# A filtering waveguide aperture antenna based on all-resonator structures

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RESEARCH ARTICLE

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# A filtering waveguide aperture antenna based on all-resonator structures

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**Abstract**

In recent years, there has been a large amount of attention focused on the design of filtering antennas to reduce the front-end size of modern wireless communication systems. Although numerous design approaches are presented in the literature, they are usually applicable to a certain microwave circuit structure. Additionally, their implementations demand extra matching circuits or a structure which leads to an increase in the filtering antenna size. In this paper, the design of a 3rd-order filtering antenna operating at the X-band frequencies is presented utilizing the coupling matrix approach. It is based on 3rd order coupled-resonators filter without employing any extra structure. For the physical configuration, three inline coupled rectangular waveguide cavity resonators operating at $TE_{101}$ mode are employed. The output of the last resonator is coupled to free space via a rectangular aperture. The dimensions of the aperture are manipulated to control the radiation quality factor ($Q_r$). To validate the simulated results, the design has been fabricated using the Computer Numerical Control technique. Excellent agreement between the simulation and measurement results has been obtained. The fractional bandwidth (FBW) is more than 10% when the reflection coefficient $S_{11} = -20$ dB. The gain response is very flat (7.54 $\pm$0.2 dBi) from 9.5 to 10.5 GHz. The proposed filtering antenna is compact and low profile which may be of interest in radar applications.

**KEYWORDS**

aperture antenna, coupling matrix theory, filtering antennas, waveguide cavity resonators

## 1 | INTRODUCTION

Recently, integrations among the front-end components of wireless communication systems have become more popular, particularly among bandpass filters (BPFs) and antennas (so-called filtering antennas).[1–4] Such integration not only introduces filtering functionality to the antenna, but also reduces the losses and the front-end size of the system.[5] Numerous approaches have been presented in the literature to enhance the bandwidth (BW) of the filtering antennas so as to increase the data rate capability and reduce spurious signals.

Exciting surface waves to support the evanescent mode were presented in Ludlow et al.[6] to enlarge the BW of the filtering waveguide slot antenna. A low-quality factor cavity with extended ground plane integrated with a 3rd order Chebyshev BPF in Yusuf and Gong[7] was to widen the BW of the filtering aperture antenna. An E-shaped resonator integrated with two PIN diodes in Fakharian[8] was mainly to enhance the BW of the slot antenna. In Xie et al.,[9] the use of a dual-mode cavity resonator based on substrate-integrated waveguides was not only to increase the BW of the filtering slot antenna but also to increase the selectivity of the frequency. A SIW cavity-backed structure employed beneath a truncated patch was used to provide filtering functionality to the circularly polarized patch antenna.[10] Different feed techniques utilized in Tang et al.[11] were to realize the filtering and tri-polarization diversity features to the microstrip patch antenna. A coupled-slot structure presented in Hu et al.[12] was designed to achieve filtering response and enlarge the BW of the dielectric resonator antenna. An equivalent circuit for the 2nd order filter theory presented in García-Alcaide et al.[13] was capable to improve the BW of the stacked microstrip antenna up to 30%.

A slotline-based filtering power divider integrated with a $2 \times 2$ microstrip array was used to increase the BW and frequency selectivity of the array.[14] Four resonant modes were merged all together to achieve a large BW to the circular patch antenna.[15] A square ring etched from a rectangular SIW was used to achieve dual mode excitation and radiation for the self-diplexing antenna.[16] A rectangular slot inserted on the top cladding of a half-mode SIW cavity formed two unequal apertures, leading them to resonate at 5.2 and 5.8 GHz.[17] Similarly, the two printed microstrip lines formed by the shorting pins were to excite two radiating patches at 8.20 and 10.55 GHz.[18] With the dielectric resonator[19] a tunable gain and BW were added to the filtering waveguide antenna. Also, a filtering waveguide aperture antenna based on the evanescent-mode dielectric resonator was presented in Singhal and Dhwaj.[20] It is pertinent to mention that almost all the approaches mentioned above for the design of filtering antennas produce a BW which is narrower than a standard antenna with the same volume. Additionally, these approaches usually require extra circuit sections to implement, and then increase the filtering antenna circuit size and complexity.

