Design of a Compact HMSIW Cavity-Backed Dual-Band 4-Port MIMO Antenna

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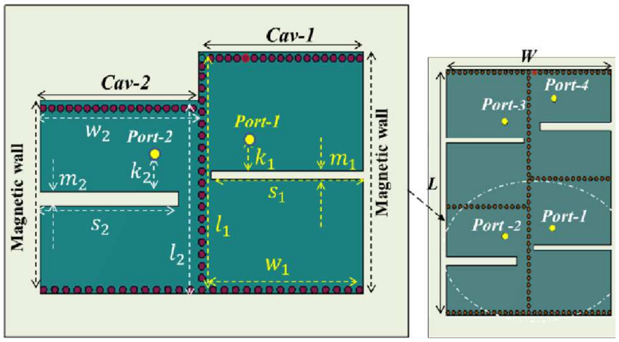
***Abstract*— In this article, a novel, compact, dual-band 4-elements multi-input and multi-output (MIMO) antenna diplexer is investigated, prototyped, and tested. The proposed design is based on a planar half-mode Substrate Integrated Waveguide (HMSIW) technology, that diminishes size by 50% than of full-mode Substrate Integrated waveguide (FMSIW) cavity. Later, to enhance the bandwidth around 50%, a rectangular slot is introduced at the center of each cavity. The slot splits the dominant mode half-TE$_{110}$ into an odd- and even-modes. The proposed antenna resonates at 3.3 GHz and 3.4 GHz when either *Port-1* or *Port-3* is fed, and *Port-2* or *Port-4* are terminated with matched loads. Similarly, the antenna operates at 4.2 GHz and 4.3 GHz, either *Port-2* or *Port-4* is fed, and the rest are matched terminated. The intrinsic isolation between any two ports is achieved below -23 dB with an antenna footprint of 1.0λ_l × 0.8 λ_l. The average gain in the lower and upper frequency bands are around 5.15 dBi and 6.1dBi, respectively while radiation efficiency is more than 80% in both frequency bands. The envelope correlation coefficient (ECC) of the MIMO antenna has been achieved < 0.13, directive gain (DG) around 9.9 dBi, and mean effective gain (MEG) around -3.05 dB in both frequency bands.**

Keywords—Isolation, multi-input multi-output (MIMO), half-mode substrate integrated waveguide (HMSIW), envelop correlation coefficient (ECC)

I. INTRODUCTION

In cell phone communication, the degradation of signals due to multipath propagation is a critical issue. This limitation can be easily overcome by utilizing a multi-input multi-output (MIMO) antenna system. This technology improves communication reliability with spatial diversity and channel capacity with spatial multiplexing by utilizing an additional level of processing power [1-2]. The enhanced channel capacity allows for transferring more data between transmitter and receiver at the same time. Nowadays, Wi-Fi, LTE, and other RF technologies use MIMO antennas to enhance link capacity and spectral efficiency [3]. Despite all the advantages, MIMO antennas occupy a larger space which restricts it from adding further radiating elements. Therefore, antenna elements with compact size and higher isolation levels among the channels [4, 5] are always demanded to accommodate in limited space. In literature [4-13], numerous MIMO antennas have been reported with improved isolation levels. In [4], the isolation is improved by using PBG, creating filed cancellation between two radiating elements in [5], using cross-neutralization lines [6], and introducing an L-shaped radiating slot in [7]. A compact MIMO antenna is investigated using eight-mode sub cavities, however, it shows poor isolation (i.e., < 20 dB) [8]. Moreover, the modern wireless communication demands the compact RF-seamless connectivity between transmitter and receiver. To ease the connectivity between transmitting/receiving channels with dedicated self-isolated ports, self-diplexing antenna is considered an important element to enhance the performance of whole RF module. [9-11]. It avoids a separate filtering network for each antenna which makes the whole design simple and compact [12,13]. In recent times, Substrate Integrated Waveguide (SIW) [14] technology has attracted a lot of attention to realize microwave components in a planar laminate. The half-mode substrate integrated waveguide (HMSIW) has gained special attention as it offers the realization of a planar low-profile structure in half of the space as compared to the full-mode substrate integrated waveguide (FMSIW) cavity [15]. In literature [16-20] many self-diplexing antennas have been investigated with compact size, however, they suffer from narrow bandwidth response due to excitation of dominant mode in a single resonance. In [16], the bandwidth is improved by coupling of modes, but it covers a larger size. The bandwidth is improved by different methods in HMSIW-inspired structures [17-18], however, these studies are limited only to 2-elements antenna. In this paper, a dual-band self-diplexing 2×2 elements MIMO antenna is designed and developed to operate around 3.4 GHz (3.35-3.55 GHz) in TD-LTE system and 4.2 GHz (4.1-4.3 GHz) in FCC ID WLAN for LTE frequency bands in 5G communication. The size is



