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RESEARCH ARTICLE

Compact Self-Octaplexing Circular EMSIW Antenna for Sub-6 GHz Communication Systems

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ABSTRACT A compact eighth mode circular substrate integrated waveguide (EMSIW) self-octaplexing antenna is proposed for sub-6 GHz communication systems in this paper. The designed antenna consists of coaxial fed eight EMSIW cavity resonators arranged in circular fashion. Each EMSIW cavity resonator utilizes the fundamental TM_{010} mode of the circular SIW cavity. The designed antenna operates at eight distinct frequencies of sub-6 GHz frequency spectrum. Isolations better than 23 dB is obtained among the different ports of the designed antenna. Moreover, each frequency band of designed antenna exhibits independent tunability without affecting the other frequency bands. Each resonator of the designed antenna can be tuned to any frequency between 3-5 GHz. The self-octaplexing antenna operates at 3.35, 3.58, 3.73, 3.91, 4.09, 4.32, 4.61 and 4.96 GHz with respective gains of 4.53, 4.62, 4.67, 4.74, 3.83, 3.89, 3.42, 3.55 dBi. The proposed antenna exhibits high inter-port isolation, good radiation characteristics and compact dimensions which makes it suitable candidate for sub-6 GHz communication systems.

INDEX TERMS 8-port, antenna, coaxial fed, EMSIW, self-octaplexing, SIW, sub-6 GHz.

I. INTRODUCTION

With the advancement in emerging wireless technologies, low cost, low profile and efficient multiband antennas are in great demand to meet the requirements for the multi-standard communication systems. These multi-standard communications require multiband antenna systems that operates in several distinct frequencies for efficient utilization of available spectrum. Several single port multiband antennas are reported in the literature [1], [2], [3]. These antennas can be used either in transmit mode or in receive mode. For the simultaneous transmission and reception, multiplexers are required which not only requires external circuit elements but also make the system bulky, power consuming and increases its complexity. One of the best solutions to overcome this problem is the usage of self-multiplexing antennas. The self-multiplexing antennas offers simultaneous transmit and receive operations in different frequency bands within the compact dimensions.

Substrate integrated waveguide (SIW) technology based self-multiplexing antennas are designed and developed by the researchers utilizing its inherent characteristics such as low cost, low-profile, low loss, high inter-port isolation, high gain, unidirectional radiation characteristics and ease of integration with planar circuits [4], [5], [6], [7], [8], [9], [10], [11], [12]. These include dual-port self-diplexing antennas [4], [5], [6], [7], triple-port self-triplexing antennas [8], [9] and quad-port self-quadruplexing antennas [10], [11], [12]. These self-multiplexing antennas are generally SIW cavity backed

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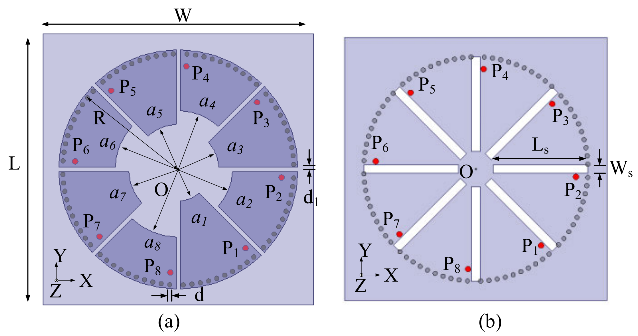

FIGURE 1. **Proposed Self-Octaplexing Circular EMSIW Antenna (a) Top view (b) Bottom view [L = 60, W = 60, R = 26.5, a_1 =7, a_2 = 12, a_3 = 9, a_4 = 13, a_5 = 10, a_6 = 14, a_7 = 11, a_8 = 15, d = 1, d1= 1, L_s = 25.6, W_s = 2, (all are in mm)].**

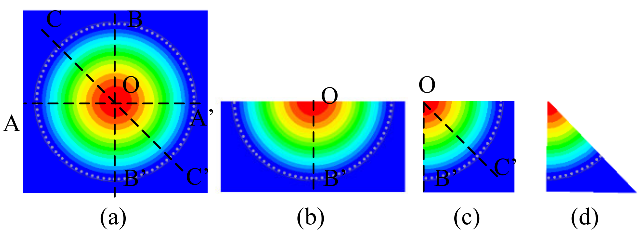

FIGURE 2. **(a) FMSIW Cavity (b) HMSIW Cavity (c) QMSIW Cavity (d) EMSIW Cavity.**