In this paper, a filtering antenna design approach based on general coupling matrix theory is presented. As a result of this approach, the entire filtering antenna design can be constructed solely from coupled resonators. Moreover, the approach can be implemented without requiring additional matching circuits. As a result, the filtering design layout is simplified. It can also provide a controllable BW, which is extremely important for modern communication systems. To validate the approach, a prototype based on three coupled X-band rectangular waveguide cavity resonators has been designed, fabricated, and measured. The prototype has a low profile and is compact, making it ideal for radar applications.

## 2 | FILTERING ANTENNA DESIGN

### 2.1 | Coupling matrix and topology

The design approach presented in this paper is based on general coupling matrix theory.[5,21] The theory uses an $[A]$ matrix to design the filtering antenna based solely on $n$-coupled resonators, where $n$ is the number of resonators. Once the topology and specifications of the filtering antenna are chosen, the elements of the $[A]$ matrix can be computed using the g element value of Chebyshev low pass prototype filters.[22] The topology of the proposed filtering antenna is shown in Figure 1a. It consists of three inline coupled resonators. The last resonator is named *resonator-radiator* due to serving as a radiator in addition to its frequency filtering role. The equivalent circuit of the filtering antenna is shown in Figure 1b. The resonators are electrically coupled via mutual capacitances. The *resonator-radiator* is treated as a lossy resonator, in which it can start radiating under the resonant condition when the reactance ($X$) or susceptance ($B$) of the *resonator-radiator* circuit is zero.

The filtering antenna is designed to have the following specifications: center frequency $f_0 = 10$ GHz, fractional bandwidth $FBW = 10\%$ when the reflection coefficient $S_{11} = -20$ dB, and filter order $n = 3$. The $FBW$ is in inverse relation with the external quality factor ($Q_e$) ($Q_e = q_e/FBW$) and radiation quality factor ($Q_r$) ($Q_r = q_r/FBW$); While, it is in proportional relation with the coupling coefficient ($M_{ij}$) ($M_{ij} = m_{ij}\,FBW$). After computing ($Q_e$), ($M_{ij}$), and ($Q_r$) utilizing the relations given in[5] and inserting them into the $[A]$ matrix, the $S_{11}$ response of the proposed filtering antenna can be calculated using the relation[5]:

$$S_{11} = \pm\left(1 - \frac{2}{q_e}[A]_{11}^{-1}\right). \tag{1}$$

### 2.2 | Physical configuration

Figure 1c shows the physical configuration of the proposed filtering antenna. Three rectangular waveguide

