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A Monolithically Printed Filtering Waveguide Aperture Antenna

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***Abstract*—This letter presents the design of a 3rd order filtering waveguide aperture antenna based on coupled cavity resonators. Three offset-coupled rectangular waveguide cavities are employed in the design realizing two nested loaded-stubs without costing extra structure and size. The loaded-stubs introduce two controllable transmission zeroes and enhance the out-of-band realized gain selectivity. To validate the predicted results, a prototype operating at the X-band frequencies has been fabricated monolithically using the 3-D selective laser melting printing technique. The measured results are in very good agreement with the simulated results, showing a flat gain response of 7.0 ± 0.2 dBi from 9.5-10.5 GHz with very good out-of-band selectivity. The fractional bandwidth is about 10% at 10 GHz when S_{11}=-20 dB. Compared to the previously designed filtering antennas, the proposed design has the advantages of stronger out-of-band gain selectivity and low profile.**

***Index Terms*— Aperture antennas, cavity resonators, coupling matrix, filtering antennas, 3-D printing, selective laser melting, transmission zeros, waveguide.**

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I. Introduction

FILTERING antennas have received significant attention of researchers due to combining the radiation characteristics of an antenna and frequency selectivity of a Bandpass filter (BPF) all in a single component. They reduce the front-ends size of a wireless communication system, and eliminate the transition losses caused due to the matching circuits [1, 2]. The filter synthesis technique, which allows the last coupled-resonator to radiate in addition to its filtering functionality role, has been widely used in the design of filtering antennas [3-6]. Strengthening the out-of-band realized gain selectivity and enhancing the bandwidth without costing the filtering antenna an extra circuit or structure are desirable for many wireless applications.

In [7], two resonant modes excited in the resonator was to widen the bandwidth of the filtering slotline antenna. Four slots inserted into the patches of the magneto-electric dipole antenna were not only to enhance the out-of-band realized gain selectivity, but also to enlarge the impedance bandwidth [8]. The defected ground structure in the Fan-shaped patch has improved the frequency selectivity and the bandwidth to some extent [9]. A unique cross-coupling scheme employed in the cavity of the slot antenna was mainly to increase the selectivity [10]. A complementary split ring etched in a 3-D substrate integrated waveguide (SIW) filtering antenna has achieved a significant bandwidth enhancement [11]. Similarly, a double-slot coupling structure etched in the SIW slot antenna was to merge the three resonance modes and then enlarge the bandwidth [12].

In [13], two resonance windows were employed in the cavity-backed filtering slot antenna to excite three modes and enlarge the bandwidth up to 24%. However, it was at the expense of the frequency selectivity. In [14], a T-shaped resonator has introduced two additional realized gain TZs to the dual-band microstrip antenna. However, the bandwidths were extremely narrow, and the realized gains were not stable within the passbands. In [15], although the three-line coupling scheme in the fed-port of the Leaf-shaped filtering antenna has brought TZs near the passband edges, the peak gain value is 4.02 dBi which may not be sufficient. Similarly, in [16], a dual mode SIW cavity has strengthened the frequency selectivity of the filtering slot antenna. However, its bandwidth does not exceed 4.1%, and the peak gain value is 5.38 dBi.

More recently, attentions are paid to the design of filtering antennas based on 3-D high-quality (Q) cavity structures. Such structures inherently maintain stronger frequency selectivity and lower insertion losses. However, the performance sensitivity of filtering antennas to the fabrication tolerance and fabrication cost remains as two significant challenges. In [17-19], the 3-D printing techniques have adapted for the design of narrow bandwidth filtering antennas. It should be mentioned that the 3-D printing technique has numerous advantages over conventional techniques such as making the whole filtering antenna device out of a single piece. This avoids the post processing assembly issue, and eliminates losses due to the electromagnetic leakage.

In this letter, a 3rd order filtering waveguide aperture antenna based on the coupling matrix approach is designed and fabricated using the 3-D selective laser melting (SLM) printing technique. Two nested loaded-stubs are realized inside the proposed filtering antenna without increasing the size and complexity. Also, they generate two controllable TZs, and hence increase the out-of-band realized gain selectivity.

