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Inline Bandpass Filtering Waveguide Antenna with Two Transmission Zeros Based on All-resonator Structures

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***Abstract* - Nowadays, a significant amount of effort is being devoted to miniaturizing the design of filtering antennas for future wireless communication systems. However, there are numerous design strategies documented in the literature, most of which are relevant to specific microwave circuit configurations. Moreover, they often require additional matching circuits, which increase the overall size of the filtering antenna. This study introduces a generic coupling matrix approach for developing a second-order filtering antenna with two transmission zeros operating at cross-band frequencies. The last resonator's output is physically connected to free space, and two inline coupled rectangular waveguide cavity resonators operating in the TE_{101} mode are employed. Impressive, simulated results have been achieved, demonstrating a fractional bandwidth (FBW) exceeding 5% at a reflection coefficient S_{11} of −9.98 dB. Additionally, the gain response remains remarkably flat, spanning from 8.9 to 9.3 GHz, with a negligible variation of ±0.07 dB around 3.77 dB. The tiny and low-profile design of the suggested filtering antenna offers significant advantages for radar applications.**

Keywords* - *Filtering antenna, Gain, FBW, Waveguide resonator, Transmission zeros

I. INTRODUCTION

Presently, there is an increasing tendency to combine the front-end elements of wireless communication systems, specifically bandpass filters (BPFs) with antennas, resulting in what is referred to as filtering antennas [1 - 3]. This integration offers multiple benefits, including adding filtering capabilities to the antenna, minimizing losses, and reducing the overall size of the front-end system [4]. Several techniques had been suggested in the literature to increase the bandwidth of these filtering antennas. The goal is to enhance data throughput capabilities and reduce the occurrence of unwanted signals. Ludlow *et al.* in their work [5] proposed the idea of using stimulating surface waves to enhance the evanescent mode, hence increasing the bandwidth (BW) of the filtering waveguide slot antenna. In the study by Yusuf and Gong [6], an aperture antenna with a narrow bandwidth was improved by combining it with a low-quality factor cavity and a 3rd order Chebyshev bandpass filter.

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This integration allowed for a wider bandwidth to improve the slot antenna's BW mainly, Fakharian [7] combined two PIN diodes with an E-shaped resonator. A substrate-integrated waveguide-based dual mode cavity resonator was used by Xie *et al.* [8] to enhance the filtering slot antenna bandwidth and improve its selectivity. In another approach, under a truncated patch, a substrate-integrated wave (SIW) cavity-backed structure was used to give the circularly polarized patch antenna filtering capabilities [9]. Tang *et al.* [10] looked at a variety of feed strategies to provide filtering and tri-polarization diversity characteristics for the microstrip patch antenna.

A coupled-slot construction was proposed by Hu *et al.* [11] in order to increase the dielectric resonator antenna's bandwidth and produce a filtering response. García-Alcaide *et al.* [12] proposed an equivalent circuit for the 2nd order filter theory, which can boost the BW of stacked microstrip antennas by up to 30%.

A 2 × 2 microstrip array and an integrated slot line-based filtering power divider were used to improve the array's bandwidth (BW) and selectivity [13]. Four resonant modes were coupled in the circular patch antenna [14] to generate a large BW. A self-duplexing antenna uses a square ring carved from a rectangle substrate-integrated waveguide (SIW) for dual-mode excitation and radiation [15]. Modifications were implemented on the upper cladding of a half-mode Substrate Integrated Waveguide (SIW) cavity, resulting in the creation of two asymmetrical openings that exhibited resonance at frequencies of 5.2 and 5.8 GHz [16]. Two printed microstrip lines were created using shorting pins. Two radiating patches on these lines were simulated at 8.20 GHz and 10.55 GHz [17]. A dielectric resonator was used in [18] to create a filtering waveguide antenna with configurable gain and bandwidth. Furthermore, a filtering waveguide aperture antenna that makes use of an evanescent-mode dielectric resonator was proposed by Singhal and Dhwaj [19]. It is important to recognize that while these solutions lead to a narrower beam width when compared to classic antennas of similar dimensions, they also improve the design of filtering antennas. Furthermore, these methods often need the addition of extra circuit elements, increasing the complexity and size of the filtering antenna circuit.