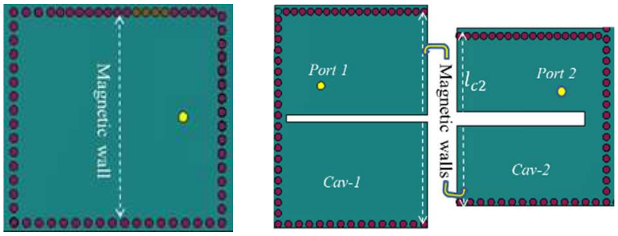
(a) (b)

Fig. 1. Schematic diagram of self-diplexing antenna, Dimensions ($w_1 = w_2 = 26.5$, $l_1 = 35.5$, $l_2 = 28.5$, $s_1 = 24.5$, $s_2 = 22.3$, $k_2 = 5.3$, $k_1 = 4.3$, $m_1 = 1.2$, $m_2 = 2.2$, $d = 1$, $s = 2$, $L = 64$, $W = 52$) (Units: mm), (b) Schematic diagram of 2×2 MIMO antenna

minimized up to half by employing HMSIW cavities while bandwidth is enlarged up to double by placing the slots at the center of each cavity, which excites odd- and even-half-TE_{110} modes in proximity. The MIMO properties of the proposed antenna have been evaluated in terms of envelope correlation coefficients (ECC), diversity gain (DG) and mean effective gain (MEG) [19]. The proposed antenna maintains decoupling among the elements below -23 dB, the peak value of ECC is 0.13, DG around 9.9 dB, and MEG around -3.05 dB. The self-diplexing property, low profile, planar configuration, simple design, and easy flexible tuning of resonant frequencies make the proposed antenna exceptional alternative. Moreover, the proposed MIMO antenna demonstrate better radiation properties in both frequency bands.

II. TWO-PORT SELF-DIPLEXING ANTENNA DESIGN PROCESS

The HMSIW cavity-backed antenna-diplexer and its designing steps have been demonstrated in Fig. 2. Initially, the dimensions of an FMSIW cavity have been selected as 53×36 mm^2 to excite the dominant mode around 3.5 GHz using equations stated in [12]. Later, the dimensions of the half-mode SIW cavities are evaluated from SIW cavity equations stated in [14]. The dimensions of the *Cav-1*(i.e., w_1, l_1) and *Cav-2* (i.e., w_2, l_2) are selected to obtain the resonant frequencies around 3.4 GHz in the lower frequency band and 4.3 GHz in the upper frequency band, respectively. The sidewalls of the SIW cavity are realized by implanting the chain of shorting vias that connects the top and bottom metallic claddings. The leakage of energy through the metallic vias is diminished by maintaining the specific conditions for the diameter (d) and pitch distance (p) of the vias are $d/s \geq 0.5$ and $d/\lambda_o \leq 0.1$ [20]. To accomplish adequate intrinsic isolation between the ports (typically 22 dB) between the ports, the magnetic walls are placed 180° phases apart while cavities share the common electric walls. To enlarge the bandwidth by maintaining the same size and thickness, the rectangular slots of different dimensions are inserted at the center of each cavity. The slots split the half-TE_{110} mode into odd- and even- modes in close vicinity. When *Port-1* is fed and *Port-2* is terminated with matched load, the odd mode excites at 3.4 GHz and even mode at 3.5 GHz in *Cav-1*. On the other hand, when *Port-2* is fed and *Port-1* is terminated with matched load, the odd and even modes are getting excited at 4.3 and 4.4 GHz, respectively in *Cav-2*. The odd- and even- half TE_{110} modes can be observed from vector E-field distribution in Fig. 3. The odd half-TE_{110} mode consists of filed distribution out of phase in two sections of the cavity, while the even mode shows an in-phase fields in both sections of the cavity across the slots. The slot plays a key role in improving the bandwidth in both lower and upper frequency bands. The position of the slot from the feed plays an important role in the impedance matching of resonant frequencies in each frequency band. If the distance between the slot and feed (k_1) is decreased from 4.25–3.75 mm, the impedance matching is getting improved. A similar behaviour can be observed, if k_2 is varied in the range of 5.5– 5 mm, the impedance matching is improved,



(a) (b)