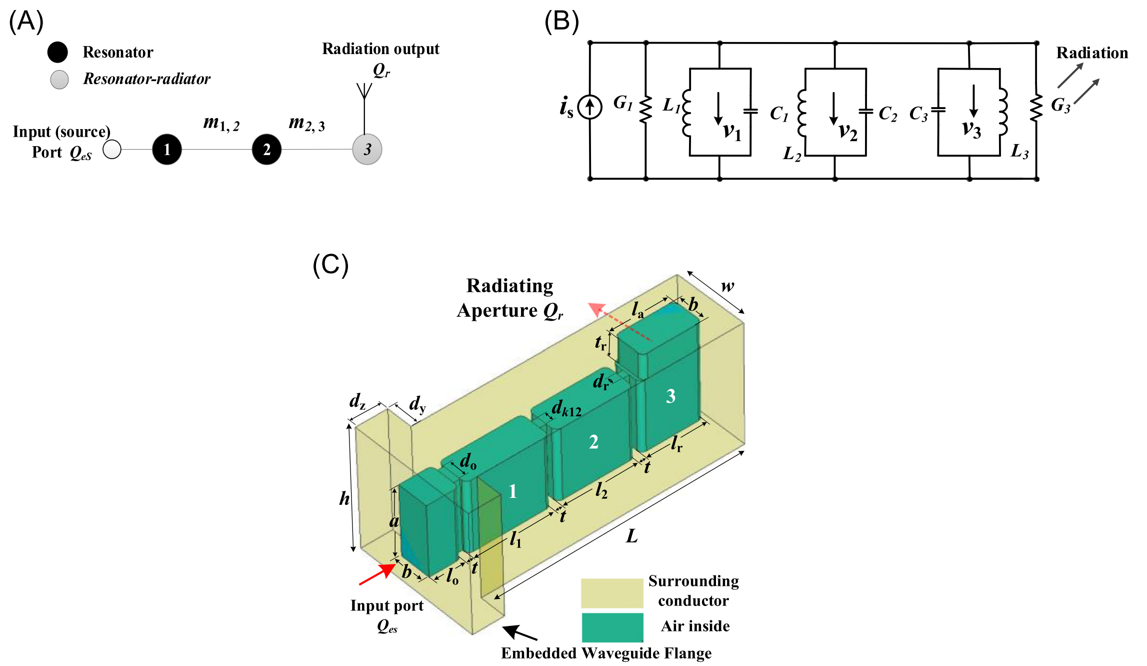


FIGURE 1 Diagram of the proposed filtering antenna: (A) topology, (B) equivalent circuit, and (C) physical configuration. The resonators are coupled by the mutual capacitances. Dimensions in mm are $a = 22.86$, $b = 10.16$, $t = 2$, $t_r = 9$, $l_o = 10$, $d_0 = 6.0$, $d_{k12} = 3.18$, $d_r = 2.31$, $l_1 = 26.0$, $l_2 = 24.47$, $l_r = 19.85$, $l_a = 19.0$, $h = 40$, $w = 24$, $L = 88$.

cavities-based resonators operating at $TE_{101}$ mode are employed, where they are coupled with each other inline via capacitive irises. The *resonator-radiator* is coupled to free space via the rectangular aperture ($l_a \times$ b). The values of the initial physical dimensions ($dk_{12}$, $d_r$, $d_o$ $l_a$, $l_1$, $l_2$, $l_r$) are obtained using the relations given in.[5,23] Later, the dimensions are optimized using the genetic algorithm method in the Computer Simulation Technology (CST) simulator[24] so as to meet the desired $S_{11}$ response. The optimized dimensions are given in the caption of Figure 1.

## 2.3 | Simulated results

The simulated responses of the filtering antenna are shown in Figure 2. A very good agreement between the simulated and the calculated $S_{11}$ responses was found. The realized gain is extremely stable, fluctuating only 0.2 dBi between 9.5 and 10.5 GHz. The peak gain is 7.74 dBi at 10.1 GHz. In the lower band frequencies, the realized gain selectivity is poorer because the capacitive irises used to couple the resonators resonate at the waveguide cut-off frequency (near the lower band). The conductor utilized to model the filtering antenna in CST is Aluminum Alloy 6082 having a conductivity of $3.56 \times 10^7$ S/m. More than 95% of the total efficiency is predicted from 9.5 to 10.5 GHz according to simulations. While, poor efficiencies are observed around the band edges due to the filtering characteristics of the filtering antenna.

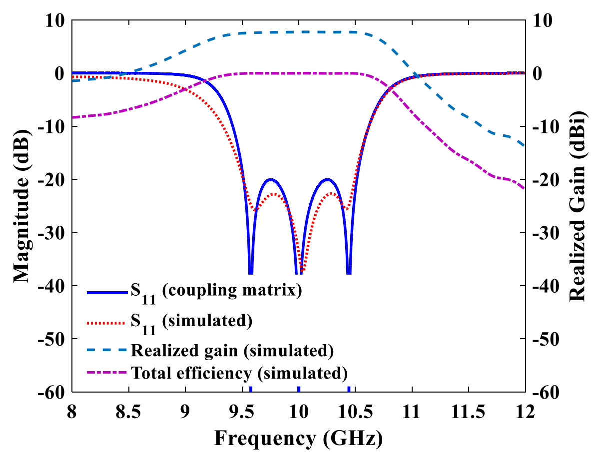


FIGURE 2 The simulated results compared with the desired responses computed from the coupling matrix.

# 3 | FABRICATION AND MEASUREMENT

The proposed filtering antenna has been fabricated as shown in Figure 3A using the Computer Numerical Control (CNC) milling machine which has a tolerance of