This work uses the universal coupling matrix theory to provide a new approach to filtering antenna design. This method's primary advantage is that it may construct the entire filtering antenna by joining resonators, negating the need for additional matching circuit. This makes the antenna design setup simpler. Moreover, this method permits bandwidth (BW) adjustment, which is an essential feature of satellite communication system.

II. FILTERING ANTENNA DESIGN

The design that is being discussed builds a filtering antenna by utilizing the basic concept of general coupling matrix theory. This method creates a matrix represented by [A] by connecting a number of resonators. with n representing the total number of resonators in the system. The approach uses the g element values acquired from Chebyshev low-pass prototype filters to calculate the elements of the [A] matrix. Figure 1(a) shows the configuration of the filtering antenna, which consists of two inline linked resonators. The last resonator, known as the resonator-radiator, has a dual purpose as both a radiator and for frequency filtering. The filtering antenna's equivalent circuit, seen in Fig. 1(b), demonstrates the electrical connection of resonators via mutual capacitances. When the reactance (X) or susceptance (B) of the resonator-radiator circuit nearly reaches zero during resonance, the resonator-radiator is considered to have losses and can emit radiation.

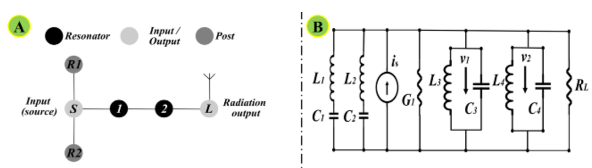

Fig. 1. Diagram of the suggested filtering antenna: (a) configuration, (b) representation of the circuit.

The specific design parameters for the filtering antenna are as follows: central frequency $f_0 = 10GHz$, fractional bandwidth $FBW = 10\%$, reflection coefficient $S_{11} = -9.98\ dB$, and filter order $n = 2$. The fractional bandwidth (FBW) is directly proportional to the coupling coefficient $(M_{ij} = m_{ij} * FBW)$ and inversely proportional to the radiation quality factor $(Q_r = \frac{q_r}{FBW})$ and the external quality system $(Q_e = \frac{q_e}{FBW})$ [4]. Once these values are computed, they are inserted into the matrix [A] to calculate the S_{11} and S_{21} responses using the given equations.

$$S_{11} = 1 - \frac{2}{q_{e1}}[\bar{A}]_{11}^{-1} \tag{1}$$

$$S_{21} = 2\frac{1}{\sqrt{q_{e1} . q_{n1}}}[\bar{A}]_{n1}^{-1} \tag{2}$$

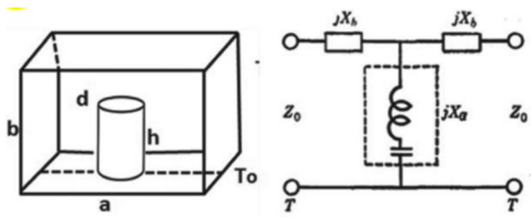

Fig. 2. Resonant coupling: (a) physical layout and (b) circuit equivalent.

The coupling between resonators is established through the strategic positioning of metal-coated partial height holes within a rectangular metal block [20]. These holes play a key role by serving as impedance inverters across a wide filter bandwidth, thus shaping the bandpass filter's response. Simultaneously, they generate transmission zeroes within the filter's stopband. The corresponding equivalent circuit for this coupling arrangement is depicted in Fig. 2.

$$(f_c)_{mm} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m.\pi}{a}\right)^2 + \left(\frac{n.\pi}{b}\right)^2}\ [Hz] \qquad (3)$$

$$(\lambda_c)_{mm} = \frac{2}{\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}}\,[m] \qquad (4)$$

, where a = width inside (m), representing the longest dimension, b = height inside (m), representing the shortest dimension, m = quantity of half-wavelength variations of the fields in the "a" direction, n = Quantity of half-wavelength variations of the fields in the "b" direction, $\varepsilon = 8.854187817 \times 10^{-12}$, permittivity for free space, $\mu = 4\pi \times 10^{-7}$, permeability for free space.

