Design of a Novel Filtering Antenna using Open Loop Resonators along with Metallic Via

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***Abstract*— This paper demonstrates a novel, planar, and compact third-order filtering antenna for WLAN application. The filtering antenna is designed using a conventional rectangular microstrip patch antenna along with a 2nd-order highly selective bandpass filter. This filter is realized with the help of four simple open-loop resonators and a metallic via that connects the source and load. To improve the matching between the filter and antenna, a pair of parallel open stubs are connected to one side of the filter. The simulation results of the proposed filtering antenna exhibit good filtering performance, including a flat gain response with good band-edge selectivity in the desired frequency band (5.33 GHz - 5.52 GHz) with a fractional impedance bandwidth of 3.5% and keeping the center frequency at 5.4 GHz. The other significant results observed are radiation efficiency of 85.3%, cross-polarization rejection level of more than 30 dB, front-to-back ratio (FTBR) of 25 dB, and a realized gain of 5.7 dBi.**

Keywords—Filtering antenna, Bandpass filter, Microstrip antenna, Open-loop resonator, Stub

I. Introduction

With the fast progress of current wireless communication systems over the last several years, antennas and filters have emerged as one of the most major elements of wireless transceiver systems. The bandpass filter accepts signals within the operational bandwidth and rejects out-of-band signals, whereas the antenna acts as a transducer that transmits and receives signals. There is always a high demand in making the radio-frequency (RF) systems compact, simple, and cost-effective. In light of the requirement to miniaturize and improve performance characteristics in RF front-ends, the development of multifunction structures should be a viable option for shrinking the size of these front-end devices. Owing to this need, it is preferable to combine filter and antenna into a single device, known as "filtenna" or "filtering antenna". The filtering antenna is an innovative concept that can execute both radiation and filtering functions simultaneously instead of designing the filter and antenna separately. It helps in reducing the interconnection lengths between the filter and antenna and mismatch signal losses. Subsequently, the RF front-end systems become more compact in size with improved performance.

So far, several studies on filtering antenna design have been reported. The two methods which have been extensively followed are (a) The co-design method which follows the filter synthesis process where the antenna serves as both a radiating element and a final stage resonator [1], [2]. This filter synthesis approach exhibits good selectivity. At the same time, several resonators occupy more space resulting in high insertion loss and low gain. (b) Designing the antenna and filter separately and then integrating both using impedance matching networks [3]. This integration method eliminates the need for additional areas. There are many reported articles on how to implement filtering antennas in different configurations. It can be configured as a single-layered structure [4],[5], and multi-layered structures [6],[7]. In [4], a monopole fan-shaped radiator antenna was coupled with the capacitively loaded loop (CLL) resonator. To enhance the bandwidth, they modified the design by including another CLL and made slots in the ground plane. For both cases, a flat in-band gain response was achieved. Tunable radiation null characteristics were added along with the filtering characteristics and 7% impedance bandwidth [5]. Slots of different lengths were introduced in the rectangular patch to have the radiation nulls in both the band edges. In [6], a slot of split-ring shape was etched on the rectangular patch, and a U-shaped strip beneath the patch was placed to produce lower and upper radiation zeros. In [7], a filtering diplexing antenna with better band-edge frequency selectivity was proposed. Slots with different widths were etched on the ground plane for having good isolation between the operating bands.

This work proposes a planar, third-order filtering antenna structure for wireless LAN communications. Four open-loop square resonators and a metallic via in the 50 Ω transmission line are integrated with a capacitively coupled conventional rectangular patch as a radiating element. The capacitive coupling is obtained using a pair of parallel open stubs that ensures improved filtering performance. Among the three poles of the filtering antenna, two poles appear due to filter and another one due to antenna. Since the proposed second-order filter is highly selective, similar characteristics are observed in the filtering antenna design.

II. Filter design

A. Design specification

To design the filtering antenna for WLAN application, the design specification of the proposed 2nd-order bandpass filter are as follows:

i. Center frequency = 5.4 GHz
ii. Fractional bandwidth (FBW) = 5.85%
iii. Two transmission zeros at 5.0 GHz and 6.0 GHz
iv. Minimum return loss in the passband = 15 dB

The proposed bandpass filter's schematic representation is shown in Fig. 1. The filter is configured in such a way that four open-loop square resonators are placed on the left and right sides of the 50 Ω transmission line. The source and load are directly coupled, and the coupling is controlled by a metallic via. The metallic via is placed at the center of the four resonators. The orientation of the four resonators is such that there is capacitive coupling between each pair of resonators, i.e. resonator 1-2 and resonator 3-4.

