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Research Article

HMSIW

Compact HMSIW based Centre-Fed Series Antenna Array for ISM Band Energy Harvesting

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The global move towards wireless access point densification has alluded towards the possibility of harvesting the unused ambient RF energy, especially in the 2.4GHz and 5.8GHz unlicensed ISM bands, in order to power useful electronic devices. This is done by collecting the ambient RF energy present in the environment growing more and more as a result of the rapid growth in the wireless communication business and transforming that collected energy into electrical power. This paper focus on realization of a compact, dual band, linearly polarized HMSIW antenna and two- and four-element centre-fed series array antenna designed based on HMSIW technique used as a receiving antenna in the RF energy harvesting system. The HMSIW is formed by bisecting the SIW along the quasi-magnetic wall when operating at TE101 and TE201 modes with the similar magnetic field strength observed at both the resonance modes. The feeding position and edge to edge spacing between the elements of the array antenna for HMSIW is chosen such that the proper impedance matching is achieved. Moreover, a truncation is made in HMSIW to suppress the unwanted bands at the TE201 mode. The antenna's performance is analysed based on comparing the simulated and measured return loss, VSWR, gain, axial ratio and radiation pattern which matches well for both the frequencies of interest (2.45GHz and 5.8GHz) can be used in a RF energy harvesting (RF-EH) system.

Keywords: Antenna, Energy Harvesting, HMSIW, and VSWR

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Introduction

Radio frequency energy transfer and harvesting techniques have recently become alternative methods to power the next generation wireless networks collectively called as low energy internet of things (LEIoT) by using the untapped source of energy available in the environment [1]. The Low Power Wide Area Network(LPWAN), Wireless Neighbourhood Area Network(WNAN), Wireless Local Area Network(WLAN), Wireless Field Area Network(WFAN), Wireless Home Area Network(WHAN) and Wireless Personal Area Network(WPAN) are used for various applications like Onramp/Ingenu, Wi-Sun, WiFi, WiFi WAVE, Wireless HART, ISA100.11a, ZigBee, Thread, Bluetooth 4.0/4.1/4.2 Low Energy, ANT+ and MiWi operating at unlicensed ISM bands(2.45GHz and 5.8GHz) makeup the source of energy for powering LEIoT [2].

In order to replace the inefficient microstrip devices operating at higher frequency, the SIW concept is adopted where the transition from the microstrip to dielectric-filled waveguide to SIW is made by introducing metalized via holes in the side walls of the dielectric-filled waveguide. The TM modes do not exist because of the presence of metalized via holes in the side walls so the existing dominant mode is TE mode. The SIW is transformed into HMSIW by cutting the SIW into half with the benefit of reduced radiation loss (which is achieved by the distribution of energy to the air region by the open aperture sides) and size (without affecting the electric field distribution performance) [3].

Recently various antennas based on HMSIW technology are developed for millimetre-wave application [4], WLAN application, WBAN application [5] and inter-satellite communications [6]. Nowadays the HMSIW based antennas finds application in ambient energy harvesting and wireless power transmission systems due to minimal loss and leakage, maximum isolation and compactness which leads to ease of implementation of arrays. The HMSIW based array antenna for energy harvesting generally works on single frequency band [7], but due to the availability of low-power densities of the RF source at a particular frequency a wideband or multiband antenna is considered with omnidirectional radiation patterns. The array antennas feed network design plays An important role in impedance matching where inline series feed network is employed for narrow band antennas which brings in compactness and minimize radiation and insertion losses [8].

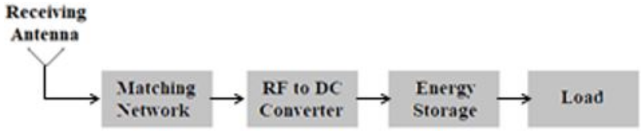


Figure 1: RF Energy Harvesting System (Receiver Side)

The paper focus on antenna part (illustrated in Figure 1) of the harvesting system where the evolution of the HMSIW based single element design from the rectangular waveguide is presented with the equivalent circuit model and numerical analysis followed by the two element and four element array implementation. The analysis of TE101 and TE201 resonance modes for the SIW and HMSIW based antenna with the help of magnetic field strength is furnished. Finally, the analysis of simulated and measured array antenna performance parameters (return loss, VSWR, gain, axial ratio and radiation pattern) are employed.

HMSIW based centre-fed series array antenna

The development of the proposed single element HMSIW based antenna from the rectangular waveguide is designed, simulated and analysed using the ADS simulation tool and their resonant modes are compared is shown in Figure 2 and 3. The configuration of the rectangular SIW resonator and proposed HMSIW resonator is illustrated in Figure 2(a) and 2(d).