III. PHYSICAL CONFIGURATION

Figure 3 depicts the actual arrangement of the suggested filtering antenna. The system comprises of two resonators based on rectangular waveguide cavities, operating in TE_{101} mode and equipped with dual posts. The resonators are connected to each other in a series using capacitive irises and are powered by a coaxial connection. The resonator's radiation is directed to free space through a rectangular aperture ($L_o \times b$).

The initial physical dimensions (in mm) are as follows: $a = 10.16$, $b = 22.5$, $l_o = 21.89$, $p_1 = 5$, $h_1 = 5.38$, $x_1 = 5.75$, $rad_1 = 1.5$, $x_2 = 16.75$, $h_2 = 6.25$, $p_2 = 5$, $off_1 = 10.8$, $rad_3 = 0.65$, $off = 1.8$, $z_p = 6.9$, $zx = 8.75$, $rad_4 = 1.8$, $wx = 6.5$, $t = 0.5$.

The material properties relevant to the proposed design are listed in Table I.

Table I. Material properties.

Material	Vacuum	Perfect Electric Conductor (PEC)	Copper	Teflon (TM)
Relative Permittivity	1	1	1	2.1
Relative Permeability	1	1	0.999991	1
Dielectric Loss Tangent	0	0	0	0.001
Bulk Conductivity (S/m)	0	1×10^{30}	5.8×10^{7}	0
Lande G Factor	2	2	2	2
Mass Density	0	0	8933	2250

IV. RESULTS AND DISCUSSION

Figure 4 displays the simulated output of the filtering antenna. A high level of consistency was observed between the simulated and calculated S_{11} and S_{21} responses. The actual increase in gain remains highly consistent, varying by only 0.2 dBi within the frequency range of 8.9 to 9.3 GHz. At 9.1 GHz, the maximum gain is 7.74 dBi as depicted in blue trace of Fig. 4. Because the resonant capacitive irises used to link the resonators resonate at the waveguide cutoff frequency close to the lower band, the realized gain selectivity is diminished at the lower band frequencies.

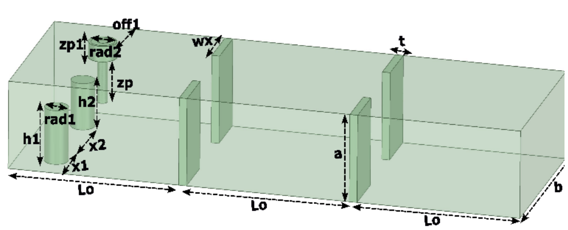

Fig. 3. 3D model of Filtering Antenna.

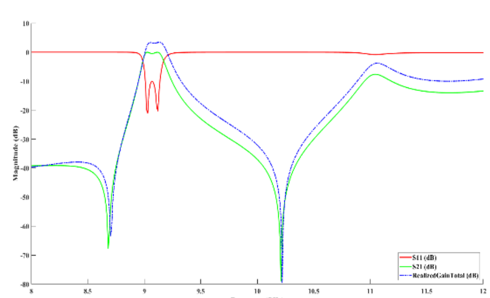

Fig. 4. Simulated S_{11} and realized gain responses.

The bandwidth achieved based on the S_{11} response is around 1.1 GHZ. The reflection coefficient of S_{11} value of -11.25 dB achieved. The conductor used to simulate the filtering antenna in Ansys is a Perfect Electric Conductor (PEC) with a conductivity of 1×10^{30} S/m. The simulations suggest that the total efficiency will be over 95% within the range of frequency from 8.68 to 10.21 GHz. Suboptimal efficiencies are noticed around the boundaries of the frequency range as a result of the filtering properties of the antenna. The radiation pattern has been determined for both the two-dimensional (2D) and three-dimensional (3D) configurations at frequencies of 8.68, 9.03, 9.3, and 9.9 GHz as seen in Figs. 5-6.

