Dielectric resonator loaded high-gain half-mode substrate integrated waveguide triangular antenna for microwave imaging and radar applications

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Abstract

In this paper, an equilateral triangular HMSIW antenna excited with coaxial feed is chosen at 5.28 GHz representing TE_{101} mode with next higher TE_{202} mode operating at 9.57 GHz frequency in the X-band. Two sides of the antenna with fitted with metallic vias while the third side remains barren. The antenna is found to exhibit gain of 5.7 dBi and 7.5 dBi for the TE_{101} and TE_{202} mode respectively. A rectangular box-shaped dielectric resonator (DR) is now placed over the radiating wall. The antenna-DR composite structure resonating at the higher TE_{202} mode at 9.5 GHz and depicting an enhanced gain of 12 dBi is presented here for X-band microwave imaging and radar applications. All antennas are made-up with Arlon AD270 substrate and simulation results show a close resemblance when compared with measured ones.

Keywords Antenna gain · Substrate integrated waveguide (SIW) · Dielectric resonator (DR) · Ground-penetrating radar (GPR) · Microwave imaging · Synthetic aperture radar (SAR)

1 Introduction

The successful development of commercial RF broadband system depends on cost effectiveness, mass-producibility, superior-performance ability and high quality microwave and millimetre wave technologies. At millimetre wave, the circuit building blocks and antennas are very closely related. Though classical metallic waveguide still remains as the mainstream for designing superior-performance millimetre wave systems, it is not suitable for en-mass production with lower cost. In addition to its heavy weight and volume, the costly and cumbersome process of its tuning post-fabrication along with difficulty in assembling makes it unsuitable for widespread applications and use. Moreover other challenging problems involve designing of low loss ICs. Tremendous research worldwide is being carried out to develop high-performance microwave and millimetre wave components that can be fabricated using

low cost technologies. A promising candidate for alleviating all such problems is the development of substrate integrated waveguide (SIW) technology [1–3]. This structure exhibits the propagation characteristics of classical waveguide including field pattern and dispersion characteristics as well as preserves all the advantages of the latter. By this technology the non-planar waveguides are converted into planar form structure which are compatible with printed circuit board (PCB) technology or other prevalent planar processing techniques like low-temperature co-fired ceramic (LTCC) technology.

Microwave imaging, an important and essential tool, has been developed to analyze embedded objects in a medium. It offers a plethora of applications in a variety of areas including medical imaging, concealed object detection for security, structural engineering, through-the-wall imaging, etc. [4]. However, security and medical imaging received significant importance in the last decade.

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The non-invasive profile of microwave imaging helped in promising detection of breast cancer at an early stage [5]. Tomography coupled microwave systems have been reported to be successful in accurately extracting malignant tumor information and reconstruction [6]. In [7], the authors have further proposed a new low cost technique to construct 3D images for medical and security applications using indirect holographic approach along with microwave imaging. Consequently, efficient microwave imaging technique development is of utmost importance in medical, structural and security applications. The synthetic aperture radar (SAR) used to create 2 or 3-D images of objects or the ground-penetrating radar (GPR) used for geological observations are very popular qualitative microwave imaging methods. They calculate qualitative profile to represent hidden objects. It is herein that the demand of developing antennas as microwave sensing element has essentially attracted the attention of researchers worldwide. In this context, half-mode substrate integrated waveguide (HMSIW) based sensing antenna elements have been developed to work at both S- and C-band [8]. Also a CP DRA array with enhanced gain has recently been developed for microwave imaging applications [9].

The SIW based components and antennas marks a revolutionary change in construction of all electrical microwave and millimetre wave electronics component structures. They eliminate cross talks in sensitive microwave and millimetre wave circuits owing to their high EMI isolation property; provide enhanced signalling performance due to low conductor loss and provide excellent frequency stability for coupled filters and resonators owing to the capability of able to handle more power with proper electrical shielding. The SIW technology offers assimilation of passive and active elements including antennas on the alike substrate which creates system-in-package (SiP) with additional extension to system-on-substrate (SoS) enabling mounting of a single or multiple chip sets on a single substrate. In the last decade, tremendous growth and research has been witnessed in developing SIW based antennas for communication systems. Several antenna structures have already been proposed that are available in literature which includes the classical slotted-waveguide antennas, leaky-wave antennas, modified Vivaldi radiator, cavity-backed SIW antennas, H-plane sectoral horn antenna, HMSIW antennas, quarter-mode SIW (QMSIW) antennas, eighth-mode SIW (EMSIW) antennas, etc. The HMSIW [10–16], a special structure leading to miniaturization of antenna footprint, results from the division of full-mode SIW (FMSIW) along the quasi-magnetic wall keeping the field circulation identical to that of FMSIW structure.