II. Coupling Matrix, Topology, and Physical Structure of Filtering Antenna

The general coupling matrix approach represents the element of a BPF and/or a filtering antenna in the form of an $N \times N$ coupling matrix [2, 20]. N is order of the filter and/or the filtering antenna. The main advantage of the approach is to create diverse topologies for the design of a filtering antenna. A novel topology and the equivalent $N \times N$ coupling matrix for the proposed filtering antenna are given below.

A. Topology and N×N Coupling Matrix

Fig. 1 shows the topology proposed for the 3rd order filtering antenna. Each black node represents a non-radiating cavity resonator, the green nodes represent the nested loaded-stubs, and the grey node represents a resonant-radiator formed of a resonator with a radiating aperture. The specifications are chosen to have a passband fractional bandwidth (*FBW*) of 10% when the reflection coefficient S_{11}= -20 dB at the center frequency f_0=10 GHz. Using these specifications, the normalized $N \times N$ coupling matrix $[m]$ can be obtained, using the general all-resonator coupling matrix synthesis technique given in [21], as follows:

$$[m] = \begin{array}{c} \begin{array}{ccc} 1 & 2 & 3 \end{array} \\ \begin{bmatrix} -0.0070 & 0.09954 & -0.1440 \\ 0.09954 & 0.1465 & 0.12996 \\ -0.1440 & 0.12996 & -0.0803 \end{bmatrix} \end{array} \qquad (1)$$

The theoretical frequency response can be calculated using the above $[m]$ matrix. The physical design parameters of the filtering antenna can be extracted from the above $[m]$ matrix using the relations in [20], which are: $M_{12} = 0.0099$, $M_{23} = 0.01299$, $Q_{ex} = Q_r = 8.516$.

B. Physical Structure

Fig. 2 shows the physical layout of the filtering antenna which is configured from three offset-coupled TE_{101} mode rectangular waveguide cavity resonators. There is a direct coupling between the input port and resonator 1 via the iris having a width of (d_0). The resonators 1 and 2 are coupled from the sides via the iris (dk_{12}). Finally, resonators 2 and 3 are coupled in series directly by the iris (d_r). Two nested loaded-stubs are realized in each of the resonator 1 and 2 due to the offset coupling structures as explained here. In each of the resonator 1 and 2, there are two paths for the signal to pass. The main path is indicated by the yellow arrow, and a secondary path indicated by red arrows. The secondary path in resonator 1 causes a 180° phase shift for the signal and thus a transmission zero is created due to the interference. This happens at the frequency at which the stub length (Z2) is 90° long. Similarly, another TZ is generated due to the secondary path in resonator 2 and it takes place at a frequency at which the stub length (Z1) is 90° long.

A great feature of the proposed waveguide cavity configuration with offset-coupling scheme is that it provides quasi-elliptic gain response with improved out-of-band selectivity. It is found the dimensions (Z_1, Z_2) can control the frequency positions of the TZs. This will be investigated in the section II-C. The design parameters obtained from the $[m]$ matrix given in section II-A can be interpreted to obtain the initial physical dimensions of the filtering antenna (d_0, d_{k12}, d_r, and l_a), using the technique presented in [2]. These dimensions are optimized later by CST simulator [22], in order to meet the calculated response, as given in the caption of Fig. 2.

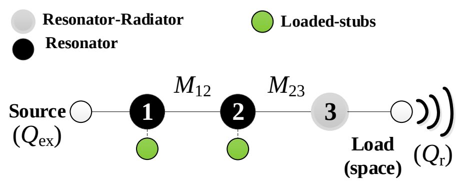


Fig. 1. Topology of the proposed 3rd order filtering antenna.