A. Single Element Design

Rectangular SIW Resonator: The proposed antenna is designed based on the substrate integrated waveguide (SIW) technique. Initially a rectangular waveguide is transformed into SIW by introducing array of metallic via holes around the walls of the rectangular waveguide which forms the resonance 10GHz and 16.8GHz at T_{101} and T_{201} modes. The optimized length (L_{SIW}) and width (W_{SIW}) of rectangular SIW is 11.1mm and 12.493mm with the dimension of spacing between the adjacent metallic via holes of $G_{VIA} = 1.3mm$ and diameter of the metallic via holes of $D_{VIA} = 0.8mm$. The rectangular SIW resonator is designed on a FR_4 substrate with substrate height h=1.6mm, dielectric constant ε_r=4.6 and loss tangent T_δ=0.01. The resonance frequency of the T_{mop} modes for rectangular SIW resonator is calculated using the formula [9],

$$f_{m0p} = \frac{c}{2\sqrt{\varepsilon_r}} \sqrt{\left(\frac{m}{L_{eq}}\right)^2 + \left(\frac{p}{W_{eq}}\right)^2} \quad (1)$$

$$L_{eq} = L_{SIW} - 1.08\frac{D_{VIA}^2}{G_{VIA}} + 0.1\frac{D_{VIA}^2}{L_{SIW}} \quad (2)$$

$$W_{eq} = W_{SIW} - 1.08\frac{D_{VIA}^2}{G_{VIA}} + 0.1\frac{D_{VIA}^2}{W_{SIW}} \quad (3)$$

Where $m = p = 1, 2,\ldots$, L_{eq} and W_{eq} are the equivalent length and width of SIW resonator. The condition $G_{VIA} \leq 0.25\lambda$ (where λ is the free space wavelength calculated with known operating frequency and speed of light values) must be satisfied for a SIW resonator in order to avoid radiation loss caused by the gaps in between the metallic via holes. The rectangular SIW resonator is modified by removing via holes at top and bottom of the waveguide in order to move the resonance towards the desired frequency range forming resonance at 6.6GHz and 8.6GHz which corresponds to T_{101} and T_{201} modes.

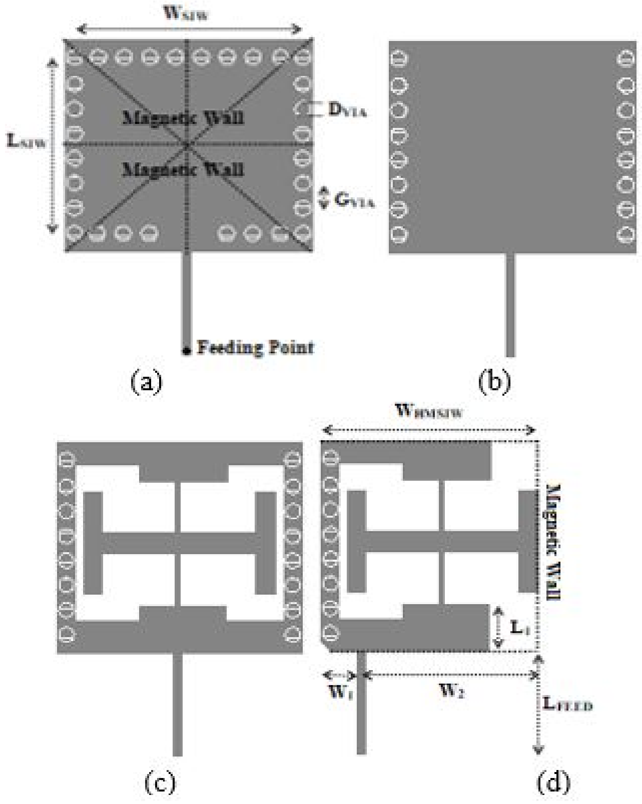


Figure 2: Evolution of the proposed single element design based on half-mode substrate integrated waveguide (HMSIW). Layout of the rectangular SIW resonator (a); Layout of the modified rectangular SIW resonator (b); Layout of the modified rectangular SIW resonator embedded with Jerusalem cross resonator (c); Layout of the proposed modified HMSIW resonator (d)

Further a Jerusalem cross-shaped resonator is embedded to the modified rectangular SIW resonator by etching at the centre thus adding more capacitance resulting in resonance shift to 2.9GHz and 7GHz. The Jerusalem cross-shaped resonator is a popular type of cross element structure where a cross structure is loaded at the ends to enhance the capacitance (the general pair of resonating element type is loop and cross structure where their resonant etiquette is caught by LC circuit) [10]. Figure 4 represents the return loss (S_{11}) performance (inset layout) of the Jerusalem cross-shaped resonator with the optimized geometrical parameters for resonance at 5.8GHz respectively. The loaded ends W_6 and L_2 of the Jerusalem cross-shaped resonator is optimized and fixed to be 0.7mm and 0.8mm in order to get the return loss response at 5.8GHz.