The dielectric resonators (DRs), on the other hand, fabricated using low loss materials with high permittivity are very popular and are extensively used worldwide

in microwave filter circuits and in other microwave structures like oscillators. They generally possess very high unloaded Q-factor with exception in open environment where reduction of Q value for the lowest order modes are observed; a property depicting their suitability in use as antenna. The DR antennas (DRAs) have emerged as promising candidate for microwave and millimetre wave communication systems owing to their several eye-catching features like small size, low cost, greater impedance bandwidth, more radiation efficiency and tolerance to temperature variation, versatility, flexibility and ease in excitation techniques [17–19]. The DRAs offers the choice of excitation through various methods like feeding through microstrip line, conformal strip, coaxial probe, aperture coupling by microstrip line or coplanar waveguide, etc. and can be designed using various shapes like rectangle, cylinder, hemispherical, spherical and others.

In this paper, a HMSIW equilateral triangular antenna is designed by authors [16] with metallic vias array placed along two sides constituting perfect electrical conducting (PEC) wall with the other wall as perfect magnetic conducting (PMC) being empty of any such vias. Coaxial feeding technique is used offering ease in fabrication, easy impedance matching and at the same time generating low spurious radiation. The resonating frequency of the antenna for TE_{101} fundamental mode occurs at 5.28 GHz generating 5.7 dBi gain and upon varying the feed position the next higher TE_{202} mode at 9.57 GHz is excited with a gain of 7.5 dBi. A rectangular box shaped DR chosen and placed on top of the PMC wall of the HMSIW triangular antenna. The antenna loaded with DR is found to be radiating at the higher TE_{202} mode of 9.57 GHz. The radiation from the PMC edge excites the DR and the antenna is found to exhibit a gain of 12 dBi which is an excess gain of 4.5 dBi. All simulation studies are carried out using ANSYS HFSS v15.0 and such studies are being tallied with experimentally measured ones.

2 HMSIW based triangular antenna with rectangular box-shaped DR

2.1 The antenna configuration

The geometrical structure of the rectangular box-shaped DR loaded parent antenna [16] excited through coaxial feeding technique is shown in Fig. 1. For the antenna, the length of the sides (S) = 31.18 mm with boundaries being 60 (L) × 60 (W) × 0.79 mm³. It is designed using Arlon AD270 substrate (tm) (dielectric constant, ϵ_r = 2.7, thickness h = 0.79 mm, and loss tangent, $\tan\delta$ = 0.002). The metallic vias are positioned along the two edges to resemble PEC walls while the other one with no vias resemble PMC wall. The vias' diameter is

Fig. 1 Geometrical structure with necessary dimensions of the HMSIW equilateral triangular antenna loaded with rectangular box-shaped DR. Antenna dimensions: $L = 60$ mm,

Antenna dimensions:

$L = 60$ mm, $W = 60$ mm, $S = 31.18$ mm, $h = 0.79$ mm, $l_1 = 12$ mm, $l_2 = 30$ mm, $l_3 = 14.41$ mm, $l_4 = 39.01$ mm.

DR dimensions:

Length = 19.05 mm, Breadth = 9.525 mm, Height = 4.7 mm.

chosen as 1 mm with distance between two centres = 1.5 mm. Vias placed at 0.7 mm apart from the edges of the triangle curtails the actual radiation area as compared to triangular patch's physical area. The TE_{101} fundamental mode is excited through coax feeding at optimized position (g) = 14 mm while for TE_{202} mode, the next higher mode, excitation occurs at g = 22 mm. Thus proposed SIW based antenna is approximated through use of formulae for that of HMSIW antenna [10, 20] whose equivalent length and width are given by

$$W_{eff}^{HMSIW} = \frac{W_{eff}^{SIW}}{2} + W \quad (1)$$

$$L_{eff}^{HMSIW} = \frac{L_{eff}^{SIW}}{2} + W \quad (2)$$

where L_{eff}^{SIW} and W_{eff}^{SIW} are the SIW resonator's equivalent length and width. The use of non-linear least squares method facilitates the calculation of additional width W [10, 21]

$$W = h \left(0.05 + \frac{0.3}{r} \right) \times \ln \left(0.79 \frac{W_{eff}^{SIW}}{4h^3} + \frac{52W_{eff}^{SIW} - 261}{h^2} + \frac{38}{h} + 2.77 \right) \quad (3)$$

For the TE_{m0p} modes of the HMSIW triangular antennas, the resonant frequency calculation is through the use of equations related to SIW counterpart structure [22]

$$f_{mnp}^{HMSIW} = \frac{1}{2\pi\sqrt{\mu}} \sqrt{\left(\frac{m\pi}{L_{eff}^{HMSIW}} \right)^2 + \left(\frac{p\pi}{W_{eff}^{HMSIW}} \right)^2} \quad (4)$$