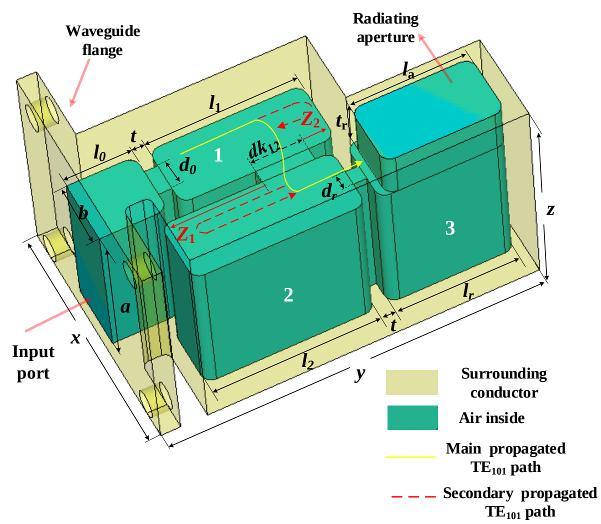


Fig. 2. Layout of the proposed filtering antenna. Dimensions in mm are: a = 22.86, b = 10.16, t = 2, t_r = 9, l_o = 10.16, d_0 = 4.5, d_{k12} = 10.6, d_r = 1.86, l_1 =24.10, l_2 =25.9, l_r =19.7, l_a = 19.6, Z_1 = 11.4, Z_2 = 2.8. The whole design dimensions excluding the embedded flange are: x = 29.34, y = 62.5, z = 33.86.

C. Simulated Results

The simulated and calculated results of the filtering antenna are shown in Fig. 3. A good agreement is observed with the ones calculated from the coupling matrix. Two TZs can be depicted on both sides of the simulated realized gain and total efficiency responses. It should be mentioned that both the simulated realized gain and total efficiency responses at the lower transition are poorer than the upper transition. This could be due to the capacitive irises used to couple the resonators which they resonate near the start band, and hence degrading the attenuation [23]. Also, the coupling iris (dk_{12}) value is relatively large, which may support different modes to propagate around the start band frequencies. The realized gain is extremely stable, having only 0.2 dBi fluctuations from 9.5 to 10.5 GHz. The peak gain is 7.1 dBi at 10.4 GHz. The total efficiency including the conductor loss is more than 95% over the passband. The *FBW* is 10% when S_{11}= -20 dB at f_0=10 GHz, and the 3-dB gain bandwidth is more than 14.5%.

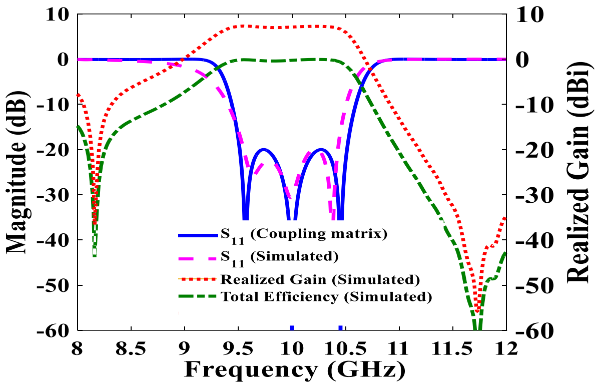
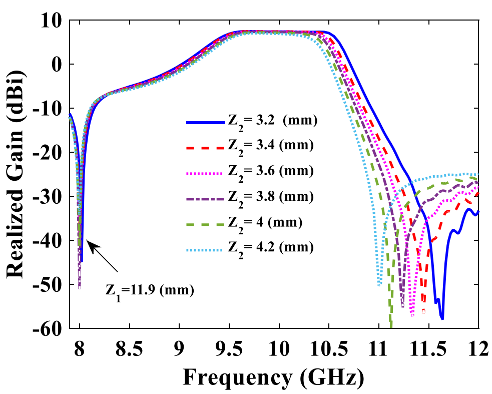
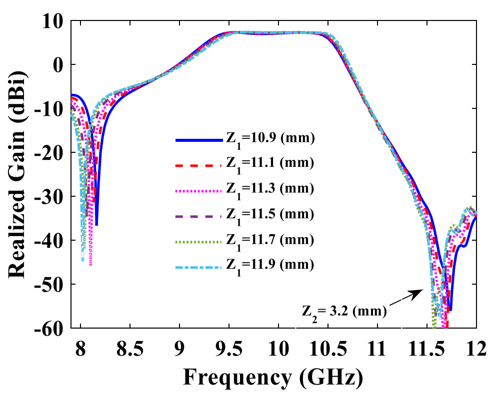


Fig. 3. Simulated and calculated response of the proposed filtering antenna.



(a)



(b)

Fig. 4. Simulated realized gain response under the influence of (a) changing Z_1, and (b) Z_2 dimensions.