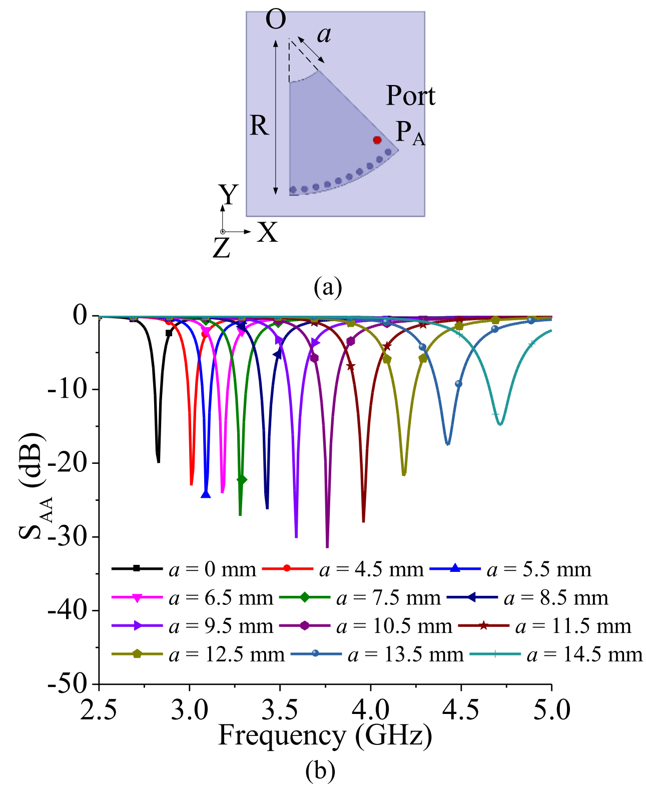

FIGURE 3. **(a) Unit element of self-octaplexing antenna (b) S-parameters for different values of *a*.**

slot antennas that utilizes different radiating slots such as rectangular slot, U-shaped slot, bow-tie slot, I-shaped slot, etc. Most of these antennas utilizes full-mode SIW (FMSIW) cavity resonators. Several miniaturized versions of FMSIW such as half-mode SIW (HMSIW), quarter mode SIW (QMSIW) are also explored for the design of compact self-multiplexing antenna systems [10], [11], [13], [14], [15], [16]. In [13], a half mode SIW (HMSIW) self-quadruplexing antenna for microwave and millimeter wave applications is presented. Four equal QMSIW cavities along with V-shaped slots of different lengths [10] and four unequal QMSIW cavities based quadruplexing antennas are designed and developed [11]. In [13], four HMSIW cavities are used for the design of self-multiplexing antenna at microwave and millimeter wave frequencies. These fractional modes of the SIW cavity resonators are also combined with other resonators to obtain self-multiplexing operations in a SIW cavity resonator. In [15], HMSIW, QMSIW cavities are combined with two patches in a rectangular SIW cavity to obtain self-quadruplexing antenna. Recently, self-pentaplexing [14] and self-hexaplexing [15], [16], [17] antennas are also reported in the literature. In [14], two QMSIW cavity resonators and three microstrip patches are utilized for the design of self-pentaplexing antenna operating at the five distinct frequencies which lies in 2.29 GHz to 5.08 GHz.

A hexagonal SIW cavity based self-hexaplexing is designed and developed in [15]. In [16], a self-hexaplexing antenna operating in S- and C-bands is presented that utilizes TE_{110}, TE_{120} and TE_{210} modes of the rectangular SIW cavities. In [17], a SIW based hexaplexing antenna operating in C- and X-band is designed which utilizes four square-like quarter-mode SIW (SQMSIW) resonators, and two triangular quarter-mode SIW (TQMSIW) resonators. In [21], another self-hexaplexing antenna operating in sub-6 GHz is reported which utilizes 1/6th mode of the hexagonal SIW cavity.

Nowadays, the wireless communication systems require a greater number of channels to meet ever increasing demands for the efficient utilization of the available spectrum. Hence, the development of antennas with greater than six bands for self-multiplexing capability is still a challenging task. The main challenges are attaining good inter-port isolation, independent frequency tunability, high gain in a given footprint and simpler design. This motivates the authors to design and develop a simple low-profile self-multiplexing antenna with more than six frequency bands. Two self-octaplexing antennas [18], [19] which operates in eight distinct frequency bands are reported in the literature recently. The article in [18] presents the eighth mode SIW self-multiplexing antenna for sub-6 GHz wireless applications. This self-multiplexing antenna has the limitations that it has too many design parameters to obtain frequency tunability i.e. the slot length and the slot position needs to be changed to obtain the desired operating bands. Also, it has another constraint that each band can be tuned within a certain frequency range. There are constraints on the tunability range for each band due

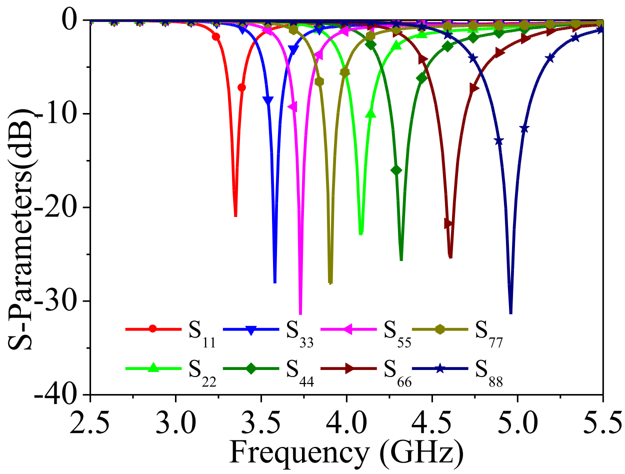

FIGURE 4. S_{ii}-parameters of the designed self-octaplexing antenna (i=1,2,3…8).