$W = 60$ mm, $S = 31.18$ mm, $h = 0.79$ mm, $l_1 = 12$ mm, $l_2 = 30$ mm, $l_3 = 14.41$ mm, $l_4 = 39.01$ mm. DR dimensions: Length = 19.05 mm, Breadth = 9.525 mm, Height = 4.7 mm

A rectangular box-shaped isolated DR is chosen and placed over the SIW antenna as shown in Fig. 1. The DR with rectangular cross-section is the most versatile one owing to its flexibility arising out of two degrees of freedom; allowing wide range of aspect ratios for a given design frequency. The rectangular DR offers hindrance in analysis for increase in edge-shaped boundaries. However, its choice over cylindrical and spherical DR is owing to the fact that the resonating frequencies of the various excited modes can be made to differ from each other through proper choice of the three dimensions of the resonator. Further, compact DRA with small footprint can be achieved, or very low profile is realizable, or adjustment in its bandwidth is achievable for a given material permittivity. The DRA's operating band width can be easily controlled and tuned over a larger range through suitable choice of resonating parameters. For lower order modes of DR antenna, the bandwidth can be varied from a fraction of a percent to about 10% or more through variation in dielectric constant of the resonator material. Another advantage over this flexibility is that various types of feeding mechanisms can be used to excite the rectangular DRA, thereby making it responsive to integration with current available technology. A fairly simple use of dielectric waveguide model enables fairly accurate prediction of resonant frequency and bandwidth of the rectangular DRA rather than resorting to time-consuming numerical methods.

The rectangular box-shaped DR of length = 19.05 mm, breadth = 9.525 mm, height = 4.7 mm and of dielectric constant 20 is directly placed partly on top of a metallic plane and partly on top of a low permittivity dielectric Arlon AD270 with dielectric constant 2.7. This results in

Fig. 2 Pattern of distribution of Electric field for HMSIW equilateral triangular antenna without rectangular box-shaped DR **a** TE_{101} fundamental mode (5.28 GHz), **b** TE_{202} higher mode (9.57 GHz)

enhancement of bandwidth of each resonance mode owing to the lowering of Q-factor value. The authors have used here Emerson and Cuming make Eccos-tock HIK DR and its dimensions are optimized for best antenna performance.

2.2 Simulated and experimental results

The location of the feed position for the HMSIW equilateral triangular antenna for both the TE_{101} and TE_{202} modes are carried out through parametric studies. The electric field distribution for the parent HMSIW equilateral triangular antenna for the two modes is depicted in Fig. 2 while the same for the antenna-DR composite structure is shown in Fig. 3. Owing to DR loading, the effective permittivity of the antenna-DR composite structure increases resulting in excitation of higher order mode. Thus Fig. 3 clearly reveals that the higher order TE_{202} mode is excited with the inclusion of DR. The separation of high-permittivity DR from the ground plane by the low-permittivity dielectric substrate forces all the electric field lines to circulate through the low-permittivity region. The prototypes of the antennas fabricated using Arlon substrate is depicted in Fig. 4. From the parametric studies of feed location for excitation of modes in a HMSIW triangular antenna, it is clearly evident from Fig. 5a that for TE_{101} mode the feed location is at $g = 14$ mm while the same for higher order TE_{202} mode is at $g = 22$ mm as shown in Fig. 5b. In case of TE_{101} mode, the final simulated return loss observed through HFSS is -29 dB at 5.28 GHz while the same experimentally obtained from Agilent VNA is found to be -26 dB at 5.34 GHz as depicted in Fig. 6a. Also for TE_{202} mode, the optimized simulated and experimental S_{11} , as shown in Fig. 6b, is -17 dB at 9.57 GHz and -28 dB at 9.61 GHz respectively. The span of 5.25–5.30 GHz impedance bandwidth, i.e., 0.95% fractional bandwidth is achieved for TE_{101}

Fig. 3 Electric field distribution for the antenna with DR loading: TE_{202} mode (9.5 GHz)

mode while a 60 MHz impedance bandwidth covering 9.53–9.59 GHz is obtained for TE_{202} mode.