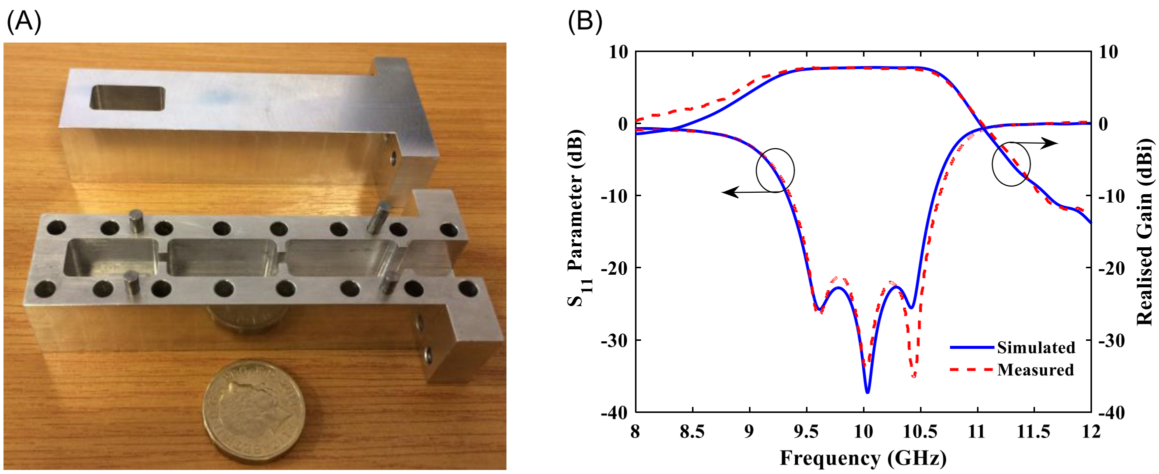


**FIGURE 3** (A) Photograph of the filtering antenna device and (B) The measured $S_{11}$ and realised gain compared with the simulation results.

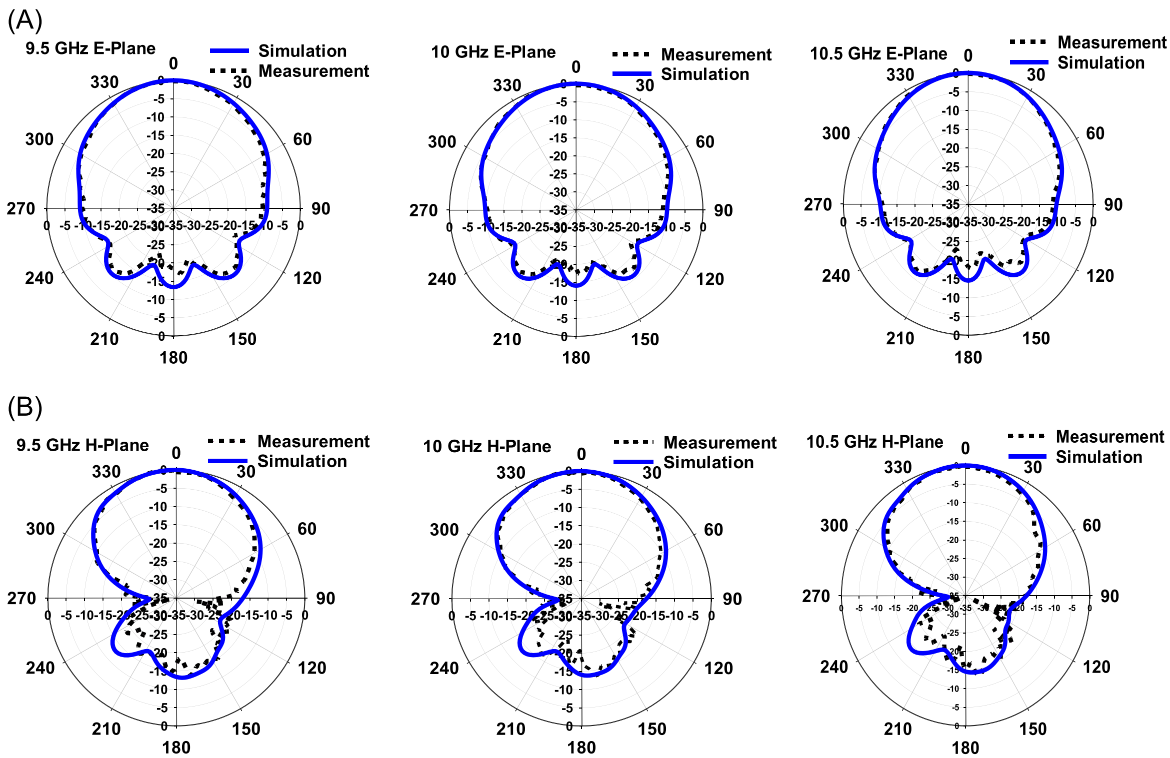


**FIGURE 4** (A) Shows the measured E-Plane radiation pattern compared with the simulated one at frequencies 9.5 GHz, 10 GHz, and 10.5 GHz. While (B) shows the measured H-plane radiation pattern compared with the simulated one at frequencies 9.5 GHz, 10 GHz, and 10.5 GHz.