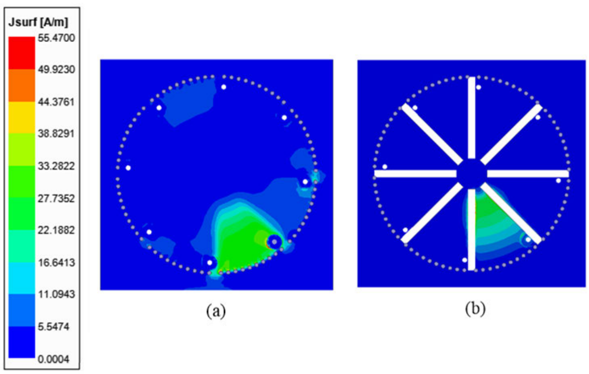

FIGURE 5. Surface current distribution in the ground plane with port P1 excitation at 3.35 GHz (a) Without ground slots (b) With ground slots (other remaining ports are terminated with matched loads).

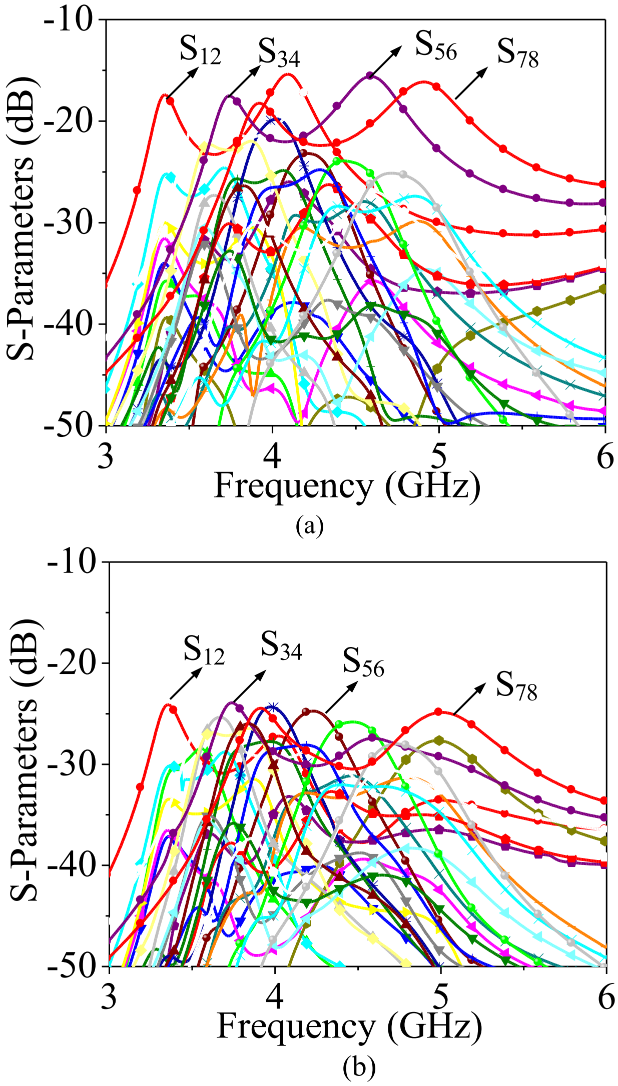

FIGURE 6. S_{ij}-parameters of the designed self-octaplexing antenna (i,j=1,2,3…8, i≠j) (a) Without ground slots (b) With ground slots.

to their dependence on various design parameters. They have provided a look-up table for each frequency band. Thus, this dependence on various design parameters makes the system quite complex. Moreover, the overall size of this antenna is $0.019\lambda_g^3$.

The paper in [19] presents SIW-based tunable self-octaplexing antenna has an overall size of $0.0242\lambda_g^3$.

Different solid materials of different permittivities are placed into specific carved region to obtain the tunability of the frequency bands. These carved regions are of depth 0.5 mm in the substrate thickness of 0.787 mm that results in the complex system design with complex fabrication along with higher cost. One of the major aspects of antenna geometry is its complexity, which should be preferably low, that makes the design simple, cost-efficient and ensure its utility in the practical environment.

In this article, an eighth mode circular EMSIW cavity based self-octaplexing antenna for sub-6 GHz communication systems is presented. It is realized using eight 1/8th part of circular SIW cavity. The designed self-octaplexing antenna operates at eight distinct frequencies of sub-6 GHz which can be independently tuned without affecting the other bands. The antenna operates at 3.35, 3.58, 3.73, 3.91, 4.09, 4.32, 4.61 and 4.96 GHz with respective gains of 4.53, 4.62, 4.67, 4.74, 3.83, 3.89, 3.42, 3.55 dBi. Moreover, good inter-port isolation (>23 dB) is also observed in the designed antenna. The proposed self- octaplexing antenna has the overall volume of $0.0129\lambda_g^3$, where λ_g is the guided wavelength at the lowest operating frequency. Compared to previous research, our proposed structure has salient key features:

1. It has maximum multiplexing capability (up to eight distinct frequency bands) along with acceptable isolation, with respect to the existing self-multiplexing antennas [10], [11], [13], [14], [15], [16], [17].
2. The design antenna is quite simple with few design parameters that makes it less complex and therefore cost-efficient.