Table II. 3D radiation pattern at different frequencies.

Frequency (GHz)	Radiation Pattern Gain (dB)	
	Max.	Min.
8.68	-4.56	-27.62
9.03	-3.64	-29.82
9.3	-2.04	-30.96
9.9	-0.81	-26.81

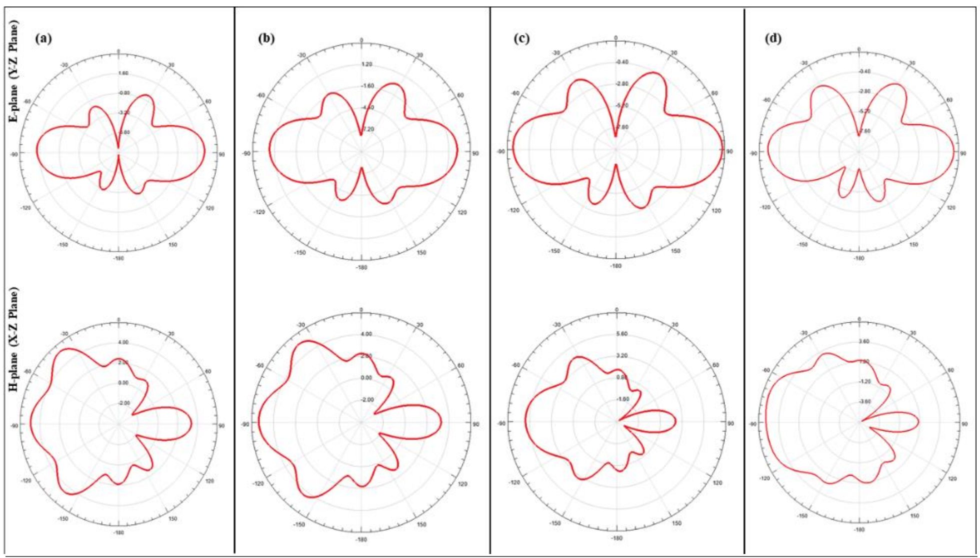

Fig. 5. 2D radiation pattern of proposed design: (a)-(d) show the three graphs of 2D radiation pattern at center frequency 9.9, 8.68, 9.03, 9.3 GHz when phi is 0 º, and 90 º.