The simulated magnetic field strength for the rectangular SIW resonator, modified rectangular SIW resonator and modified rectangular SIW resonator embedded with Jerusalem cross resonator is given in Figure 4 for the resonant modes TE101 and TE201 with the maximum observed magnetic field strength of nearly 18.013 A/m. The magnetic field strength increases when a Jerusalem cross resonator is introduced in the SIW which shifts the modes to lower frequency side resulting to achieve frequency of interest when converted to HMSIW.

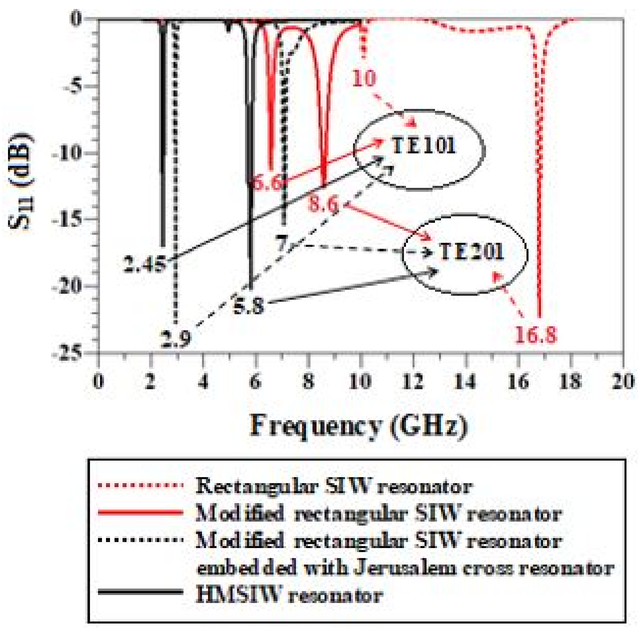


Figure 3: Simulated return loss comparison of the evolution of the proposed single element design based on HMSIW

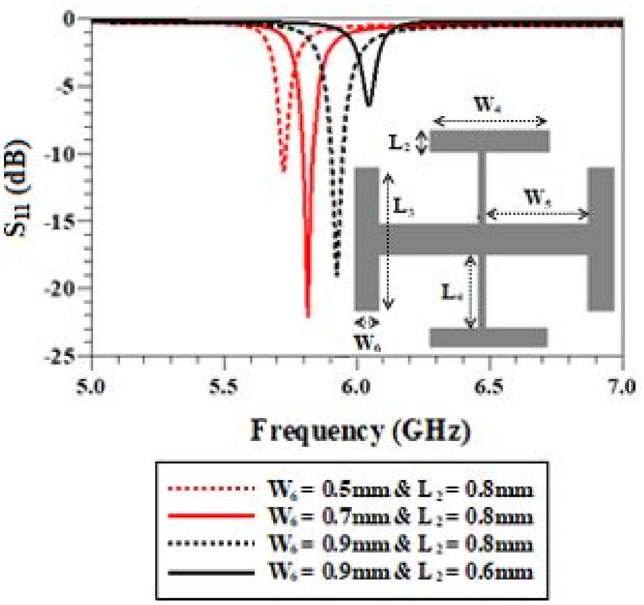


Figure 4: Simulated return loss comparison with layout of the Jerusalem cross-shaped resonator

HMSIW Resonator: In order to get the desired resonance and achieve compactness the SIW is converted into HMSIW resonator by removing the right-side wall resulting in formation of a magnetic wall without altering the radiation property. Then the position of the feed is adjusted and set at W_1=1.9mm and W_2=6.2mm in order to match the impedance between the HMSIW and feed structure resulting in 2.45GHz, 5.729GHz and 5.810GHz as illustrated in Figure. Then the truncation of W_3 = 0.25mm is made near the left side edge of the HMSIW resonator to suppress the resonance at 5.729GHz as shown in Figure.

When there is no truncation in the HMSIW structure a dual frequency at 5.729GHz and 5.810GHz is created at mode TE201 which has nearly similar magnetic field strength thus a truncation is made to eliminate the 5.729GHz frequency giving rise to resonance at desired frequency bands at 2.45GHz and 5.8GHz as shown in Figure 2(d) where the optimized width of the proposed HMSIW resonator is W_{HMSIW} = 11.1 mm length of the feed L_{FEED} = 5.4mm and L_1 = 2.5mm. The maximum magnetic field strength observed for both structures are nearly 18.013 A/m is shown in Figure. The equivalent width of HMSIW is [11]

$$W_{HMSIW} = \frac{W_{eq}}{2} + \nabla W \quad (4)$$

Where W_{eq} and ∇W are the equivalent width of the SIW resonator and additional width calculated based on [12] is

$$\nabla W = h\left[\left(0.05 + \frac{0.3}{\varepsilon_r}\right) ln\left(\left(\frac{0.79W_{eq}}{4h^3}\right) + \left(\frac{52W_{eq}-261}{h^2}\right) + \left(\frac{38}{h}\right) + 2.77\right)\right] \quad (5)$$