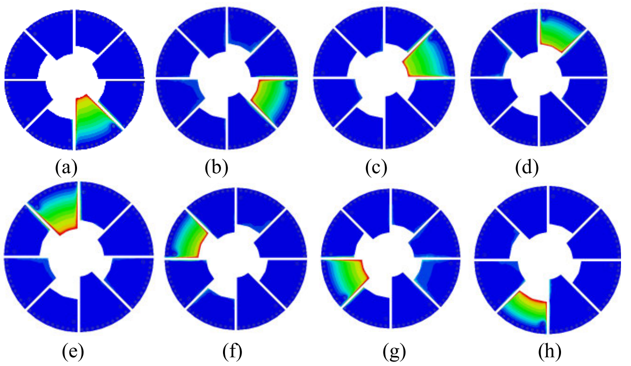

FIGURE 7. E-field distribution for (a) P_1 ON (b) P_2 ON (c) P_3 ON (d) P_4 ON (e) P_5 ON (f) P_6 ON (g) P_7 ON (h) P_8 ON at their respective operating frequencies.

3. Compared to other reported works [18], [19], that requires too many design parameters alteration for frequency tunability, the resonant frequencies in our proposed antenna structure can be altered by varying only one dimension (a's) of the resonator.
4. It also provide the flexibility that any resonator can be tuned to any frequency between 3.0 GHz to 5.0 GHz, while other reported works have the constraints for tuning of each resonator [18], [19].
5. The overall size of this antenna is $0.0129\lambda_g^3$, which is smaller than the other reported self-octaplexing antennas [18], [19].

II. ANTENNA CONFIGURATION

Fig. 1 shows the geometrical configuration of the proposed self-octaplexing circular EMSIW antenna. It is designed on Rogers RT/duroid 5880 substrate with a thickness of 1.57 mm, dielectric constant 2.2 and loss tangent of 0.0008. Each element of self-octaplexing antenna is sector-shaped along with a series of metallic vias at its periphery which act as the electric wall of EMSIW cavity resonator. The sector shaped antenna elements are fed through eight coaxial ports named as Port P_1, Port P_2,….Port P_8. The adjacent sectors are d_1 distance apart. Further, the eight rectangular slots of dimensions (L_s, W_s) are also engraved in the ground plane of self-octaplexing antenna to enhance the isolation between the adjacent ports.

III. OPERATIONAL MECHANISM

In this section, the unit element of the self-octaplexing antenna is presented and working mechanism is discussed in detail.

A. EMSIW CAVITY RESONATOR AS A UNIT ELEMENT

Circular SIW cavity resonators are widely used for the design of planar antennas. The resonant frequency of fundamental TM_{010} mode of circular SIW cavity can be evaluated as follows:

$$f_{TM_{010}} = \frac{2.405c}{2\pi R_{eff}\sqrt{\varepsilon_r}} \quad (1)$$

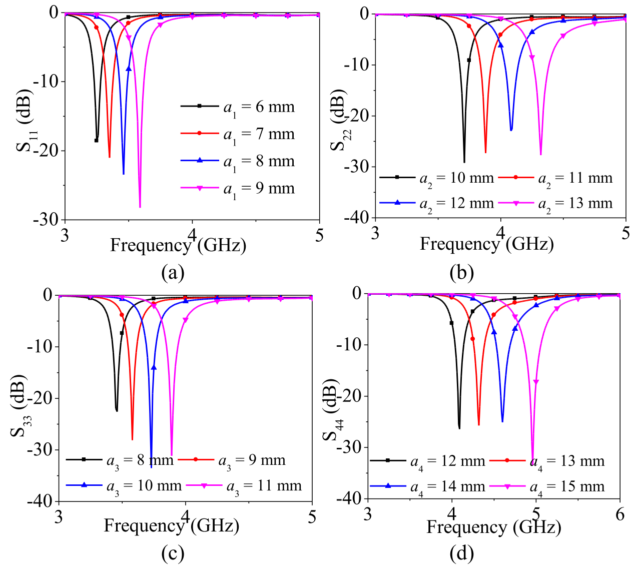

FIGURE 8. Parametric analysis for different parameter (a) a_1 (b) a_2 (c) a_3 (d) a_4.

where R_{eff} is the effective radius of circular SIW cavity, ε_r is the relative permittivity of the substrate and c is speed of light in free-space [20]. R_{eff} can be calculated from the following expression [21]:

$$R_{eff} = R_c - \frac{d^2}{1.9s}$$

where R_c is the radius of circular SIW cavity , d is the via diameter and s is the separation between two vias.