Fig. 2. Evolution of proposed dual-element HMSIW antenna: (a) FMSIW cavity with single port (b) HMSIW cavity resonators loaded with rectangular slots

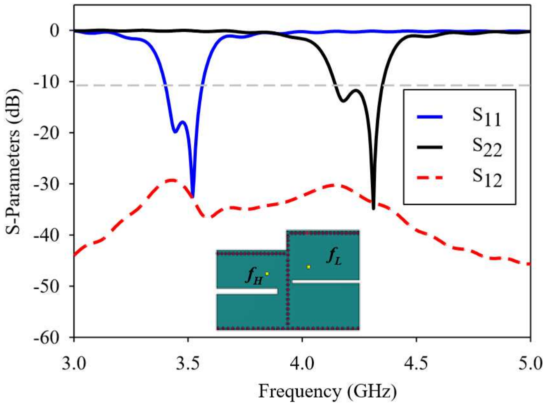
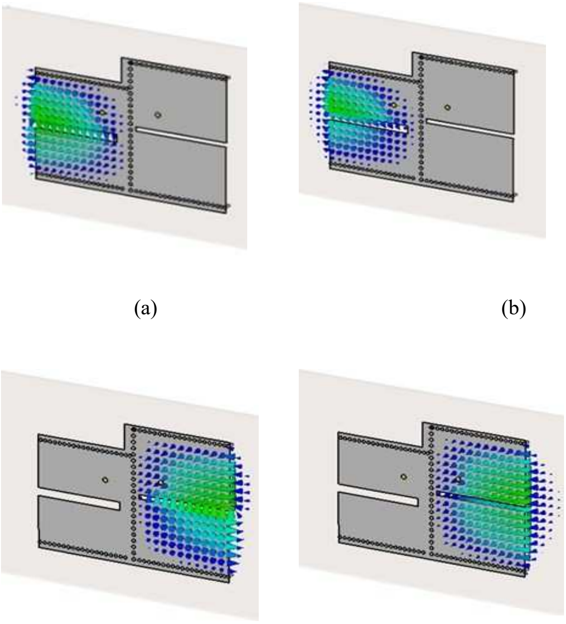


Fig. 3. *S*-parameters of dual-band dual-element antenna-diplexer



(a) (b)

(c) (d)

Fig. 4. Electric field vector at top plane: (a) odd TE_{110} mode at 3.4 GHz (*Port-1*: ON), (b) even TE_{110} mode at 3.5 GHz (*Port-1*: ON), (c) odd TE_{110} mode at 4.2 GHz (*Port-2*: ON), (d) even TE_{110} mode at 4.3 GHz (*Port-2*: ON)

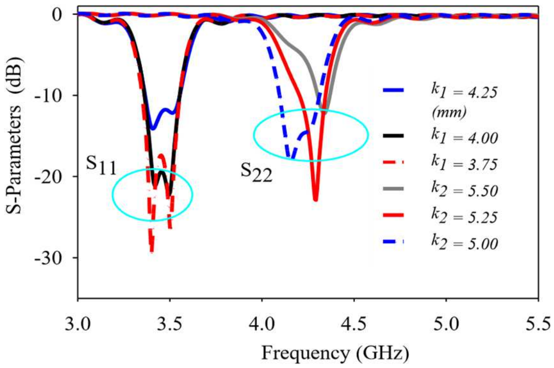


Fig. 5. *S*-parameters vs frequencies with feeds locations k_1 and k_2

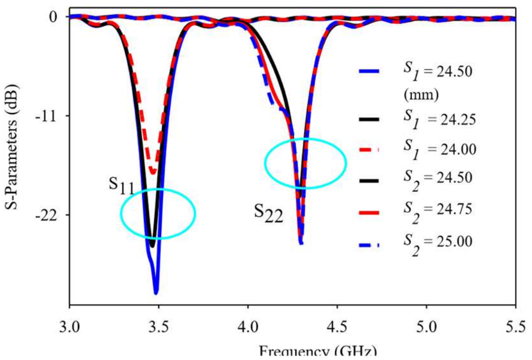


Fig. 6. S-parameters vs frequencies with different slot lengths s_1 and s_2

hence bandwidth is getting improved significantly displayed in Fig. 5. Fig. 6 illustrates the reflection coefficients against frequency with the different slot lengths s_1 and s_2. The odd and even modes coupling is improved by varying the length of the slots. By changing the length of slot s_1 in the range of 24-24.5 mm and for s_2 in the range of 24.75 -25 mm, the coupling of modes is getting improved that enlarges the bandwidth in each frequency band.