The resonant frequency modes (T_{m0p}) of HMSIW resonator are found using the following formula [13]:

$$f_{m0p} = \frac{c}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m}{L_{HMSIW}}\right)^2 + \left(\frac{p}{W_{HMSIW}}\right)^2} \quad (6)$$

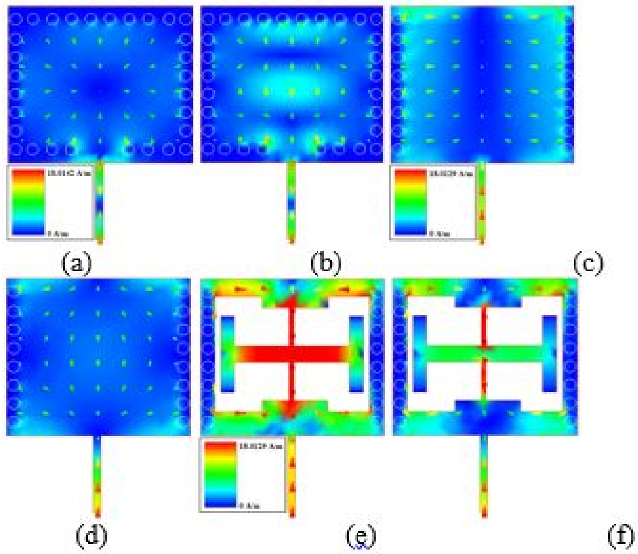


Figure 5: The magnetic field strength observed at TE101 and TE201 modes for rectangular SIW resonator ((a) and (b)), modified rectangular SIW resonator ((c) and (d)) and modified rectangular SIW resonator embedded with Jerusalem cross resonator ((e) and (f))

B. ARRAY Implementation: The HMSIW antenna array is designed by utilising the inline series feed network where the feeding is provided at the centre of the array which serially couples the input signal to the neighbouring antenna elements. This type of feed network brings in compactness, narrow bandwidth, less insertion and radiation losses. The two element and four element HMSIW centre-fed series array antenna is designed and analysed.

1x2 HMSIW Centre-fed Series Array Antenna

The two element HMSIW centre-fed series array antenna is designed and optimized to resonate at 2.45GHz and 5.8GHz. The edge to edge separation (D) between the adjacent antenna elements plays a vital role in matching the impedance which is shown in Figure 8. And the length of the line connecting the two elements is L_5 =1mm and the length and width of 50Ω impedance matching line are L_6 =3mm and W_7=3mm. The condition D < λ must be satisfied in order to avoid electromagnetic interference between the elements where the surface current in the elements

Will degrades the gain, bandwidth and radiation property of the antenna eventually resulting in radiation efficiency degradation. Thus, after analysis the value of D is fixed to be 1.25λ (≈11mm) without compromising the return loss performance as shown in Figure 8.

The magnetic field strength in Figure 9 shows that the area excluding via holes are responsible for creating TE101 mode and the partial area of the Jerusalem cross resonator corresponds to the generation of TE201 mode. At 0 degree phase the first element has maximum magnetic field strength (20.672 A/m) and at 90 degree phase the first element has maximum magnetic field strength (20.672 A/m) for 2.45GHz and whereas for 5.8GHz its vice-versa.

