating layers between the microstrip and the SRRs. The coupling between the microstrip line and the SRRs and hence the rejection depth increases as the number of separating layers decreases. The change in number of layers also increases the equivalent capacitance [8] of the SRR. So, their resonance frequency decreases with decreasing number of layers.

Next, as shown in Fig. 5(b), the bandstop filter is placed between the feeding point and the antenna with a spacing of G_2. The antenna dimensions remain as before. In this case, the spacing G_2, the width W_3 of the section between the SRR and

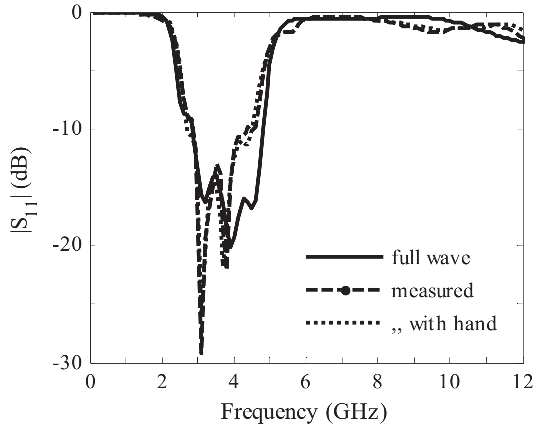


Fig. 7. Measured and simulated input matching of the filtering antenna for the lower UWB band.

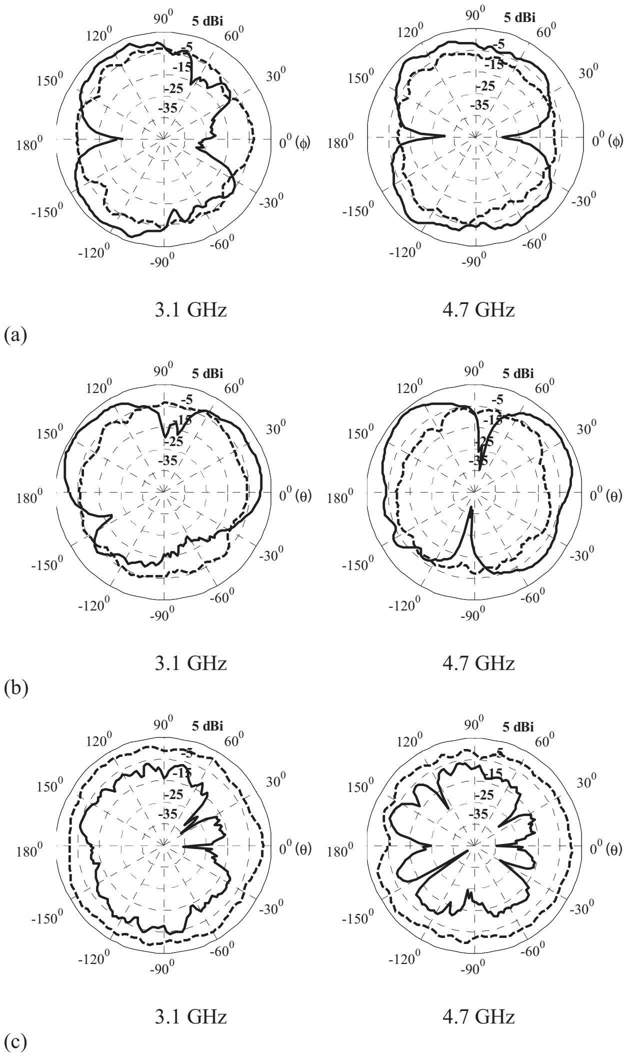


Fig. 8. Radiation patterns of the filtering antenna for the lower UWB band in the (a) *x-y*, (b) *y-z* and (c) *z-x* planes (solid lines- horizontal and dashed lines- vertical polarizations).

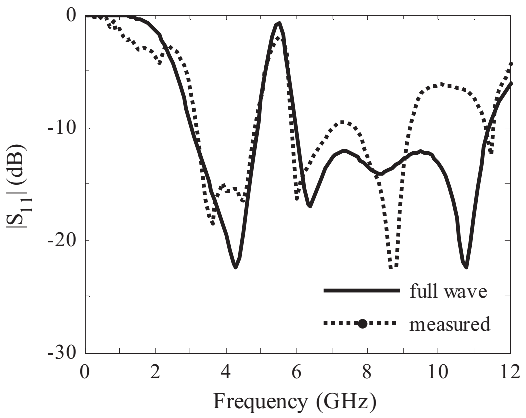


Fig. 9. Measured and simulated input matching of the notched band filtering antenna for the whole UWB band.

the antenna, and the microstrip line width W_4 just above the SRRs are tuned together for good overall input matching. The final dimensions are G_2 = 0.5 mm, W_3 =0.9 mm, W_4 = 0.4 mm, L = 27 mm and W = 15 mm.

III. Fabrication and Measurements

Two prototypes, one for the lower UWB band and another with the notched band are fabricated on the LTCC substrate.