For the design of miniaturized components, miniaturized versions of the SIW cavity resonators such as half mode SIW (HMSIW), quarter mode SIW (QMSIW) and eighth mode SIW (EMSIW) are preferred over the full-mode SIW (FMSIW) cavity resonators. These miniaturized versions not only offer size reduction but also preserves the modal characteristics. An HMSIW cavity is constructed by bifurcating a FMSIW cavity along the symmetrical plane AA' by applying fictitious magnetic wall concept as shown in Fig. 2 (a). Further, bisecting the HMSIW cavity along the symmetrical plane OB' give rise to QMSIW cavity [Fig. 2(b)]. Finally, the unit element of self-octaplexing antenna, i.e. circular EMSIW resonator is created by bisecting QMSIW resonator along the symmetrical plane OC' [Fig. 2(c)]. This circular EMSIW resonator is only 12.5% of the original FMSIW resonator leading to 87.5% size miniaturization [Fig. 2(d)].

The circular EMSIW resonator is fed through the coaxial port to obtain unit element of proposed self-octaplexing antenna. Fig. 3 shows the coax fed unit element along with its S-parameters. It resonates at 2.84 GHz using TM_{010} mode ($a = 0$). For self-octaplexing operation, each of the EMSIW unit element must operates at a distinct frequency. To obtain these distinct frequencies, a sector of radius a is etched out from the top surface of the EMSIW resonator as shown in Fig. 3 (a). As the value of a increases, the effective

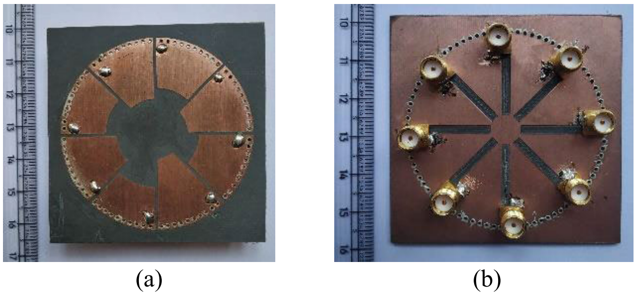

FIGURE 9. Fabricated prototype (a) Top view (b) Bottom view.

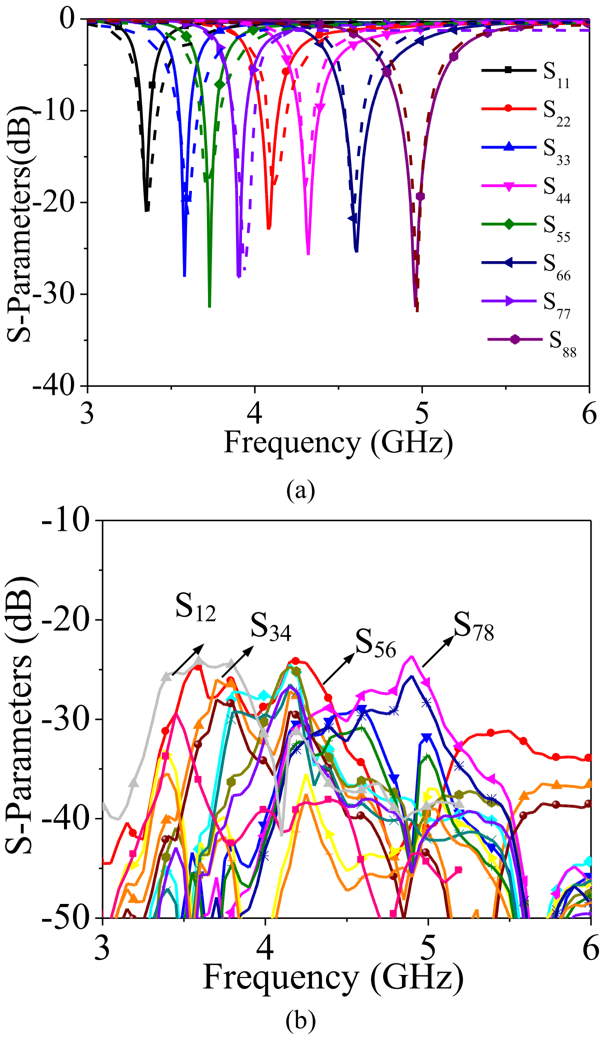

FIGURE 10. (a) Simulated (solid line) and measured (dashed line) S_{ii}-parameters (i=1,2…8) (b) Measured S_{ij}-parameters (i≠j, i,j=1,2….8).

dimensions of the unit element decreases that in-turn shifts the resonant frequency to a higher value. Thus, by varying the value of a, the different frequencies of EMSIW cavity resonator can be obtained for self-octaplexing operation as shown in Fig. 3(b).

B. PROPOSED SELF-OCTAPLEXING EMSIW ANTENNA

The proposed self-octaplexing antenna uses the basic unit element as EMSIW resonator designed in the above sub-section. These elements are arranged in circular manner with inter-element separation d_1 to accommodate all the miniaturized EMSIW resonators in a compact environment with low mutual coupling among them. Fig. 1 shows the designed self-octaplexing circular EMSIW antenna which operates at eight closely-spaced sub-6 GHz frequency bands. These distinct frequencies are obtained by choosing the different values of a in each circular EMSIW resonator. However, the value of a of the adjacent EMSIW resonators are chosen in such a way that they have at least 400 MHz frequency separation which ensures self-octaplexing operation along with good inter-port isolation.