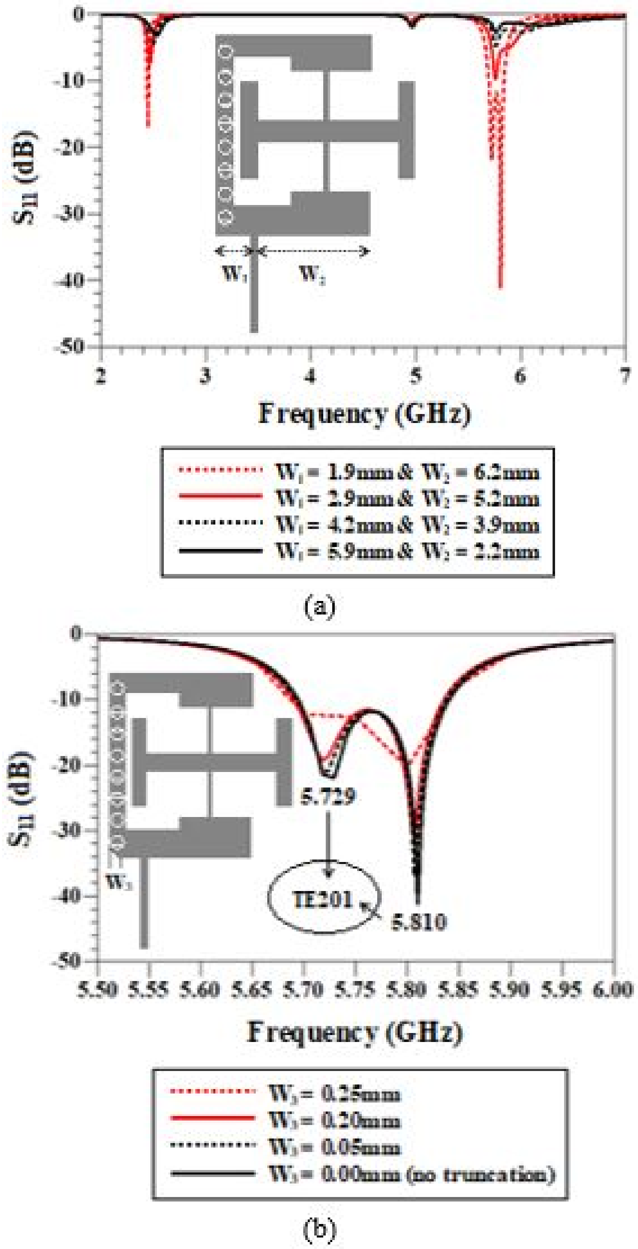


Figure 6: S_{11} (return loss) comparison For proposed modified HMSIW resonator without (a) and with (b) truncation for varying width

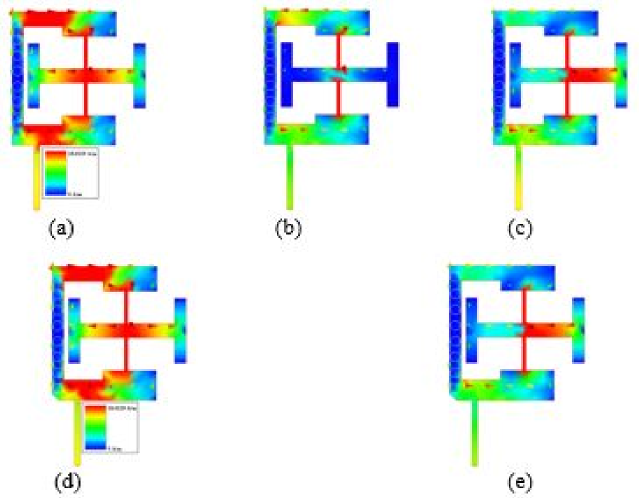


Figure 7: The magnetic field strength observed at TE101 and TE201 modes for proposed modified HMSIW resonator without ((a), (b) and (c)) and with ((d) and (e)) truncation

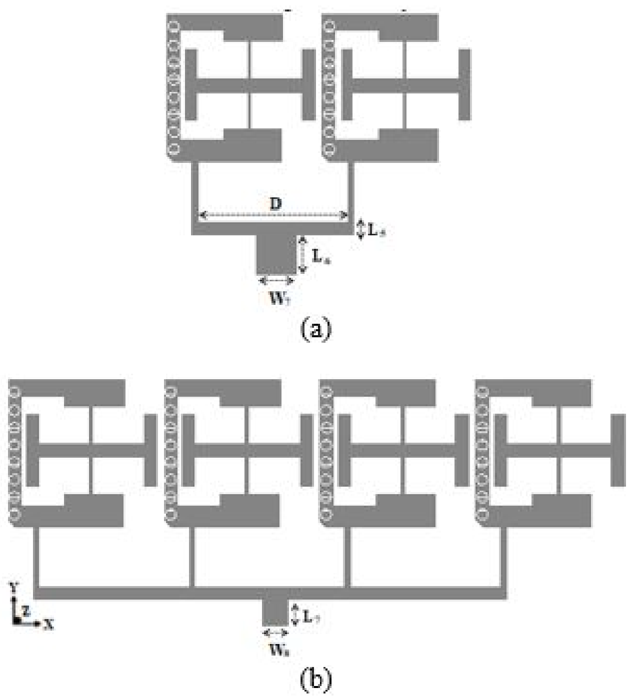


Figure 8: Two element (a) and four element (b) HMSIW centre-fed series array antenna

1x4 HMSIW Centre-fed Series Array Antenna

The proposed 1x4 HMSIW centre-fed series array antenna is fabricated on a FR-4 substrate with the feed dimensions of L_7= 2mm and W_8= 2mm optimized using simulation tool and the return loss, VSWR, gain and radiation pattern measurements are made to verify the performance of the proposed prototype.

Figure shows the radiation pattern measurement setup (where the test antenna placement is based on the radiation pattern) with the fabricated proposed antenna array whose overall volume is 45.9mm x 18.4mm x 1.6mm including the 50Ω SMA connector as shown in Figure.

The proposed antenna array is claimed to have compact size when compared to the recently developed antenna array operating at ISM band for RF energy harvesting is summarized in Table1.

The return loss and VSWR comparison of the simulated and measured proposed antenna array shows that the 2:1 VSWR bandwidth of 660MHz and 840MHz is observed for TE101 and TE201 resonance modes.

