Progress In Electromagnetics Research Letters, Vol. 119, 59-65, 2024

PIER Letters

(Received 4 March 2024, Accepted 12 April 2024, Scheduled 21 April 2024)

A Compact Wideband Waveguide Filtering Antenna with Transmission Zero

Iqram Haider*, Ananjan Basu, and Shiban Kishen Koul

Center for Applied Research in Electronics (CARE), Indian Institute of Technology Delhi, New Delhi 110016, India

ABSTRACT: This letter describes the design of a compact, wideband waveguide filtering antenna with a transmission zero (TZ) in the upper stopband. A novel frequency-variant coupling (FVC) network that provides a TZ in addition to the pole is used to achieve compactness and higher selectivity. The position of the TZ can be changed in the upper stopband by altering the physical parameters of the proposed FVC. The radiating waveguide aperture is matched to the real admittance of the generator over a wide bandwidth by utilizing coupled-resonator theory. This leads to a wide fractional bandwidth of 23%, along with a TZ at the upper stopband. The filtering antenna has been manufactured using metal 3-D printing to achieve low manufacturing costs and light weight. The measured results are in good agreement with the simulated ones, which shows the feasibility of the proposed FVC structure for the design of the compact waveguide filtering antenna with a TZ.

1. INTRODUCTION

Modern communication systems demand highly integrated and multifunctional components in order to improve their performance and compactness. Filtering antennas are multi-functional RF front-end devices that can combine the radiation characteristics of the antenna with the filtering characteristics of a bandpass filter (BPF). This integrated design approach minimizes losses and the size of the overall system in comparison to the conventional approach of cascading filters and antennas through transmission lines [1]. To fulfill the requirement for high data rates, there have been several wide-band filtering antennas reported in the literature [2]. These reported wideband filtering antennas are built on microstrip [3], substrate-integrated waveguides [4], and metallic waveguides [5]. For long-distance communications, waveguide filtering antennas are preferred due to their high-power handling capabilities and increased radiation efficiencies [6]. A slotted waveguide filtering antenna with a fractional bandwidth (FBW) of 24% has been reported in [7]. Another wideband evanescent-mode open-ended waveguide filtering antenna has been reported with an FBW of 15% in [8]. Further, a filtering waveguide aperture antenna has also been reported with an FBW of 13.4% [9]. The selectivity of these wideband filtering antennas needs to be increased to reduce adjacent channel interference due to the presence of an overcrowded electromagnetic spectrum [10]. Conventionally, the selectivity of filtering antennas is increased by introducing transmission zeros (TZs) in their filtering response. Recently, TZs have been realized in wideband waveguide-filtering antennas using a cross-coupled resonator-based structure [11]. However, this waveguide-filtering antenna occupies a large volume. Frequency-variant coupling (FVC) networks have been reported in the literature for designing various compact waveguide filters with several TZs [12–14]. However, these proposed FVC networks have been utilized for the design of narrowband waveguide filters (BW $<$ 10%).

In this letter, the design of a compact wideband waveguide filtering antenna with a TZ is reported using coupled-resonator theory. Based on this theory, a third-order waveguide filtering antenna is designed using the proposed FVC inverter. The proposed FVC inverter consists of inductive and partial height posts that provide the TZ in addition to a pole. The compact waveguide filtering antenna is achieved by utilizing two half-wavelength resonators and the proposed FVC inverter instead of three half-wavelength resonators. The proposed filtering antenna is composed of a half-wavelength rectangular waveguide resonator that is coupled via a proposed FVC inverter to the open-ended half-wavelength rectangular waveguide resonator. Further, the iris at the aperture is utilized to match open-ended waveguide aperture's complex admittance to the real admittance of the generator over a wide bandwidth according to coupled-resonator theory. To achieve light weight and low fabrication cost, the proposed waveguide filtering antenna has been fabricated using a direct metal laser sintering (DMLS) printing process. As will be shown later (Table 1), we have achieved the smallest size reported for waveguide filtering antennas with wide bandwidth and TZ.

2. INDUCTIVE SINGLET BASED FVC INVERTER

The inductive singlet is composed of a centered inductive post and an offset partial height post that are transversely placed at the centre of the WR-90 waveguide, as shown in Fig. 1(a). This structure acts as an FVC inverter, which can provide one TZ along with a pole. The offset partial height posts in the waveguide can be modelled as shunt-connected series-type resonators

* Corresponding author: Iqram Haider (iqram.haider@care.iitd.ac.in).