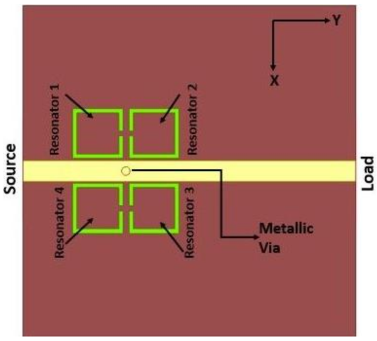


Fig. 1. Schematic of the proposed bandpass filter

Keeping 5.4 GHz as the center frequency, the size of the open-loop square resonators is determined through EM simulation by applying weak coupling in driven modal analysis, and all the resonators are identical.

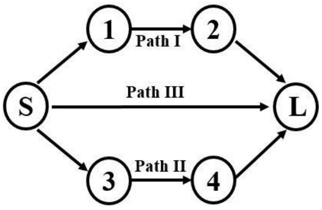


Fig. 2. Coupling topology of the bandpass filter

As depicted in Fig. 2, three signal paths exist between the source and load. Path-I links the source(S) to resonator-1-to-resonator-2-to-load(L), Path-II connects the source to resonator 3-4 to load, and Path-III connects the source to the load directly plated through hole (PTH) that controls source the load coupling. As a result, there is a cross-coupling between the source and the load. This cross-coupling produces two transmission zeros (TZs) on both sides of the filter's passband. TZs are controlled by the diameter of the metallic via. A little bit of parametric study is performed to obtain the desired result.

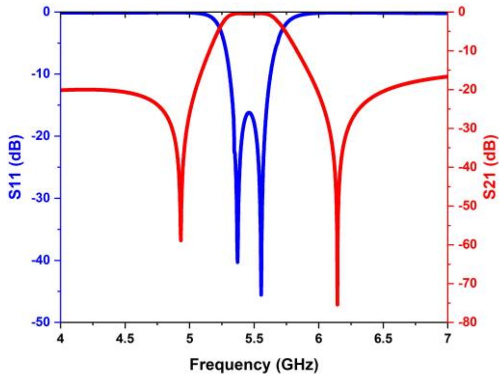


Fig. 3. Frequency response of the filter

Fig. 3 presents the simulated frequency response of the 2nd-order bandpass filter. The passband of the filter is found to be 5.31 GHz to 5.63 GHz with a 15 dB return loss. The plot shows two reflection zeros and two transmission zeroes at 5.37 GHz, 5.55 GHz, and 4.93 GHz, 6.14 GHz, respectively. The transmission zeros are introduced outside the passband to improve the out-of-band rejection, thereby enhancing the selectivity. Thus, the two-pole bandpass filter frequency response shows sharp out-of-band selectivity with good filtering performance.

III. ANTENNA DESIGN

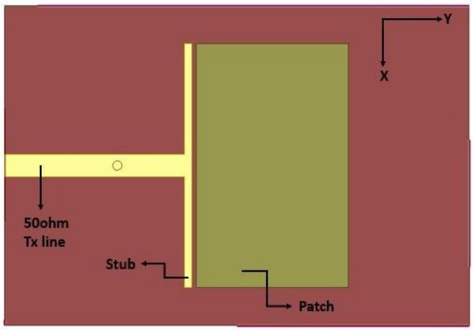


Fig. 4. Schematic of the antenna

By applying weak coupling to the tradtional rectangular microstrip antenna, the capacitively loaded radiating patch antenna is designed at 5.4 GHz to ensure its resonant frequency within the filter's passband. The antenna schematic is shown in Fig. 4, and its response is shown in

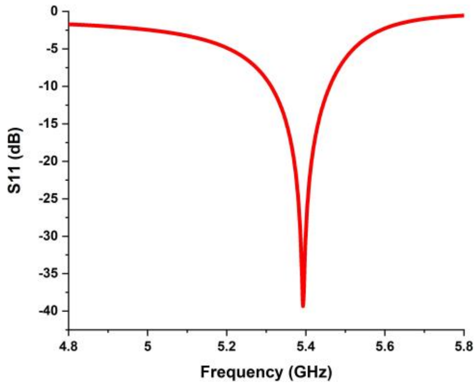


Fig. 5. S_{11} plot of the antenna

Fig. 5. After obtaining the antenna response at the desired frequency, the filter and antenna are co-designed together.

IV. FILTERING ANTENNA DESIGN

Now, the filtering antenna is realized by integrating both the filter and antenna. A pair of parallel open stubs are attached to one side of the filter and capacitively coupled with the antenna to enhance the matching between the filter and the antenna. All the designs are implemented on a low-loss Taconic TLY substrate with dielectric constant (ε_r) = 2.2, loss tangent (tanδ) = 0.0009, and 0.79 mm thickness.