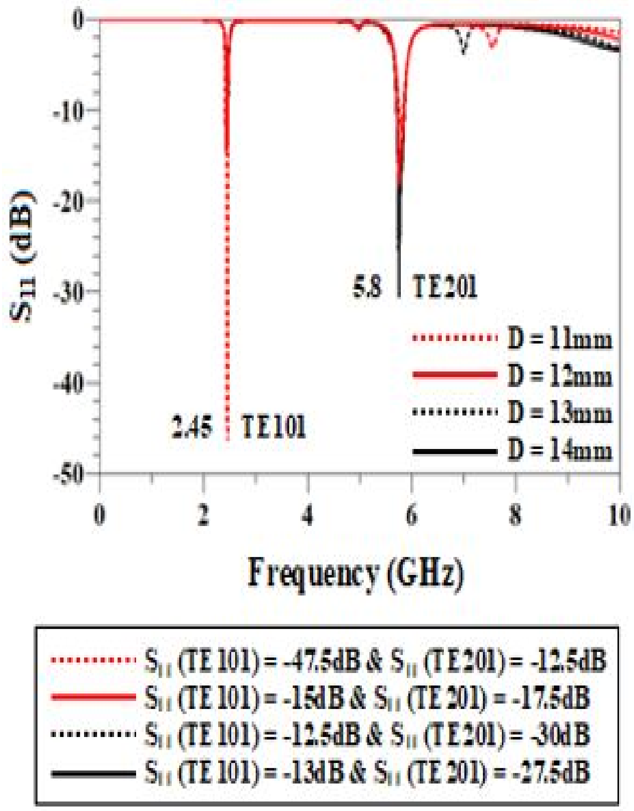


Figure 9: S11 (return loss) comparison for two element HMSIW centre-fed series array antenna with varying edge to edge separation (D)

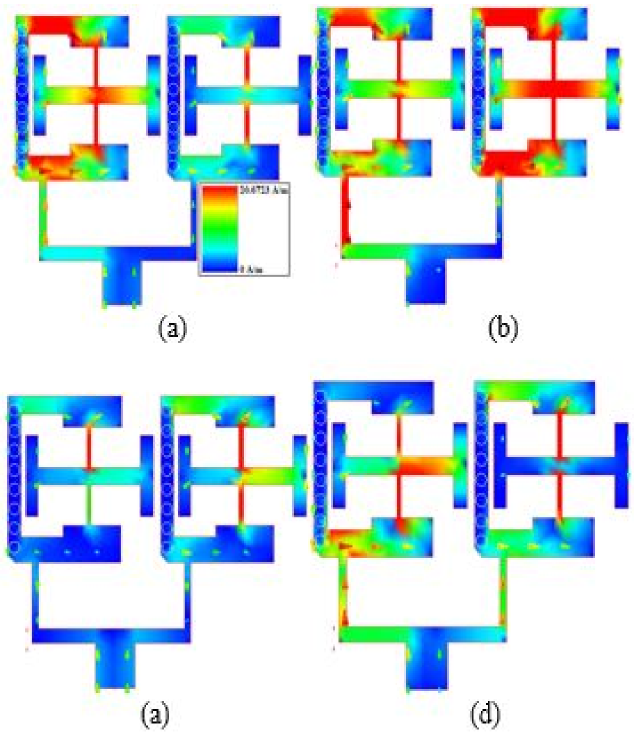


Figure 10: The magnetic field strength of two element HMSIW centre-fed series array antenna observed at 2.45GHz – 0 degree phase (a), 2.45GHz – 90 degree phase (b), 5.8GHz – 0 degree phase (c) and 5.8GHz – 90 degree phase (d).

The simulated and measured gain is plotted in Figure where at the first resonance mode the gain is 3.5dB and at second resonance mode the gain is 1dB.

The simulated and measured 2D radiation pattern for first and second resonance at E-plane and H-plane co-polarization and cross-polarization is plotted in Figure which shows that the ratio of cross-polarization level is less than -20dB in E-plane and -10dB in H-plane for 2.45GHz and vice-versa for 5.8GHz.

Table1: Comparison of key parameters of recently developed compact antenna array with the proposed antenna array covering ISM band for RF energy harvesting

References	Array	Frequency in GHz	Peak Gain	Size
[14]	4x4	1.3 – 2.83	2.217dBi	386.35mm x 380.6mm
[15]	2x2	1.8 – 2.9	5.5dBi	120mm x 130mm
[16]	3x3	2.45	NR	87mm x 87mm
This work	1x4	2.45 & 5.8	3.5dB	45.9mm x 18.4mm