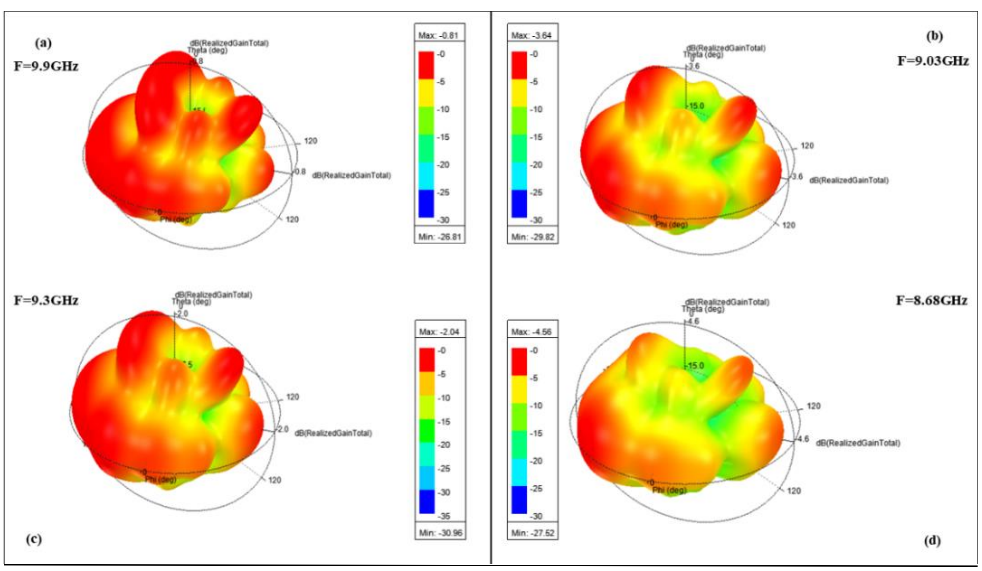

Fig. 6. 3D radiation pattern of proposed design: (a) cutoff Frequency at 9.9 GHz, (b) at first pole 9.03 GHz, (c) at second pole 9.3 GHz and (d) at second zero 8.68 GHz.

The 3D radiation pattern gain for a waveguide cavity resonator system at various frequencies is displayed in Table 2. The maximum gain values for frequencies 8.68, 9.03, 9.30, and 9.90 GHz are -4.56, -3.64, -2.04, and -0.81 dB, respectively, suggesting better performance at higher frequencies. The lowest gain values show significant variance across frequencies, with values of -27.62, -29.82, -30.96, and -26.81 dB, respectively. This demonstrates that although the system operates more efficiently at higher frequencies, the radiation patterns consistency varies.

V. CONCLUSION

A novel design for a filtering waveguide aperture antenna has been presented, which utilizes a resonator-based construction and employs a comprehensive coupling matrix technique. The arrangement consists of three TE_{101} rectangular waveguide cavity resonators that are coupled in a straight line by capacitive irises. The antenna exhibits an efficiency above 95% within the range of frequency from 8.68 to 9.3 GHz. Additionally, the filtering antenna achieves a gain of 7.74 dBi at a frequency of 9.3 GHz. The antenna design has been subjected to simulation, resulting in positive results. The good agreement is found between the simulated and measured values provides strong evidence of the effectiveness of the design process.

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REFERENCES

[1] L. Li and G. Liu, "A Differential Microstrip Antenna With Filtering Response," *IEEE Antennas and Wirel. Propag. Lett.*, vol. 15, pp. 1983 - 1986, 2016.

[2] S. Wang, F. Fan, R. Gómez-García, L. Yang, Y. Li, S. W. Wong and G. Zhang, "A Planar Absorptive-Branch-Loaded Quasi-Yagi Antenna With Filtering Capability and Flat Gain," *IEEE Antennas and Wirel. Propag. Lett.*, vol. 20, no. 9, pp. 1626 - 1630, 2021.

[3] W. Yang, S. Chen, Q. Xue, W. Che, G. Shen and W. Feng, "Novel Filtering Method Based on Metasurface Antenna and Its Application for Wideband High-Gain Filtering Antenna With Low Profile," *IEEE Trans. Antennas and Propag.*, vol. 67, no. 3, pp. 1535 - 1544, 2019.

[4] R. H. Mahmud and M. J. Lancaster, "High-Gain and Wide-Bandwidth Filtering Planar Antenna Array-Based Solely on Resonators," *IEEE Trans. Antennas and Propag.*, vol. 65, no. 5, pp. 2367 - 2375, 2017.

[5] P. Ludlow, V. Fusco, G. Goussetis and D. E. Zelenchuk, "Applying Band-Pass Filter Techniques to The Design of Small-Aperture Evanescent-Mode Waveguide Antennas," *IEEE Trans. Antennas and Propag.*, vol. 61, no. 1, pp. 134 - 142, 2013.

[6] Y. Yusuf and X. Gong, "Integration of Three-dimensional High-Q Filters with Aperture Antennas and Bandwidth Enhancement Utilising Surface Waves," *IET Microw. Antennas Propag.*, vol. 7, no. 7, pp. 468-475, 2013.

[7] M. M. Fakharian, P. Rezaei, A. A. Orouji and M. Soltanpur, "A Wideband and Reconfigurable Filtering Slot Antenna," *IEEE Antennas and Wirel. Propag. Lett.*, vol. 15, pp. 1610 - 1613, 2016.