The measured and simulated input matching of the filtering antenna for the lower band is shown in Fig. 7. An Agilent® N5230A vector network analyzer is used in the measurement. The measured 10 dB cutoffs are 2.84 and 4.7 GHz. On the left side of the radiating band, $|S_{11}|$ is higher than -1 dB from DC to 2.2 GHz. On the right side, $|S_{11}|$ is higher than -1.8 dB from 5.3 GHz to at least up to 11.8 GHz. This type of small UWB antenna usually has a strong returning ground current [9]. Due to this current, the input matching changes with the ground plane metallic patch size and feed length. One of the advantages of the present design is that it has a reduced returning ground. The reduced ground plane effect of the filtering antenna can be roughly predicted from the following experiment. The feeding cable is held in hand touching the outer metallic part of the SMA connectors approximately 2 cm away from the microstrip feeding point. If there is strong current at the outer surface of the coaxial cable, the return loss response will change significantly as the cable is touched near the connector. The measured return loss with the hand effect is also shown in the figure as dotted line. The effect of touching the SMA connector can hardly be distinguished. It suggests that the filtering antenna maintains the reduced ground plane effect. It is believed that the slight change in $|S_{11}|$ responses is due to the perturbation caused by the hand. Figs. 8(*a*), (*b*) and (*c*) show the measured far field radiation patterns of the filtering antenna at 3.1 and 4.7 GHz in the *x*-*y*, *y*-*z*, and *z*-*x* planes, respectively. The radiation patterns are almost similar to those of a monopole.

Next, the measured input matching of the filtering antenna with a notched band is presented in Fig. 9. The measured -10 dB cutoffs on the left side of the notched band are 3.18 and 4.16 GHz. On the right side, the measured input matching is not good due to a small returning ground current; the -9.5 dB cutoffs are 5.86 and 9.21 GHz. Due to the notched band, the measured $|S_{11}|$ is higher than -3 dB from 5.3 to 5.7 GHz. The measured radiation patterns are almost similar to those of a monopole.

VI. Conclusion

Compact planar LTCC filtering-radiating modules have been presented for the lower UWB band and the full UWB band with a notched band. It shows simultaneous radiating and filtering performances with good out-of-band rejection characteristics. Overall component size has been reduced to 34×15 mm and 27×15 mm for the lower and full UWB band, respectively.

References

[1] B. Froppier, Y. Mahe, E. M. Cruz, and S. Toutain, "Integration of a filtering function in an electromagnetic horn," in *Proc. 33rd European Microwave Conf.*, Oct. 2003, vol. 3, pp. 939–942.

[2] A. A. Tamijani, J. Rizk, and G. M. Rebeiz, "Integration of filters and microstrip antennas," in *IEEE AP-S Symp. Digest*, Jun. 2003, vol. 2, pp. 874–877.

[3] M. Troubat, S. Bila, M. Thévenot, D. Baillargeat, T. Monédière, S. Verdeyme, and B. Jecko, "Mutual synthesis of combined microwave circuits applied to the design of a filter-antenna subsystem", *IEEE Trans. Microw. Theory Tech.*, vol. 55, No. 6, pp. 1182-1189, Jun. 2007.

[4] C.-S. Yoo, J.-K. Lee, D. Kim, S.-D. Park, K.-H. Won, N.-K. Kang, K.-S. Seo, W.-S. Lee, "RF front-end passive circuit implementation including antenna for ZigBee applications", *IEEE Trans. Microw. Theory Tech.*, vol. 55, No. 5, pp. 906-915, May. 2007.

[5] J.-H. Lee, N. Kidera, S. Pinel, J. Laskar, and M. M. Tentzeris, "Fully integrated passive front-end solutions for a V-band LTCC wireless system", *IEEE Antennas and Wireless Propagat. Lett.*, vol. 6, pp. 285-288, 2007.

[6] G. Q. Luo, W. Hong, H. J. Tang, J. X. Chen, X. X. Yin, Z. Q. Kuai, and K. Wu, "Filtenna consisting of horn antenna and substrate integrated waveguide cavity FSS," *IEEE Trans. Antennas Propag.*, vol. 55, no. 1, pp. 92–98, Jan. 2007.

[7] P. Mondal and A. Chakrabarty, "Compact wideband bandpass filters with wide upper stopband", *IEEE Microw. Wireless Compon Lett.*, vol. 17, no. 1, pp. 31-33, Jan. 2007.

[8] J.D. Baena, J. Bonache, F. Martín, R.M. Sillero, F. Falcone, T. Lopetegi, M.A.G. Laso, J.G.–García, I. Gil, M.F. Portillo, and M. Sorolla, " Equivalent-circuit models for split-ring resonators and complementary split-ring resonators coupled to planar transmission lines," I*EEE Trans. Microw. Theory Tech.*., vol. 53, no. 4, pp. 1451-1461, Apr. 2005.

[9] Z. N. Chen, T. S. P. See, and X. Qing, "Small printed ultrawideband antenna with reduced ground plane effect", *IEEE Trans. Antennas Propag.*, vol. 55, no. 2, pp. 383–388, Feb. 2007.