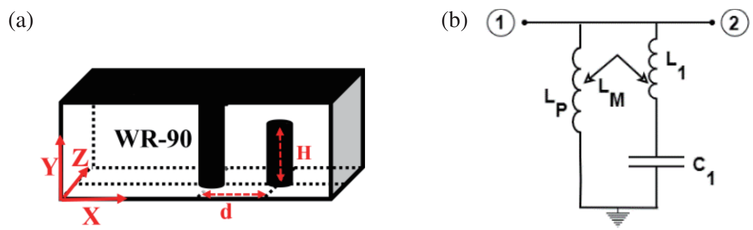

FIGURE 1. Proposed inductive singlet based NFVC inverter. (a) physical structure of the proposed inverter. Relevant dimensions are $H = 5.45$ mm, $d = 3.6$ mm. (b) Equivalent circuit of the proposed NFVC inverter.

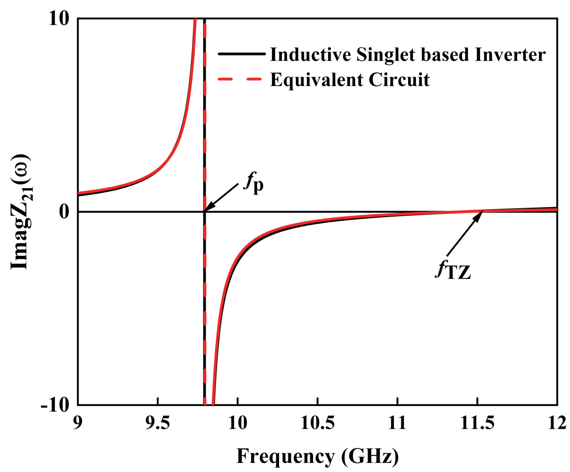

FIGURE 2. Comparison of the transimpedance parameter (Z_{21}) of the proposed NFVC inverter with its equivalent circuit. Relevant values for equivalent circuit are: $L_1 = 19.76$ pH, $L_M = 0.08$ pH, $C_1 = 9.305$ pF, $Lp = 7.45$ pH.

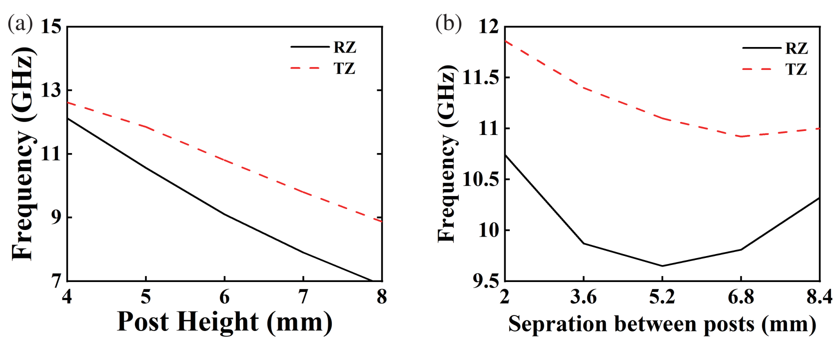

FIGURE 3. Effect of physical parameters of proposed inductive singlet based FVC on pole (RZ) and TZ positions. The relevant dimensions for case: (a) $d = 3.6$ mm, and case (b) $H = 5.45$ mm.

that can provide a TZ in the frequency response, as mentioned in [15]. The centered inductive post can be modelled as a shunt-connected inductance [16]. Furthermore, the effect of separation between the posts is modelled as mutual inductance, as given in [18]. Based on this, the equivalent circuit of the proposed inductive singlet is presented in Fig. 1(b). To verify, the transimpedance parameters of the equivalent circuit and the proposed inductive singlet structure are shown in Fig. 2. The frequency of pole and TZ according to the given equivalent circuit is given by the following formula:

$$f_z = \frac{1}{2\pi\sqrt{(L_1 \pm L_M)C_1}} \tag{1}$$

$$f_p = \frac{1}{2\pi\sqrt{(L_1 + L_p \pm L_M)C_1}} \tag{2}$$

Furthermore, the height of capacitive post and the separation between the inductive and capacitive posts influences frequency of pole and TZ. The effect of parametric variation on the frequencies of pole and TZ is studied and shown in Fig. 3. It is evident from Fig. 3(a) that the TZ and pole frequencies can be altered by changing the height of the capacitive post. Moreover, these positions of poles and TZ can also be changed by altering the separation between the posts. It must be marked that the proposed arrangement can realize TZ frequency always below the pole frequency.