Fig. 4 shows the simulated S-parameters of the self-octaplexing antenna. The self-octaplexing antenna operates at 3.35 GHz (P_1 ON), 4.09 GHz (P_2 ON), 3.58 GHz (P_3 ON), 4.32 GHz (P_4 ON), 3.73 GHz (P_5 ON), 4.61 GHz (P_6 ON), 3.91 GHz (P_7 ON), 4.96 GHz (P_8 ON). The eight rectangular slots of dimensions (L_s, W_s) are also etched in the ground plane to enhance the isolation between the adjacent ports. Fig. 5 shows a comparison between the surface current distribution on the ground plane without and with rectangular slots under Port P_1 excitation at 3.35 GHz. When these rectangular slots are not present in the antenna structure, a significant amount of surface currents flows from port P_1 to other remaining ports [as shown in Fig. 5(a)], which is due to electromagnetic coupling between the Port P_1 and other remaining ports, which results in lower isolations. On the other hand, with the introduction of rectangular slots, the surface currents accumulate near the edges of the rectangular slots that prevents the flow of electromagnetic energy from Port P_1 to other remaining ports, which results in high port-to-port isolations [Fig. 5(b)]. It is also clear from Fig. 6 (a) that the isolations among all the ports is better than 18 dB without rectangular slots. With the introduction of ground slots, the isolation among the ports is better than 23 dB [Fig. 6(b)], which guarantees that proposed antenna is a potential candidate for self-multiplexing operations for sub-6 GHz communications.

C. E-FIELD DISTRIBUTION AND PARAMETRIC ANALYSIS

The electric field distributions under each port excitation of the designed self-octaplexing antenna at their corresponding operating frequencies are shown in Fig. 7 for proper understanding of the antenna characteristics. All the remaining other ports are terminated with 50 Ω matched loads. It can be visualized from the E-field distribution that the sector shaped antenna element radiates through the open-ended region of EMSIW resonator with the excitation of modified fundamental TM_{010} mode. Moreover, it can also be noted from the E-field distributions that the proposed self-octaplexing antenna is linearly polarized even if the orientation of the surface currents and its respective alignment varies from one port to another. Under the respective port excitation,

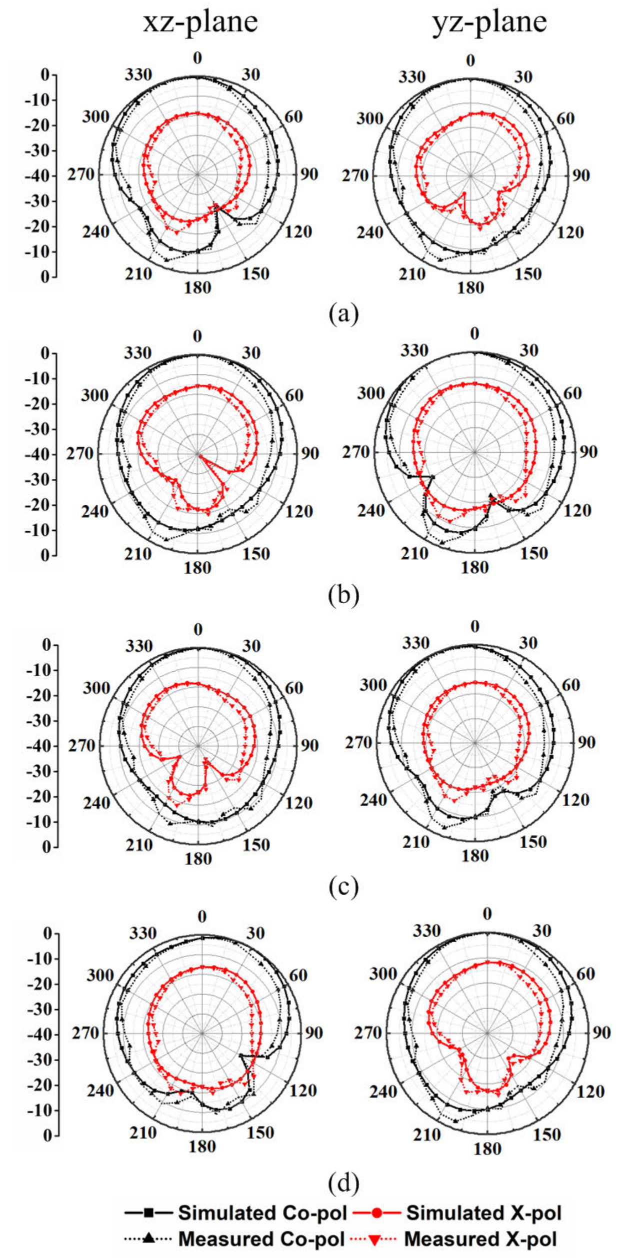

FIGURE 11. Radiation pattern (a) P_1 (b) P_2 (c) P_3 (d) P_4 at their respective operating frequencies.