III. 2×2 ELEMENTS FOUR-PORT MIMO ANTENNA DESIGN AND EXPERIMENTAL RESULTS

To accomplish a 4-elements MIMO antenna, two more identical cavities including slots are added in a 2-elements antenna-diplexer configuration. The 4-HMSIW cavities share the common electric walls that make the overall MIMO antenna compact. The proposed MIMO antenna occupies an overall space of 64×52 mm^2. The proposed structure achieves intrinsic isolation -23 dB, between any two ports without using any defective ground structure [19, 20] or interelement spacing. Therefore, the proposed design antenna maintains ground plane integrity and avoids backward radiations in a more compact space compared to its counterparts. To verify the MIMO properties of the proposed dual-band antenna-diplexer ECC, DG, and MEG are evaluated. The ideal value of ECC should be 0, DG should be 10 dB, and MEG should be -3 dB. The ECC plot determines the independence between adjacent antennas which has been extracted from the S-parameters. The peak value of ECC is obtained as 0.13 in the lower frequency band and 0.05 in the upper frequency band, DG is averaged 9.95 dB over the entire bandwidth, and MEG is -3.01 dB in both frequency bands. In order to verify the viability of MIMO antenna, the extracted parameters are close to the desired values [1, 2]. Moreover, the ECC against frequency has been plotted in Fig. 7. All the simulations are carried out on CST Microwave studio 3D electromagnetic solver based on Finite difference time domain (FDTD) method. A prototype of the proposed dual-band self-diplexing 2×2 MIMO antenna is manufactured on a Rogers 5880 laminate of thickness of 1.57 mm, the dielectric constant of the material is 2.2, and loss-tangent 0.0009. The antenna is prototyped using the conventional printed circuit board procedure (PCB) procedure and the chain of via holes is manufactured using plated through-hole (PTH) technique. The fabricated prototype of the proposed antenna has been displayed in Fig. 8. The proposed structure is experimentally verified in terms of *S*-parameters, gain, and 2D-radiation pattern.

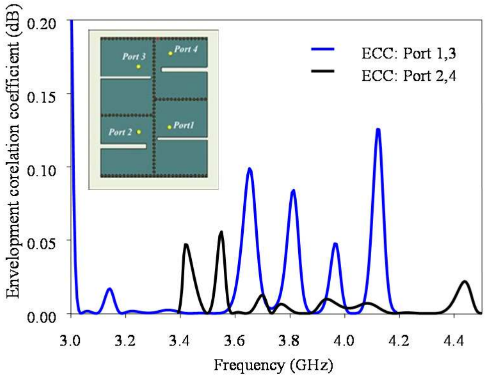


Fig. 7. ECC against frequency of 2×2 MIMO antenna when (*Port-1*, *3*: ON) and (*Port-2, 4*: ON)

The measurements are performed using E5080A vector network analyser. The antenna shows the measured results at 3.4 GHz and 3.51 GHz when *Port-1* is fed, and *Port-2* is terminated with the matched load. Similarly, it provides resonance at 4.05 GHz and 4.3 when *Port-2* is fed and *Port1* is matched terminated, illustrated in Fig. 9. The measured results are obtained in good correlation with the simulated results. The proposed antenna yields fractional bandwidth of 5% in the lower frequency band and 4.7% in the higher frequency band. The measured values of average gain in the lower operating frequency are around 5.15 dBi and in the upper frequency band around 6.1 dBi. have been achieved of 5.35 dB$_i$ in the lower frequency band and 6.75 dB$_i$ in the upper frequency band. The radiation efficiency varies in the range of 82%~92% in the lower frequency band while 80%~90% in the upper frequency band. The 2D-radiation pattern of the antenna has been plotted at two cut planes (ϕ = 0°) and (ϕ = 90°) at 3.4 GHz in the lower frequency band

and 4.2 GHz in the upper frequency band, displayed in Fig. 10. The front-to-back ratio is obtained better than 14 dB at each resonant frequency. The proposed antenna reveals a stable radiation pattern along with maximum radiation in the broadside direction. The antenna demonstrates a unidirectional radiation pattern due to the cavity-backed configuration. The co- to cross-polar levels are achieved higher than 10 dB in each direction and better than 17 dB in the broadside direction. The proposed MIMO antenna is flexible in scaling both frequency bands simply by altering the dimensions of the HMSIW cavities. The design of proposed antenna is simple, low-profile, compact, and easily scalable.