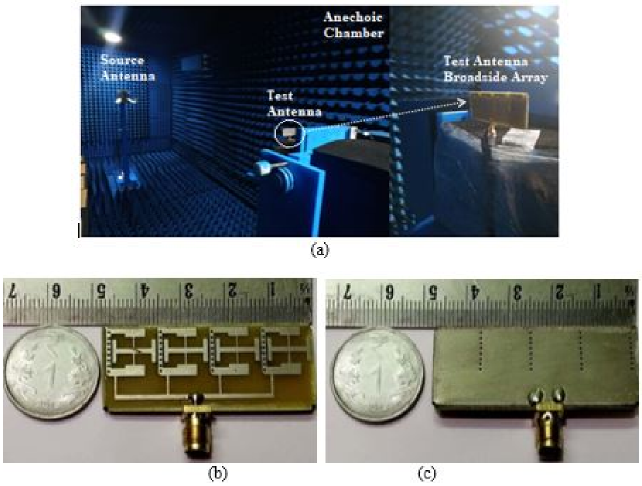


Figure 11: Radiation pattern setup (a) with the fabricated proposed array antenna prototype (b)

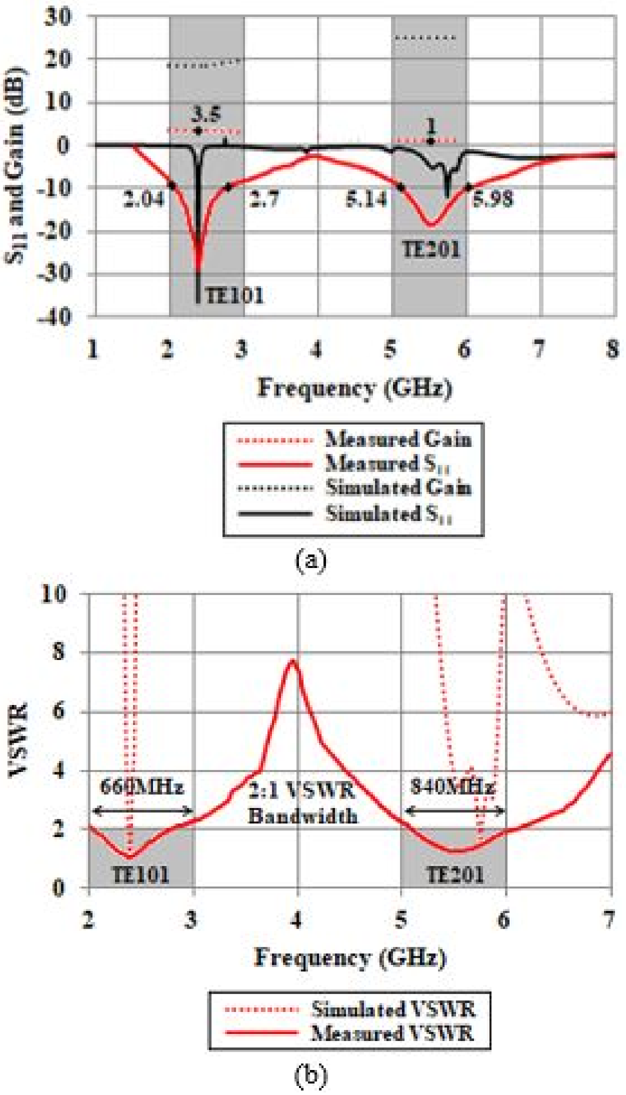


Figure 12: Simulated and measured return loss, gain and VSWR comparison for the proposed prototype