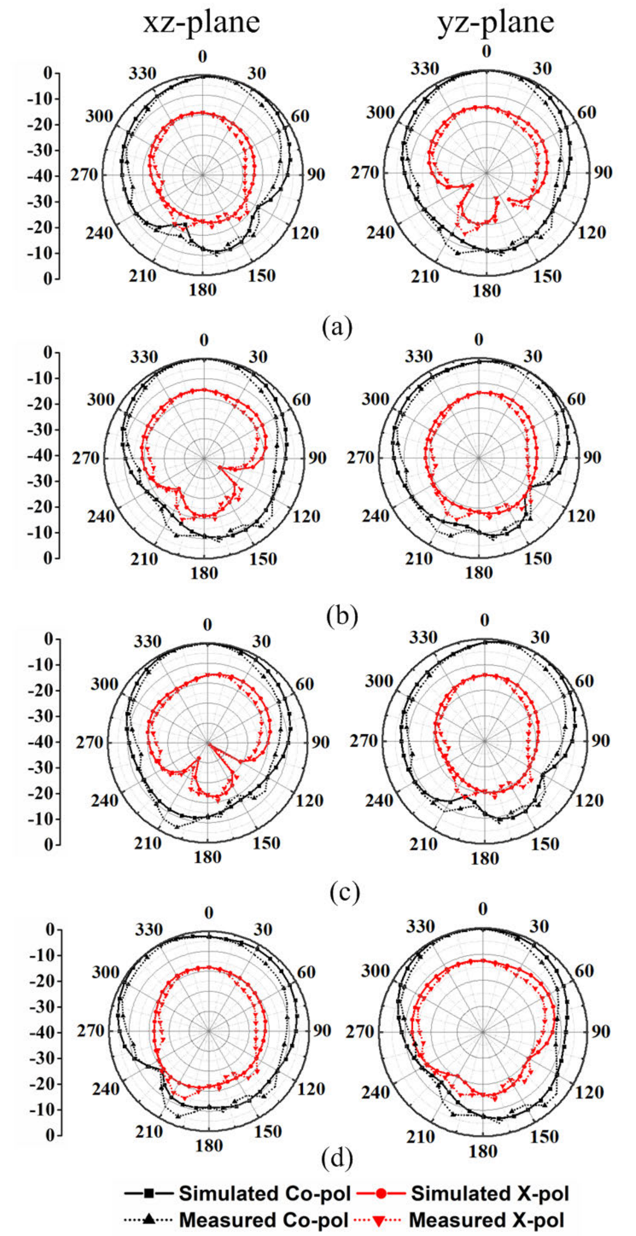

FIGURE 12. Radiation pattern (a) P_5 (b) P_6 (c) P_7 (d) P_8 at their respective operating frequencies.

the electric fields are present only on the active EMSIW resonator with negligible fields present on the other remaining EMSIW resonators, resulting in good isolation between the ports.

To demonstrate the independent frequency tunability of each operating band, a parametric analysis of only first four design parameters (a_1, a_2, a_3, a_4) are performed for brevity and their corresponding simulated results are plotted in Fig. 8. During the simulations of the concerned parameters, all other remaining design parameters are kept constant. It is clear from the figures that as the value of a_i's increases, the effective dimensions of the corresponding EMSIW cavity decreases which in-turn shifts the resonant frequency to a higher value providing independent frequency tunability.

IV. EXPERIMENTAL RESULTS

As a proof of concept, the designed self-octaplexing EMSIW antenna is fabricated and its characteristics are evaluated. It is fabricated on low loss RT/duroid 5880 substrate with dielectric constant 2.2, thickness 1.57 mm and loss tangent 0.0008 using standard PCB fabrication techniques. The top and bottom views of the fabricated prototype of self-octaplexing antenna is shown in Fig. 9.

TABLE 1. Comparison table.

Ref.	Freq. (GHz)	Min. Iso. (dB)	Gain (dBi)	Efficiency (%)	vol. (λ_g^3)	No. of Bands
[13]	8.19,8.8,9.7,11	22	5.5,6.9,7.47,7.45	NA	0.0119	4
[10]	2.45,3.5,4.9,5.4	29	3.85,5.33,5.95,5.97	85-90	0.0640	4
[11]	4.35,5.35,5.9,6.75	27	4.04,4.48,4.55,6.12	>82	0.0031	4
[14]	2.29,2.98, 3.65,4.37,5.08	29	3.59,4.55, 3.91,5.7,4.92	80-92	0.0034	5
[15]	5.33,5.76,6.31, 6.86,7.34,7.8	24	4.5,4.94,4.9, 5.12,6.12,6.6	NA	0.0155	6
[16]	2.29,2.96,4.30, 5.0,5.61,6.18	27	3.73,4.35,5.57, 5.46,5,4.73	NA	0.0030	6
[17]	4,5.8,6.6, 7.8,9.8,10.62	27	4.9,5.11,5.4, 5.43,5.32,5.3	>94	0.0023	6
[18]	5.15,5.67,6.18,6.6, 7.18,7.85,8.25,8.85	20	3.9,3.2,4.05,4.14, 3.8,3.37,3.55,3.28	85-95	0.0242	8
[19]	3.54,3.81,4.12,4.5, 4.85,5.22,5.5,5.87	30	4.07,4.3,4.72,5.11, 4.43,4.51,4.97,4.47	65-80	0.0193	8
Prop.	3.35, 3.58, 3.73, 3.91, 4.09, 4.32, 4.61, 4.96	23	4.53, 4.62, 4.67, 4.74, 3.83, 3.89, 3.42, 3.55	>85	0.0129	8