~±0.02 mm. It is made out of Aluminum Alloy 6082. The structure is cut alongside the center of the waveguide broadside walls (where the surface current is minimum) and divided into two pieces to ease the fabrication process and minimize the signal leakage. The measured $S_{11}$ is presented in Figure 3B. An excellent agreement is obtained with the simulated values over the entire operating frequency band. The smaller shift of $S_{11}$ to higher frequencies could be due to the fabrication tolerance. The realized gain has been measured in anechoic chamber room using a well-known comparison method.[25] A broadband horn antenna was used as the reference antenna, and the filtering antenna was placed in the far-field region. The measured and simulated

TABLE 1 Comparison of recent filtering waveguide antenna work.

| Refs. | $f_0$ (GHz) | Fabrication technique | Volume ($\lambda_0^3$)[a] | *FBW* (%) at $S_{11} = -10$ dB | Peak gain (dBi) |
|---|---|---|---|---|---|
| [9] | 5.365 | SIW | 1*0.96*0.98 | 7.64 | 5.3 |
| [16] | 9.5 | SIW | 0.050*0.65*0.65 | 1.32 | 5.75 |
| | 10.5 | | 0.055*0.725*0.725 | 1.46 | 5.95 |
| [17] | 5.2 | SIW | 0.027*0.44*0.44 | NA | 3.23 |
| | 5.8 | | 0.030*0.49*0.49 | NA | 4.38 |
| [18] | 8.20 | SIW | NA*0.60*1.23 | NA | 4.0 |
| | 10.55 | | NA*0.77*1.58 | NA | 4.3 |
| [19] | 8.23 | CNC | 0.796*0.796*0.796 | 10 | 5.8 ± 1 |
| [20] | 8.1 | CNC | 0.42*0.26*NA | 3.7 | 4.5 |
| This work | 10 | CNC | 1.33*0.8*2.93 | 13.4 | 7.74 |

Abbreviations: CNC, Computer Numerical Control; FBW, fractional bandwidth.

[a]$\lambda_0$ is free space wavelength at the center frequency.

realized gain responses are in excellent agreement. The radiation patterns have been measured for both the E- and H-planes at 9.5, 10, and 10.5 GHz as shown in Figure 4. Excellent agreements with the simulated results are obtained. The side lobe levels are below −11 dB. It should be pointed out the asymmetries in the H-plane patterns are due to the asymmetric physical structure of the filtering antenna. Table 1 summarizes the performance of proposed filtering antenna in comparison with some other published designs. It can be observed that the design described here has advantages in terms of high gain and large BW.

## 4 | CONCLUSIONS

A new configuration of a filtering waveguide aperture antenna based on all resonator-structure has been designed and presented using the general coupling matrix approach. Three $TE_{101}$ rectangular waveguide cavity resonators, which were coupled together inline via capacitive irises, were employed in the configuration. The filtering antenna has been fabricated to validate the simulated results. Excellent agreement between the simulated and measured values was obtained, validating the design approach.

## AUTHOR CONTRIBUTIONS

*Conceptualization*: Rashad H. Mahmud and Xiaobang Shang. *Data curation*: Rashad H. Mahmud. *Funding acquisition*: Rashad H. Mahmud and Yi Wang. *Investigation*: Yi Wang, Idris H. Salih, and Talal Skaik. *Methodology*: Rashad H. Mahmud, Xiaobang Shang. *Project administration*: Yi Wang, Talal Skaik, Idris H. Salih. *Resources*: Rashad H. Mahmud, Xiaobang Shang. *Software*: Rashad H. Mahmud. *Supervision*: Yi Wang. *Validation*: Rashad H. Mahmud. *Visualization*: Rashad H. Mahmud and Idris H. Salih. *Roles/Writing—original draft*: Rashad H. Mahmud. *Writing—review and editing*: Rashad H. Mahmud, Yi Wang, and Talal Skaik.

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## CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

## DATA AVAILABILITY STATEMENT

Not applicable.

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