[8] H. Y. Xie, B. Wu, Y. L. Wang, C. Fan, J. Z. Chen and T. Su, "Wideband SIW Filtering Antenna With Controllable Radiation Nulls Using Dual-Mode Cavities," *IEEE Antennas and Wirel. Propag. Lett.*, vol. 20, no. 9, pp. 1799 - 1803, 2021.

[9] Y. Dong, S. Gao, Q. Luo, L. Wen, C. X. Mao, S. W. Dong, X. Li, G. Wei, G. Wen, Y. Geng and Z. Cheng, "Broadband Circularly Polarized Filtering Antennas," *IEEE Access*, vol. 6, pp. 76302 - 76312, 2018.

[10] M. C. Tang, D. Li, X. Chen, Y. Wang, K. Hu and R. W. Ziolkowski, "Compact, Wideband, Planar Filtenna With Reconfigurable Tri-Polarization Diversity," *IEEE Trans. Antennas and Propag.*, vol. 67, no. 8, pp. 5689 - 5694, 2019.

[11] P. F. Hu, Y. M. Pan, X. Y. Zhang and S. Y. Zheng, "A Compact Filtering Dielectric Resonator Antenna With Wide Bandwidth and High Gain," *IEEE Trans. Antennas and Propag.*, vol. 64, no. 8, pp. 3645 - 3651, 2016.

[12] N. García-Alcaide, A. Fernández-Prieto, R. R. Boix, V. Losada, J. Martel and F. Medina, "Design of Broadband Aperture-Coupled Stacked Microstrip Antennas Using Second-Order Filter Theory," *IEEE Trans. Antennas and Propag.*, vol. 70, no. 7, pp. 5345 - 5356, 2022.

[13] Y. M. Zhang, S. Zhang, G. Yang and G. F. Pedersen, "A Wideband Filtering Antenna Array With Harmonic Suppression," *IEEE Trans. Microw. Theory and Techniq.*, vol. 68, no. 10, pp. 4327 - 4339, 2020.

[14] P. Liu, W. Jiang, W. Hu, S. Y. Sun and S. X. Gong, "Wideband Multimode Filtering Circular Patch Antenna," *IEEE Trans. Antennas and Propag.*, vol. 69, no. 11, pp. 7249 - 7259, 2021.

[15] A. A. Khan and M. K. Mandal, "Compact Self-Diplexing Antenna Using Dual-Mode SIW Square Cavity," *IEEE Antennas and Wirel. Propag. Lett.*, vol. 18, no. 2, pp. 343 - 347, 2019.

[16] A. Kumar, D. Chaturvedi and S. Raghavan, "Dual-Band, Dual-Fed Self-Diplexing Antenna," in *2019 13th Europ. Conf. Antennas and Propag.*, Krakow, Poland, 2019.

[17] A. Kumar and S. Raghavan, "Planar Cavity-Backed Self-Diplexing Antenna Using Two-Layered Structure," *Progr. Electromagnet. Res. Lett.*, vol. 76, pp. 91-96, 2018.

[18] D. Singhal, S. S. Chauhan and K. Dhwaj, "Compact Reconfigurable Waveguide Filtering Antenna," *IEEE Antennas and Wirel. Propag. Lett.*, vol. 22, no. 2, pp. 392 - 396, 2023.

[19] D. Singhal and K. Dhwaj, "Dielectric Resonator-Based Evanescent-Mode Waveguide Filtering Antenna," *IEEE Antennas and Wirel. Propag. Lett.*, vol. 21, no. 7, pp. 1413 - 1417, 2022.

[20] M. Y. Sandhu, Z. Ahmed, S. Hyder and S. Afridi, "Inline Integrated Ceramic Waveguide Bandpass Filter with N+1 Finite Transmission Zeros," *IETE J. Res.*, vol. 69, no. 1, pp. 173-179, 2023.