The two TZs, TZ_1 at the lower transition and TZ_2 at the upper transition, can be adjusted by changing the dimensions Z_1 and Z_2 as can be observed in Fig. 4. With Z_1 fixed at 11.9 mm and changing the Z_2 value, TZ_2 can be adjusted, while TZ_1 remains unchanged as shown in Fig. 4 (a). Similarly, with Z_2 fixed at 3.2 mm and changing Z_1 value, TZ_1 can slightly be adjusted with negligible influence on the TZ_2 position. To exhibit the advantages of the proposed filtering antenna over our previous related work [24, 25], which is based on an inline 3rd order topology structure as shown in the inset of Fig. 5, a comparison is made. It can be observed that both filtering antennas have almost the same gain values within the passband. However, the proposed design has stronger out-of-band selectivity and a smaller total volume.

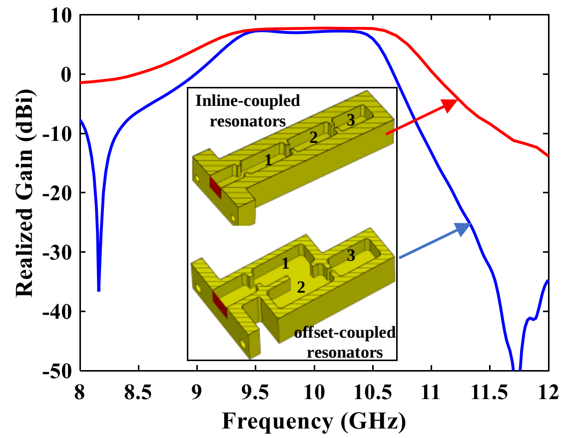


Fig. 5. The proposed and previous inline filtering antennas realized gain responses with their physical layouts.

III. Fabrication and Measurement

The proposed filtering antenna has been fabricated of stainless-steel using SLM process [26], as shown in Fig. 6. It was printed monolithically using SLM500 HL printer with a tilt angle of 45^0 to avoid overhanging structures. It is worth pointing out that this fabrication technique allows the whole design to be made from a single piece. This eliminates contact and misalignment losses.

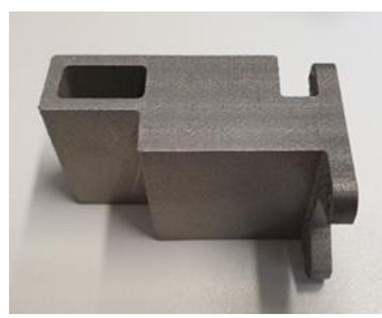


Fig. 6. Photograph of the fabricated filtering antenna.

The performance of the filtering antenna has been measured in an anechoic chamber room. The measured S_{11} and realized gain responses are compared with their simulation responses in Fig. 7. They are in very good agreement with each other. The measured S_{11} is below -18 dB over the passband, having a *FBW* of about 10%. The measured realized gain is flat over the passband, and is equal to 7.0 GHz at f_0=10 GHz. The two TZs are clearly identifiable at the start and stop bands. The inconsistency appeared round 8.5 GHz might be due to the fabrication tolerance of the 3-D printing technique. The radiation patterns for both the E- and H- planes are measured at 9.5, 10, and 10.5 GHz, as shown in Fig. 8. They agree well with the simulations. It is important to address that the inconsistency in the backside lobes is due to the waveguide adaptor, which is attached to the device during the measurement, is not counted during the simulation.

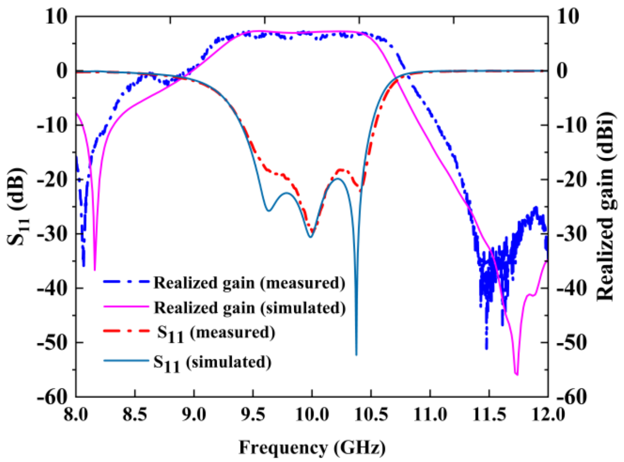


Fig. 7. Simulated and measured response of the filtering antenna.