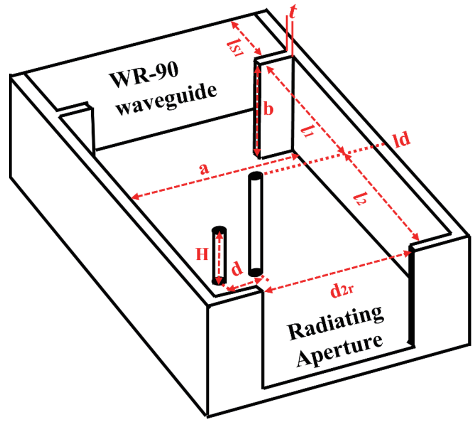

FIGURE 4. Top-view layout of the proposed inline waveguide filtering antenna using inductive singlet-based FVC.

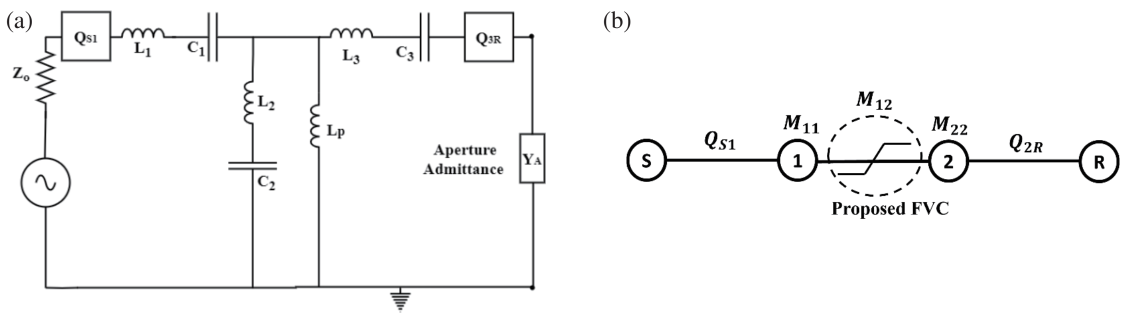

FIGURE 5. (a) Equivalent circuit model of the proposed waveguide filtering antenna. (b) Coupling routing diagram of the proposed filtering antenna.

3. WAVEGUIDE FILTERING ANTENNA

The physical configuration of the proposed waveguide filtering antenna is shown in Fig. 4. The proposed design configuration is composed of an input side half-wavelength rectangular waveguide resonator that is coupled via a proposed FVC inverter to the output side open-ended rectangular waveguide resonator. The input resonator is excited by a standard WR-90 waveguide through a rectangular iris. Furthermore, the iris at the aperture of the open-ended waveguide resonator is utilized to match its complex admittance to the generator's real admittance across a wide BW [9, 11, 21].

The proposed third-order filtering antenna has been designed for the following specifications: center frequency $f_0 = 9.3\,\text{GHz}$, return loss 10 dB over the fractional bandwidth FBW $= 22.22\%$, and a TZ positioned in the upper stopband $f_z = 11.4\,\text{GHz}$. The filtering antenna equivalent circuit [see Fig. 5(a)] parameters can be evaluated according to the given specifications using the synthesis approach based on FVC inverters, as given in [18]. Such synthesis techniques are well established today [12–14, 18, 19]. This approach solves the structured inverse nonlinear eigenvalue problem to obtain coefficients of the coupling routing scheme [19], as shown in Fig. 5(b). These coupling coefficients are realized into physical structure in Computer Simulation Technology (CST) [20], using coupled-resonator theory, as mentioned in [21]. Then, minor optimization is performed to achieve the desired specifications.