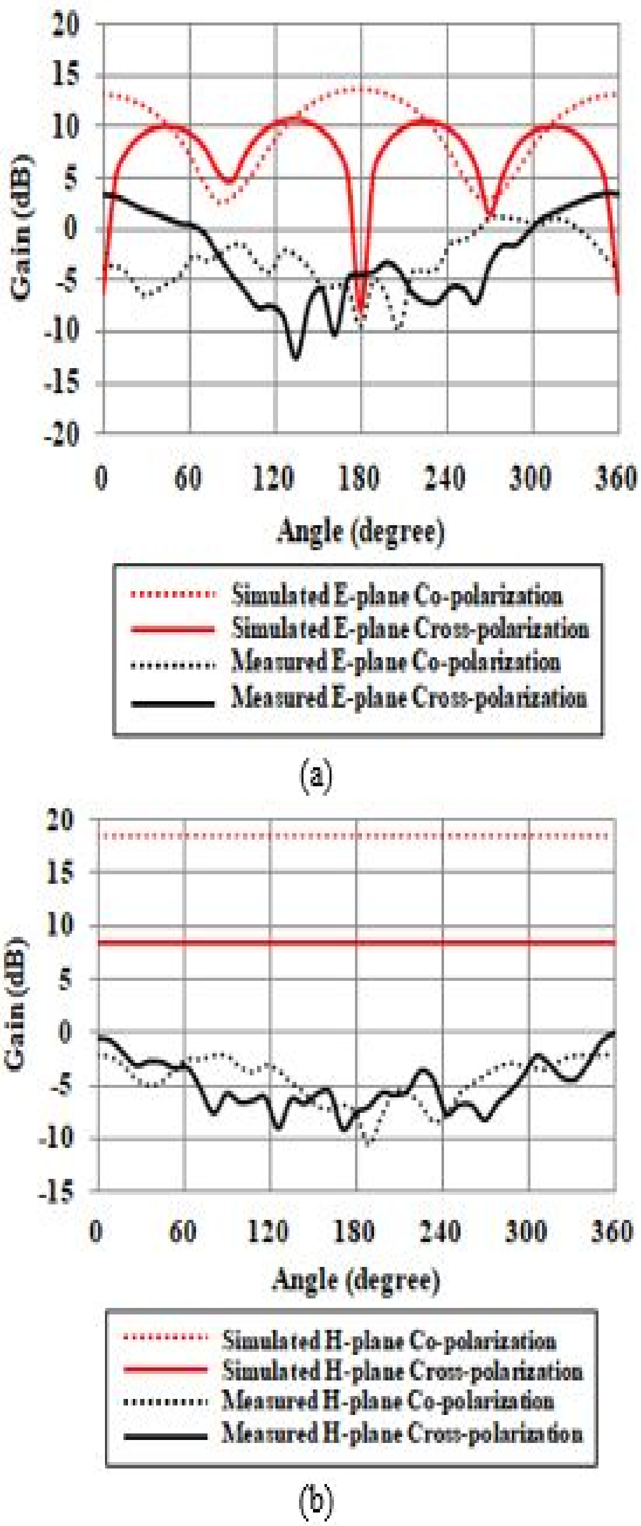
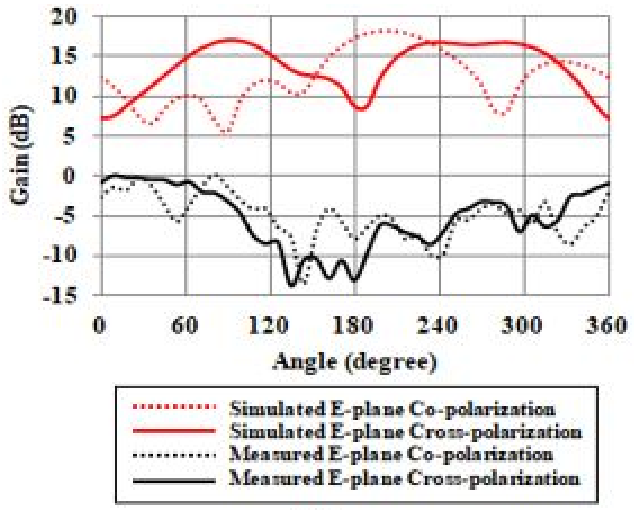
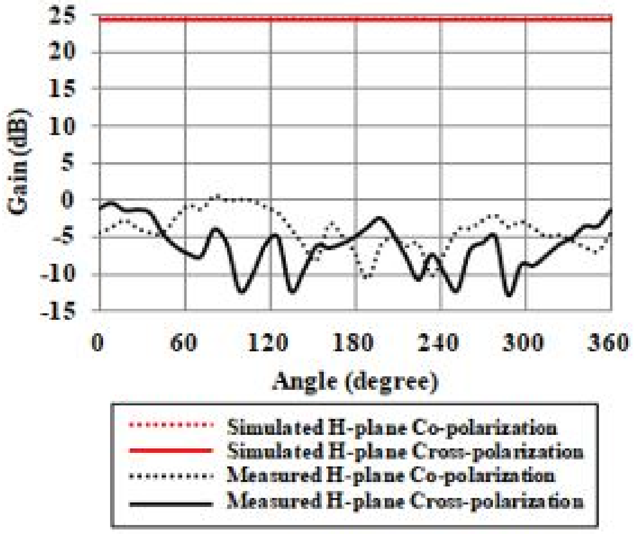


Figure 13: Simulated and measured 2D radiation characteristics at E-plane (a) and H-plane (b) for 2.45GHz



(a)



(b)

Figure 14: Simulated and measured 2D radiation characteristics at E-plane (a) and H-plane (b) for 5.8GHz

Conclusion

The simulated and measured performances of the 1x4 centre-fed series array antenna are analysed and compared. The measured antenna performance parameters are found to be nearly -30dB and -20dB return loss, 3.5dBi and 1dBi gain and VSWR<2 for the frequencies 2.45GHz and 5.8GHz respectively. Moreover, the radiation pattern analysis on Co- and Cross- polarization for E- and H- plane is illustrated. In addition, the simulated magnetic field strength of the antenna in each development stage and for 2 element arrays is studied and the equivalent circuit model for the Jerusalem cross shaped resonator and HMSIW resonator is designed, simulated and analysed using the ADS software tool in order to understand the functionality of the antenna.

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