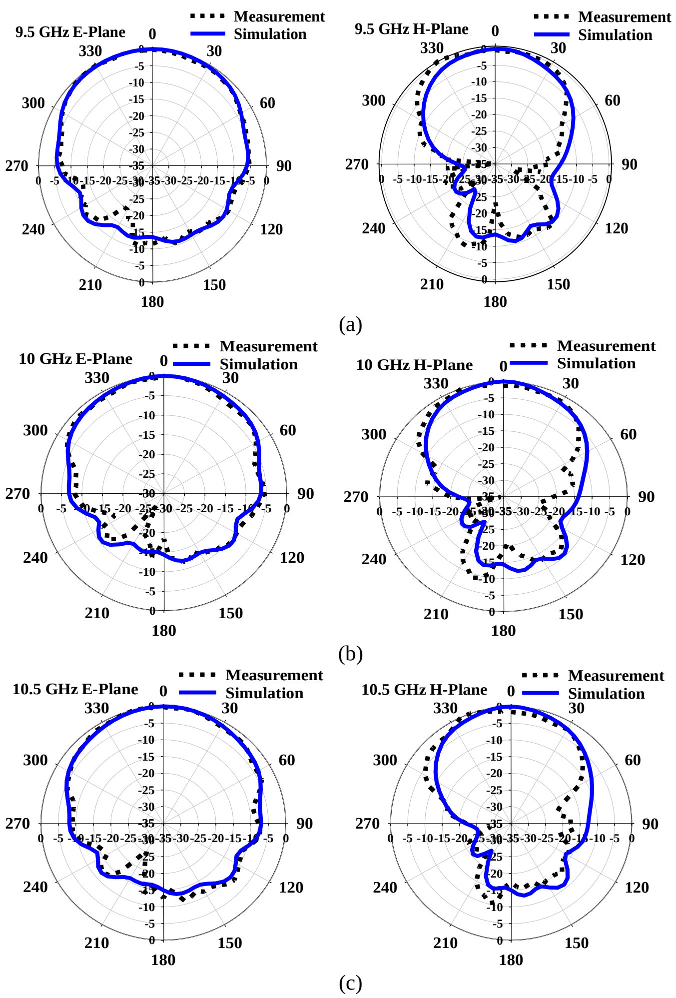


Fig. 8. Simulated and measured radiation patterns for both E- and H-planes at 9.5,10, and 10.5 GHz.

The physical and electrical properties of the proposed filtering antenna design are compared with other related designs cited herein, as shown in Table I. The design presented in [13] has a larger bandwidth, and approximately the same gain as ours. However, there are no TZs around the passband edges and the selectivity is very poor. Also, the realized gain in [18] is greater than our design. This is due to utilizing more radiating apertures than ours. But, its bandwidth is narrow and no TZs existed. Comparing to the others, our design has a better out-of-band selectivity, higher gain, and lower profile.

TABLE I
FILTERING WAVEGUIDE ANTENNAS COMPARISONS

Refs.	f_0 (GHz)	Volume (λ_0^3)*	FBW (%) at S_{11}=-10 dB	peak gain (dBi) no. of radiating element	TZs
[1]	8.1	0.42*0.26*0.87	3.7	4.5 (one)	No
[3]	2.5	0.45*0.23 *1.11	15	4.7 (one)	No
[5]	6.0	NA	8.4	6.3 (one)	Yes
[11]	2.95	0.62*0.62*0.03	6.3	6.7 (one)	No
[13]	3.03	0.97*0.89*1.48	24	7.3 (one)	No
[18]	34	1.48*3.68*3.78	2.94	12.5 (four)	No
[19]	4.85 4.6 4.75	NA NA NA	8.33 7.61 7.42	2.6 (one) 2.6 (one) 5.5 (one)	No No No
This work	10	0.97*2.08*1.12	11.1	7.1 (one)	Yes

*λ_0 is centered free space wavelength

IV. CONCLUSIONS

A high gain and wide bandwidth filtering antenna based on the coupling matrix approach was presented. Two controllable TZs were obtained due to the two loaded-stubs in which they were realized without costing extra circuit size or structure. The design was fabricated of stainless-steel using selective laser melting process. The measurements conducted for the performance of the filtering antenna were in very good agreement with the simulations. Furthermore, the design approach can be developed further and applied to filtering antenna arrays when appropriate topologies for filtering antennas are found.

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