In this case since the structure is simple, a procedure based on optimization is developed to achieve the desired specifications. First, the physical parameters (H, d) of the proposed FVC according to the specified TZ location is obtained through simulation using the CST microwave studio [20], as shown in Fig. 6. The initial dimensions of resonators are kept half-wavelength at operating frequency. Further, the post positions (ld) between two half-wavelength resonators determine the bandwidth of the proposed waveguide filtering antenna and modified length of resonators (l_1, l_2), as shown in Fig. 7. The dimensions of other parameters (l_{S1}, t, d_{2r}) are obtained to achieve specification using minor optimization in the CST. The physical parameters after the optimization are the as follows: $l_{S1} = 7\,\text{mm}$, $a = 22.86\,\text{mm}$, $b = 10.16\,\text{mm}$, $l_1 = 15.65\,\text{mm}$, $l_2 = 15.65\,\text{mm}$, $d = 3.6\,\text{mm}$, $H = 5.45\,\text{mm}$, $d_{2r} = 14.66\,\text{mm}$, and $t = 1\,\text{mm}$. The E-field pattern of the final optimized waveguide filtering antenna is also shown in Fig. 8.

4. FABRICATION AND MEASUREMENT

The proposed waveguide filtering antenna is manufactured as a single piece using AlSi10Mg material based upon direct metal laser sintering (DMLS) process. The manufacturing tolerance within $\pm 100\,\mu\text{m}$ was achieved by maintaining the printing orientation of the structure at 45°. The overall volume of the waveguide filtering antenna is $22.86 \times 10.16 \times 41.5\,\text{mm}^3$, and its weight is 59 grams. A photograph of the 3-D printed waveguide filtering is shown in Fig. 9(a).

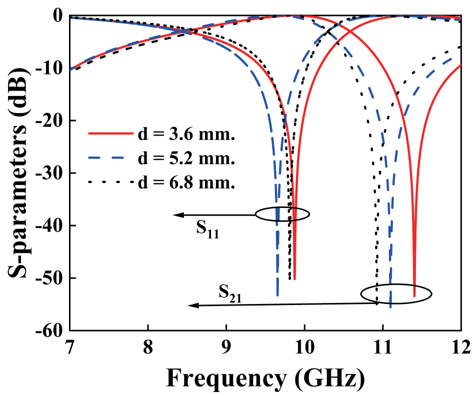

FIGURE 6. Effect of post separation on the TZ frequency of the proposed FVC inverter for fixed partial height post $H = 6.5$ mm.

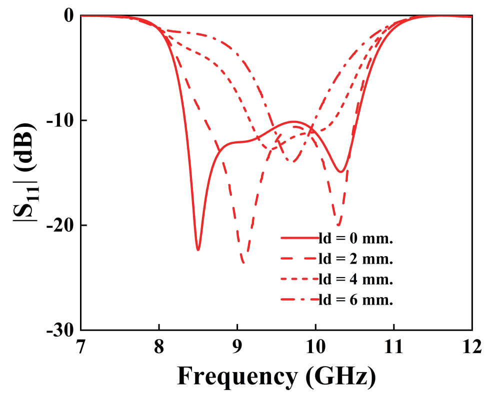

FIGURE 7. Effect of post position (ld) on bandwidth of the proposed waveguide filtering antenna.

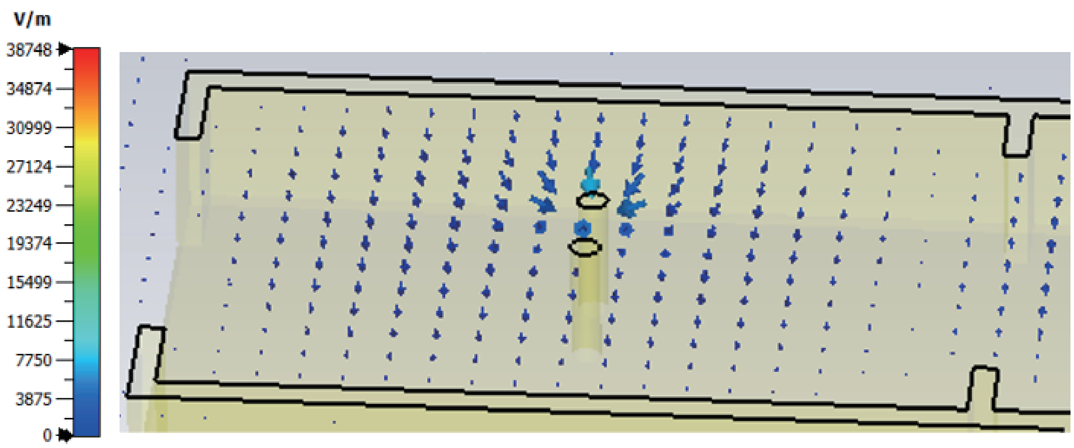

FIGURE 8. E-field pattern of the proposed waveguide filtering antenna.