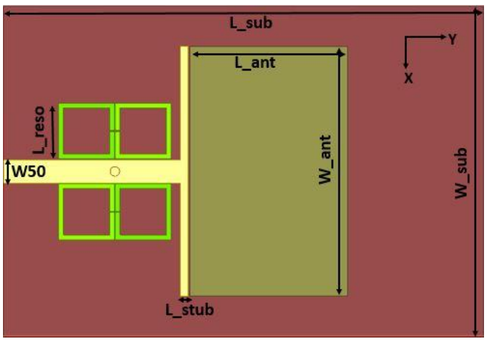


Fig. 6. Schematic of the proposed filtering antenna

The rectangular microstrip antenna, stub, and filter are printed on top of the dielectric substrate. A ground plane is placed at the bottom of it. The pair of resonators on each side of the transmission line has a gap 'd' between each other and are separated by a distance 's' from the 50 Ω transmission line. The coupling gap between the stub and radiating element is termed as 'gap_ant'.The proposed filter-antenna structure (illustrated in Fig. 6) has a small size of $1.36\lambda_g \times 0.93\lambda_g$, where λ_g represents the guiding wavelength at 5.4 GHz. All the design parameters are suitably optimized to produce a third-order filtering antenna. The optimal design specifications are included in Table I.

TABLE I.

DESIGN SPECIFICATIONS OF THE FILTERING ANTENNA IN MILLIMETERS

L_sub = 51	L_ant = 16.7	L_reso = 5.904
W_sub = 35	W_ant = 26.4	s = d = gap = 0.1
L_stub = 0.8	gap_ant = 0.2	h = 0.79
W_stub = 26.4	W50 = 2.44	via_rad = width = 0.5

V. SIMULATED RESULTS AND DISCUSSION

For validation, the proposed design is simulated using the HFSS 18 software. Fig. 7 represents the reflection coefficient and realized gain plots of the proposed three-pole filtering antenna. It shows that the filtering antenna has an operational frequency band of 5.33 GHz - 5.52 GHz with 5.4 GHz as the center frequency and an impedance bandwidth of 190 MHz. Three reflection zeros at 5.37 GHz, 5.47 GHz, and 5.50 GHz are observed in the entire operating band with reflection coefficient below -13 dB. Among the three poles of the filtering antenna, two poles appear due to filter and another one due to antenna.

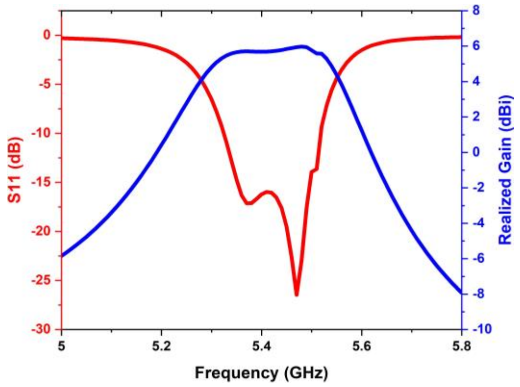


Fig. 7. Reflection coefficient and realized gain plots of the proposed filtering antenna

The realized gain plot shows a flat in-band gain response with a peak gain of 5.7 dBi. The gain falls fast as the frequency lowers below 5.33 GHz and increases beyond 5.52 GHz, resulting in significant skirt selectivity. As a result, it is comprehended that the proposed design shows good out-of-band rejection.

Fig. 8 represents the far-field radiation pattern plots. The E-plane 3-dB beamwidths at 5.37, 5.47, and 5.50 GHz are 150°, 160°, and 160°, respectively, while the H-plane beamwidths are 151°, 160°, and 150°, respectively. It is well observed that regardless of frequency variations, the primary radiation direction is upheld in the broadside direction. The antenna radiates in the boresight direction in both planes, with cross-polarization discrimination (XPD) of 39 dB, 31 dB, and 11 dB at 5.37 GHz, 5.47 GHz, and 5.50 GHz, respectively. The far-field radiation characteristic analysis suggests that our filtering antenna demonstrates a well-shaped and relatively stable radiation pattern at three different resonant frequencies in E- and H-planes for phi = 0° and 90°, respectively.