λ_g is the guided wavelength at the lowest operating frequency, NA: Not available,

For measurement purpose, the SMA connectors are soldered in each of the EMSIW cavity. The S-parameters of the fabricated self-octaplexing antenna are measured using Agilent VNA 5071C, while the radiation pattern is measured in the anechoic chamber. The simulated and measured $|S_{ii}|$ parameters, where $i = 1, 2, \ldots 8$, are plotted in Fig. 10(a). During the measurement of S_{ii}, the i^{th} is port is excited while remaining ports are terminated with 50 Ω matched loads. The simulated resonant frequencies are 3.35, 3.58, 3.73, 3.91, 4.09, 4.32, 4.61, 4.96 GHz while the measured ones are 3.38, 3.62, 3.76, 3.98, 4.12, 4.34, 4.63 and 4.98 GHz, respectively. There is slight shift in the measured resonating frequencies compared with the simulated ones, which can be attributed towards fabrication tolerances. The measured isolations between the adjacent ports of self-octapelxing antenna is better than 23 dB, whereas isolation among other ports is better than 25 dB [Fig. 10(b)].

Fig. 11 and Fig. 12 shows the simulated and measured far field radiation 2D radiation-pattern plots in both the E- and H-plane of the designed self-octaplexing antenna. The designed antenna possesses relatively high cross-pol. It can used in devices for indoor communications, where the wireless channel is mostly multipath. Due to the cavity backed configuration, the designed self-octapelxing antenna has unidirectional radiation characteristics. The peak realized gains of the self-octaplexing antenna are 4.53, 4.62, 4.67, 4.74, 3.83, 3.89, 3.42, 3.55 dBi at 3.35, 3.58, 3.73, 3.91, 4.09, 4.32, 4.61, 4.96 GHz, respectively and the radiation efficiencies of all the ports are better than 85%.

To demonstrate the merits of the designed self-octaplexing antenna, it is compared with other state-of-the-art works. Table 1 shows the performance comparison of proposed antenna with other self-multiplexing antennas reported in the literature.

The antennas in [10], [11], [13], [14], [15], and [16], provide self-multiplexing characteristics less than eight distinct frequency bands while self-multiplexing antenna in [18] and [19] can operate in eight distinct frequency bands. The self-multiplexing antenna in [18] has the limitations that it has too many design parameters to obtain frequency tunability i.e. the slot length and the slot position needs to be changed to obtain the desired operating bands. Also, it has another constraint that each band can be tuned within certain frequency range. Whereas different solid materials of different permittivities are placed into specific carved region to obtain the tunability of the frequency bands in [19]. These carved regions are of depth 0.5 mm in the substrate thickness of 0.787 mm that results in the complex system design and fabrication along with higher cost.

Thus, the designed antenna has maximum multiplexing capability, acceptable isolation, simpler design with few design parameters and provides the flexibility that any resonator can be tuned to any frequency between 3.0 GHz to 5.0 GHz. Moreover, the overall size is $0.012\lambda_g^3$, which is smaller than the other reported self-octaplexing antennas [18], [19].

The proposed self-octaplexing antenna operates in the different NR bands (n46, n78, n79) therefore being suitable for various communication system applications. The designed self-octaplexing antenna can also be beneficial for various commercial wireless applications such as WLAN (at 5.0 GHz), standard C-band (3.625–4.200 GHz), extended C-band (3.400-3.700 GHz), super-extended C-band (3.400–3.625 GHz), LMI-C-band (3.700–4.000 GHz), the terrestrial component of IMT (4.80-4.99 GHz), radio navigation services (4.20- 4.40 GHz), point-to-point links and telemetry applications (4.40-4.50 GHz).

V. CONCLUSION

In this paper, a compact 8-port self-octaplexing EMSIW antenna for sub-6 GHz frequency bands is presented. The designed self-octaplexing antenna operates in eight distinct frequencies lies from 3 GHz to 5 GHz. Each band of the self-octaplexing antenna can be independently tuned to any frequency between 3.0 GHz to 5.0 GHz, while other reported works have the constraints for tuning of each resonator. With the usage of EMSIW resonator as a unit element, the designed antenna is only 12.5% in size with respect to full mode SIW (FMSIW) cavity resonator.

Moreover, the separation between the EMSIW unit elements along with rectangular slots etched on the ground plane provides good isolation better than 23 dB. The self-octaplexing operates at 3.35, 3.58, 3.73, 3.91, 4.09, 4.32, 4.61, 4.96 GHz with the corresponding peak gains of 4.53, 4.62, 4.67, 4.74, 3.83, 3.89, 3.42, 3.55 dBi. The self-octaplexing characteristics across the eight closely placed distinct sub-6 GHz bands with good isolation, independent tunability and high peak gains with compact environment makes the proposed self-octaplexing antenna a good candidate for sub-6 GHz communication systems.

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