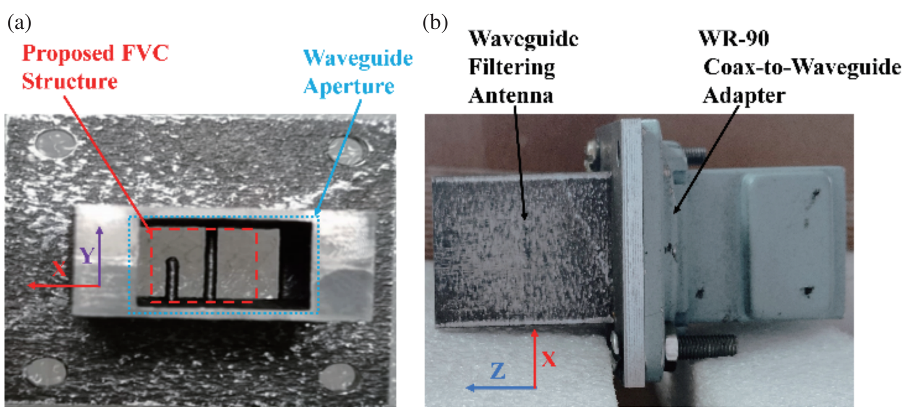

FIGURE 9. Photograph of 3-D printed waveguide filtering antenna. (a) Cross-sectional view. (b) Longitudinal view of the filtering antenna connected with WR-90 coax-to-waveguide adapter.

The 3-D-printed waveguide filtering antenna is excited by a WR-90 coax-to-waveguide adapter as shown in Fig. 9(b). The return loss of waveguide filtering antenna is measured by a Keysight PNA E8364C network analyzer, while the radiation characteristics of waveguide filtering antenna has been measured in an anechoic chamber as shown in Figs. 10(a) & (b). The measured realized gain and return loss of the waveguide filtering antenna in comparison to simulated ones are shown in Fig. 11. The measured and simulated responses are in agreement with minor differences that can be attributed to fabrication tolerance of DMLS process. The measured S_{11} is below -9.9 dB over the passband, achieving an FBW of 23% centered

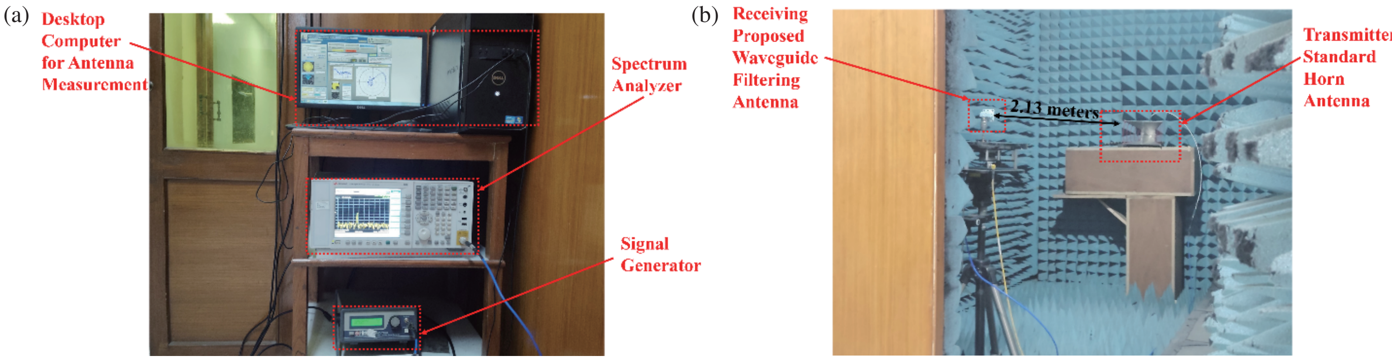

FIGURE 10. Gain and radiation measurement setup. (a) Outside anechoic chamber. (b) Inside anechoic chamber.