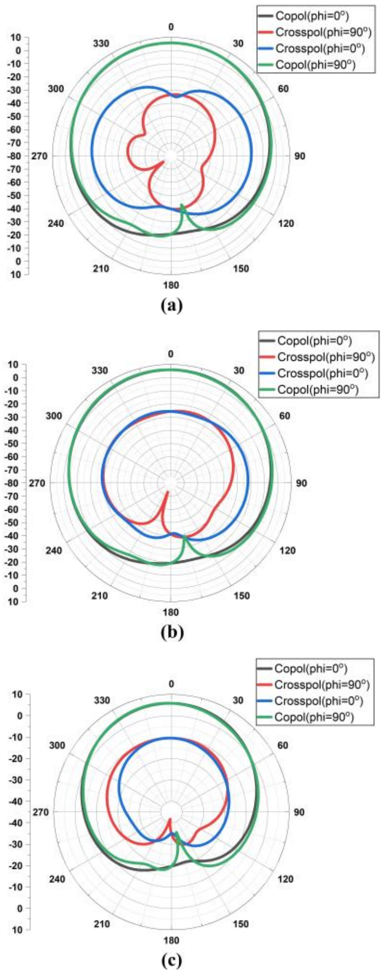
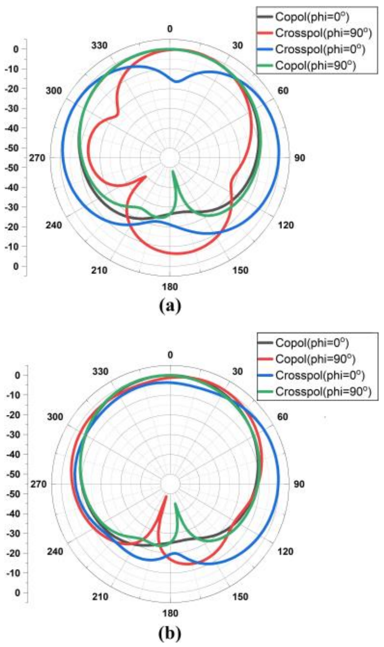


Fig. 8. Radiation pattern (E-plane and H-plane) plots of the filtering antenna at (a) 5.37 GHz, (b) 5.47 GHz, and (c) 5.50 GHz

Fig. 9 shows the normalized radiation pattern plots in E and H-planes.



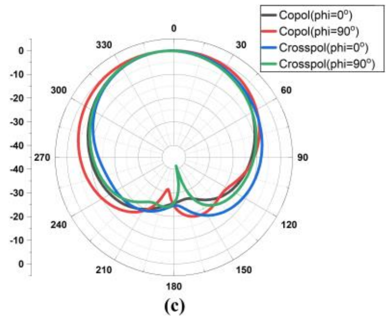


Fig. 9 Normalized radiation patterns of the filtering antenna at (a) 5.37 GHz, (b) 5.47 GHz, and (c) 5.50 GHz

Fig. 10 shows the radiation efficiency plot, and it is found to be 85.3%. Table II summarizes all the antenna parameter results. The performance comparison between the proposed filtering antenna with previously published works is mentioned in Table III. With a compact structure and simple design, the proposed antenna exhibits both radiation and filtering characteristics with fairly good gain value and selectivity, making it a good candidate for WLAN application.

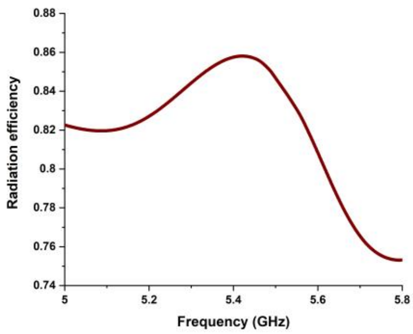


Fig. 10 Radiation efficiency of the filtering antenna

TABLE II.

SUMMARY OF FILTERING ANTENNA PARAMETER RESULTS

Sl. No.	**Antenna Parameter**	**Value**
1.	Fractional Impedance Bandwidth	3.5%
2.	Maximum Realized Gain	5.7 dBi
3.	Cross-polarization discrimination (XPD)	more than 30 dB
4.	Front-to-back ratio	25 dB
5.	Radiation Efficiency	85.33%

TABLE III.

PERFORMANCE COMPARISON BETWEEN THE PROPOSED FILTERING ANTENNA AND PREVIOUS WORKS

Ref.	Filtering technique	f_0 (GHz)	Realized gain (dBi)	No. of transmission zeros	In-band poles
[2]	Quarter-wavelength resonator	4	4.85	none	3
[3]	Open loop resonator	2.41	2.4	none	3
[4]	Open loop resonator	2.35	1.37	none	2
This work	Open loop resonator	5.4	5.7	none	3

f_0 = center frequency

VI. CONCLUSION

This article presents a single-layered filtering antenna design with good selectivity for WLAN application. The design shows a -10 dB fractional impedance bandwidth of 3.5%. As facilitated by the three in-band poles, the filtering antenna achieves a third-order bandpass filtering selectivity for both radiation gain and reflection coefficient. The filtering antenna attains a good in-band radiation performance in the passband and a significant out-of-band rejection level in the stopband. Due to its compact size, it can be easily fabricated and integrated with wireless communication system circuit boards.

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