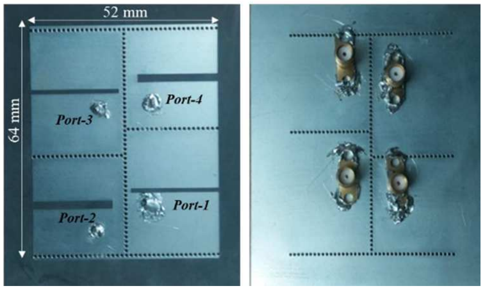


Fig. 8. Fabricated prototype of 2x2 MIMO antenna-diplexer

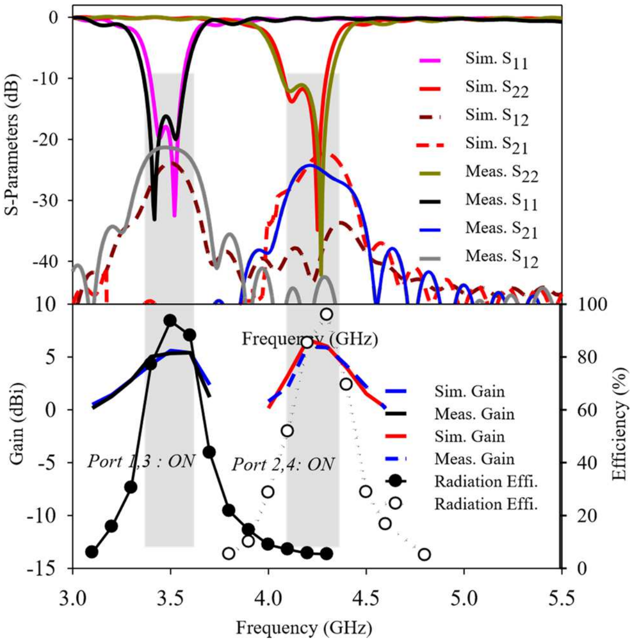
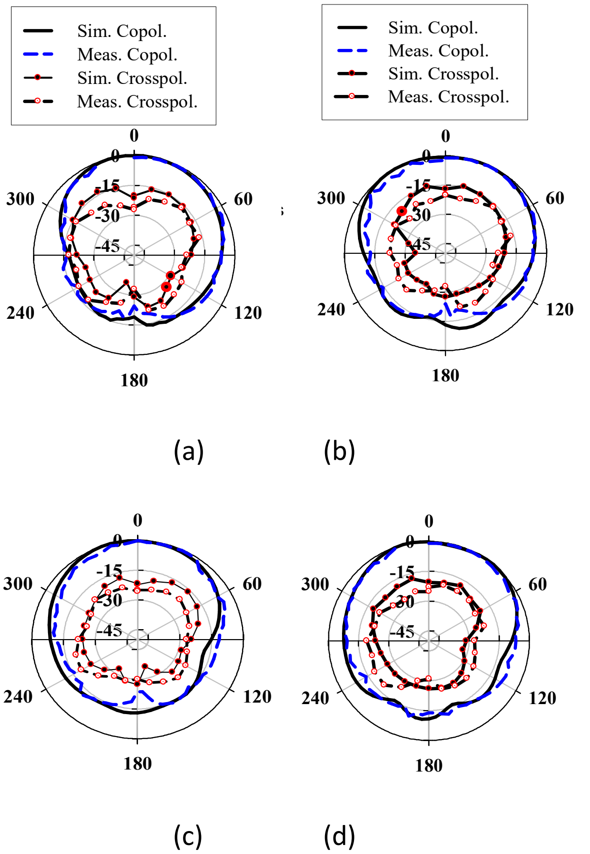


Fig. 9. Simulated and measured *S*-parameters, gain and efficiency vs frequency response



(a) (b)

(c) (d)

Fig. 10. Simulated and measured radiation patterns for E-plane (ϕ = 0°) and H-plane (ϕ = 90°) (a), (b) 2D radiation patterns at 3.4 GHz (c), (d) at 4.2 GHz

IV. CONCLUSION

This article presents a compact, low-profile HMSIW self-diplexing MIMO antenna for dual-band operations. By using the half-mode topology, the cavity size is miniaturized by around 50%, and bandwidth is enhanced by around 50% by inserting a rectangular slot in each HMSIW cavity. The bandwidth can be easily controlled by the slot dimensions while frequency bands can be easily tuned in a range by varying the cavity dimensions. The measured results of the 4-elements dual-band MIMO antenna follow the simulation counterparts. Also, the MIMO features are obtained very close to their standard values. The proposed structure is a suitable alternative to use in the lower frequency band (3.35–3.55 GHz) for the TD-LTE system and upper-frequency band (4.1–4.3 GHz) for FCC ID WLAN in 5G communication.

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