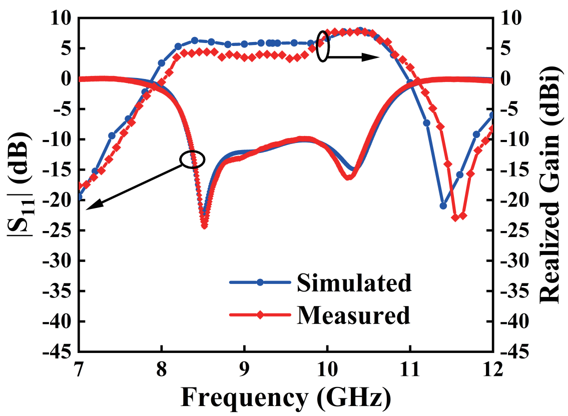

FIGURE 11. Simulated and measured responses of the proposed waveguide filtering antenna.

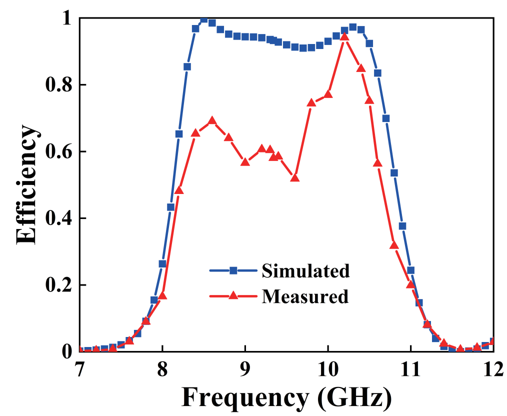

FIGURE 12. Simulated and measured radiation efficiencies of the proposed waveguide filtering antenna.

TABLE 1. Comparison of wideband waveguide filtering antennas.

Ref.	Order	f_o (GHz)	Gain (dBi)	FBW (%)	TZs	Volume /Resonators $(\lambda o)^3$
[7]	3	3.03	7.3	24	No	0.4258
[9]	3	10	7.74	13.4	No	1.0392
[11]	3	10	7.1	11.1	Yes	0.7532
This Work	3	9.3	3.53	23	Yes	0.2872

at 9.4 GHz. The measured realized gain at this center frequency is 3.53 dBi, and a TZ is clearly visible at 11.54 GHz in the upper stopband. The simulated radiation efficiency in the passband is greater than 90%; however, due to manufacturing losses, the measured radiation efficiency exceeds above 50%, as shown in Fig. 12.

The radiation patterns of the waveguide filtering antenna in both E and H-planes are measured at 8.4 GHz, 9.3 GHz, and 10.2 GHz, as shown in Fig. 13. These radiation patterns are in agreement with their simulated ones. Moreover, the measured beamwidth at f_o in the E-plane is 74°, and in the H-plane it is 90°.

In Table 1, the proposed wideband waveguide filtering antenna is compared to the other reported wideband waveguide filtering antennas in the literature. The design reported in [7] has a larger bandwidth than ours; however, there is no report of a TZ. In [11], TZs on both sides of the stopband are achieved at the expense of larger volume per resonator. Hence, this design is not suitable for applications which demand compactness. As observed, the proposed wideband waveguide filtering antenna has offered better compactness while realizing a TZ in comparison to other reported wideband waveguide filtering antennas.

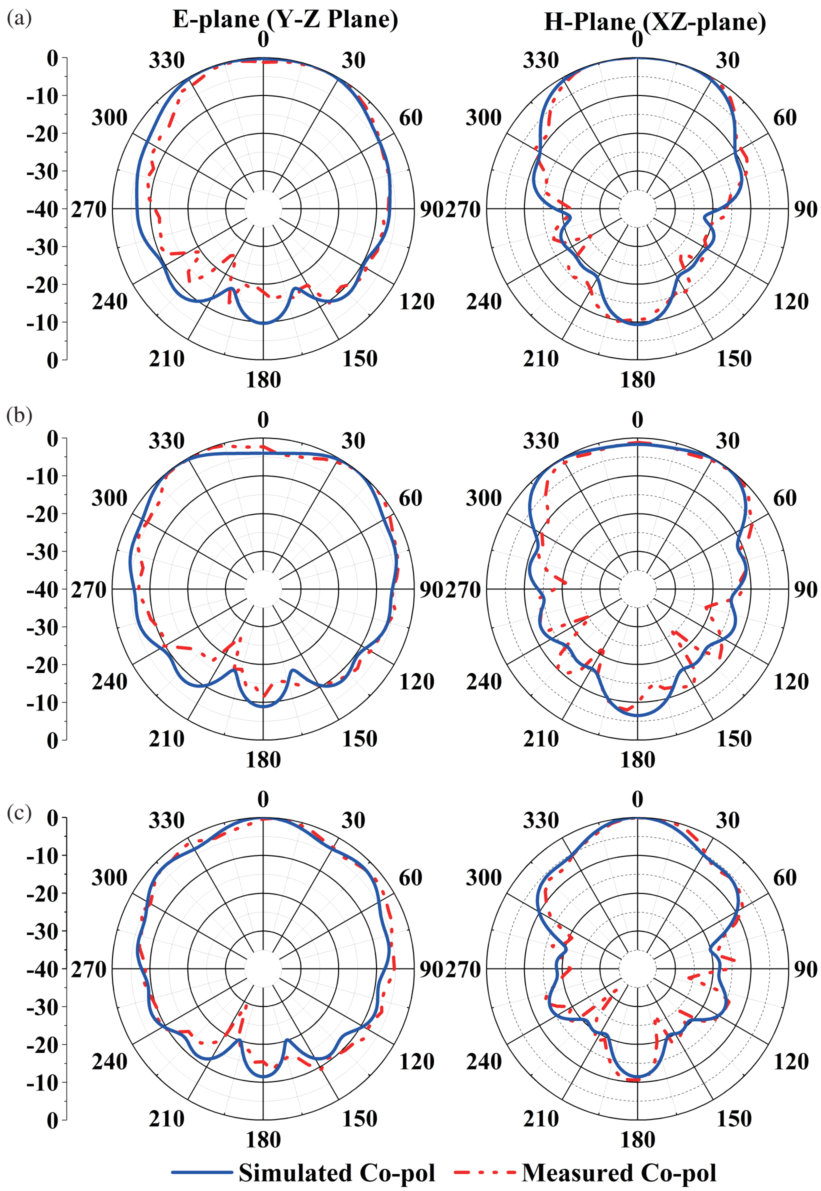

FIGURE 13. Simulated and measured radiation patterns of the filtering antenna. (a) 8.4 GHz. (b) 9.3 GHz. (c) 10.2 GHz.

5. CONCLUSION

A compact wideband waveguide filtering antenna based on an inductive singlet-based FVC inverter was presented in this letter. The compactness and TZ in the upper stopband were realized due to the proposed FVC structure, using coupled-resonator theory. The position of TZ can be altered by changing the physical parameters of the proposed FVC. The waveguide filtering antenna was manufactured monolithically by AlSi10Mg using the DMLS process. The measurement responses are in agreement with the simulated ones. The proposed waveguide filtering antenna can be utilized in those high-power applications that demand lighter weight and compactness.

REFERENCES

[1] Yusuf, Y. and X. Gong, "Compact low-loss integration of high-Q 3-D filters with highly efficient antennas," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 59, No. 4, 857–865, Apr. 2011.

[2] Mao, C. X., Y. Zhang, X. Y. Zhang, P. Xiao, Y. Wang, and S. Gao, "Filtering antennas: Design methods and recent developments," *IEEE Microwave Magazine*, Vol. 22, No. 11, 52–63, Nov. 2021.

[3] Chen, C., "A compact wideband endfire filtering antenna inspired by a uniplanar microstrip antenna," *IEEE Antennas and Wireless Propagation Letters*, Vol. 21, No. 4, 853–857, Apr. 2022.

[4] Xie, H.-Y., 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 Wireless Propagation Letters*, Vol. 20, No. 9, 1799–1803, Sep. 2021.

[5] Qi, S.-S., Y. Guo, and W. Wu, "Wideband filtering waveguide antenna based on the stepped impedance resonator," *IET Microwaves, Antennas & Propagation*, Vol. 17, No. 3, 183–189, 2023.

[6] Wertheimer, R. and L. Lewin, "Advanced theory of waveguides," *Ann. Télécommun*, Vol. 8, 312, 1953.

[7] Wu, Y.-M., S.-W. Wong, H. Wong, and F.-C. Chen, "A design of bandwidth-enhanced cavity-backed slot filtenna using resonance windows," *IEEE Transactions on Antennas and Propagation*, Vol. 67, No. 3, 1926–1930, Mar. 2019.

[8] Ludlow, P., V. Fusco, G. Goussetis, and D. E. Zelenchuk, "Applying band-pass filter techniques to the design of small-aperture evanescent-mode waveguide antennas," *IEEE Transactions on Antennas and Propagation*, Vol. 61, No. 1, 134–142, Jan. 2013.

[9] Mahmud, R. H., I. H. Salih, X. Shang, T. Skaik, and Y. Wang, "A filtering waveguide aperture antenna based on all-resonator structures," *Microwave and Optical Technology Letters*, Vol. 65, No. 8, 2378–2383, 2023.

[10] Xiang, K.-R., F.-C. Chen, and Q.-X. Chu, "High selectivity and high gain X-band waveguide filtering antenna based on triple-mode resonator," *IEEE Transactions on Antennas and Propagation*, Vol. 69, No. 10, 6953–6958, Oct. 2021.

[11] Mahmud, R. H., R. S. Jarjees, Y. Yu, E. Nugoolcharoenlap, T. Skaik, M. M. Attallah, and Y. Wang, "A monolithically printed filtering waveguide aperture antenna," *IEEE Antennas and Wireless Propagation Letters*, Vol. 22, No. 5, 1154–1158, May 2023.

[12] Sandhu, M. Y., M. Jasinski, A. Lamecki, R. Gómez-García, and M. Mrozowski, "Inline waveguide filter with transmission zeros using a modified-T-shaped-post coupling inverter," *IEEE Microwave and Wireless Technology Letters*, Vol. 33, No. 2, 145–148, Feb. 2023.

[13] Sandhu, M., M. Mrozowski, A. Lamecki, and R. Gómez-García, "Inline generalized Chebyshev dielectric waveguide filters with nonlinear frequency-variant inverters," in *2021 IEEE MTT-S International Microwave Filter Workshop (IMFW)*, 189–191, Perugia, Italy, 2021.

[14] Majeed, U. A., M. Y. Sandhu, A. Lamecki, R. Gómez-García, and M. Mrozowski, "Inline waveguide filter with compact frequency-dependent coupling producing two additional poles and three transmission zeros," in *2023 53rd European Microwave Conference (EuMC)*, 295–298, Berlin, Germany, 2023.

[15] Sandhu, M. Y., M. Jasinski, A. Lamecki, R. Gómez-García, and M. Mrozowski, "Frequency-variant double-zero single-pole reactive coupling networks for coupled-resonator microwave bandpass filters," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 72, No. 1, 321–339, 2024.

[16] Politi, M. and A. Fossati, "Direct coupled waveguide filters with generalized Chebyshev response by resonating coupling structures," in *The 40th European Microwave Conference*, 966–969, Paris, France, 2010.

[17] Matthaei, G., L. Young, and E. M. T. Jones, *Microwave Filters*, Impedance-Matching Network, and Coupling Structures, 1980.

[18] Sandhu, M. Y., A. Lamecki, R. Gómez-García, and M. Mrozowski, "Compact quasi-elliptic-type inline waveguide bandpass filters with nonlinear frequency-variant couplings," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 71, No. 11, 4933–4946, Nov. 2023.

[19] Mul, M., A. Lamecki, R. Gómez-García, and M. Mrozowski, "Inverse nonlinear eigenvalue problem framework for the synthesis of coupled-resonator filters with nonresonant nodes and arbitrary frequency-variant reactive couplings," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 69, No. 12, 5203–5216, Dec. 2021.

[20] Studio, C. M., "Darmstadt," Germany, 2009.

[21] Mahmud, R. H. and M. J. Lancaster, "High-gain and wide-bandwidth filtering planar antenna array-based solely on resonators," *IEEE Transactions on Antennas and Propagation*, Vol. 65, No. 5, 2367–2375, May 2017.