The antenna when supported with a rectangular box-shaped DR over the PMC wall, exhibits a simulated reflection coefficient value of $S_{11} = -40$ dB at 9.5 GHz which is obtained through parametric studies upon variation of DR dimensions as shown in Fig. 7. A plot of S_{11} against frequency upon variation in length of DR is plotted in Fig. 7a while variation in return loss upon individual changes in DR breadth and height is carried out as shown in Fig. 7b, c respectively. Thus the optimized DR dimensions obtained are 19.05 (length LD) $\times$ 9.525 (breadth BD) $\times$ 4.7 (height HD) mm³. The experimentally obtained return loss of the antenna-DR composite structure is -35 dB at 9.7 GHz and a comparison of it with simulated one is plotted in Fig. 7d. From the figure, both simulated and experimentally obtained values are nearly close to each other, however, a slight variation in the two values occurs owing to the several fabrication defects associated with the antenna and the mismatch occurring in the circuit with the SMA

Fig. 4 Fabricated prototype of the HMSIW equilateral triangular antennas **a** without DR, **b** with rectangular box-shaped DR

Fig. 5 Return loss variation versus feed point location of the HMSIW triangular antenna for **a** TE_{101} mode and **b** TE_{202} mode

Fig. 6 Variation of S_{11} with frequency of the antenna for **a** TE_{101} mode and **b** TE_{202} mode

connector. The impedance bandwidth for the composite structure is found to be 420 MHz spanning from 9.28 to 9.70 GHz, i.e., a fractional bandwidth of 4.4%.

From the simulated plot in Fig. 7d, it is observed that after loading with DR, two more close resonances beside the desired resonance at 9.5 GHz (TE_{202} mode) are seen—the first one occurring at 9.34 GHz owing to resonance of the rectangular box-shaped DR exciting the TE_{211} mode

and the other at 9.68 GHz owing to higher order TE_{303} mode excitation of the SIW antenna itself resulting in a combined effect of wider bandwidth for the Antenna-DR composite structure. The corresponding electric field patterns for the DR (TE_{211} mode) and the SIW antenna (TE_{303} mode) are depicted in Fig. 8a, b respectively.

The variation of gain of the HMSIW triangular antenna is revealed in Fig. 9 for the TE_{101} and TE_{202} modes at

Fig. 7 Variation of S_{11} with dimension of the rectangular box-shaped DR in the HMSIW triangular antenna for TE₂₀₂ mode (9.5 GHz)—**a** variation in length (LD) of DR, **b** variation in breadth (BD) of DR, **c** variation in height (HD) of DR and, **d** both simulated

and measured S_{11} versus frequency for optimized DR dimensions—length (LD) = 19.05 mm, breadth (BD) = 9.525 mm and height (HD) = 4.7 mm

Fig. 8 Electric field distribution of **a** rectangular box-shaped DR at 9.34 GHz and **b** SIW antenna at 9.68 GHz

5.28 GHz and 9.57 GHz respectively. The antenna gain is measured by gain transfer method using a Krytar 9000B power meter, a Hittite HMC-T2100 microwave signal generator (10 MHz–20 GHz) and a standard gain Horn antenna. For the E-plane, the cut plane is at $\phi = 0^\circ$ and for the H-plane it is for $\phi = 90^\circ$. From Fig. 9a, b it is observed

that E-plane simulated co-pol values and H-plane gain are 5.7 dBi and 5 dBi respectively with their corresponding values obtained experimentally are 5.6 dBi and 4.9 dBi for the TE₁₀₁ mode. Similarly, a close look into Fig. 9c, d reveals that for TE₂₀₂ mode, the simulated and experimental E-plane co-polarized gains are 7.4 dBi and 6.9 dBi

Fig. 9 Simulated and experimentally obtained gain pattern of the HMSIW based triangular antenna— TE_{101} mode at 5.28 GHz—**a** E-plane radiation pattern and **b** H-plane radiation pattern, TE_{202} mode at 9.5 GHz—**c** E-plane radiation pattern and **d** H-plane radiation pattern

Fig. 10 Simulated and experimental radiation pattern of the HMSIW triangular antenna with rectangular box-shaped DR for TE_{202} mode (9.5 GHz)—**a** E-plane radiation pattern and **b** H-plane radiation pattern

respectively while the same for H-plane are 5.6 dBi and 5.4 dBi respectively. In both the modes, the cross polarization values are far behind their co-polarized level by 30–40 dBi.

Figure 10 reveals that for the antenna-DR composite structure, the E-plane simulated co-polarized gain is 12 dBi with its experimental result counterpart being 11.6 dBi. For the H-plane, the simulated and experimentally obtained

Fig. 11 3D radiation pattern of the HMSIW triangular antenna **a** without DR and **b** with rectangular box-shaped DR for TE_{202} mode (9.5 GHz)

co-polarized gains are 11.4 dBi and 10.9 dBi respectively. For the E-plane, the cut plane is at $\phi = 0^\circ$ and for the H-plane it is for $\phi = 90^\circ$. For this antenna supported with DR, the cross-polarized level is approximately 20–30 dBi below its co-polarized value. Figure 11 depicts the 3D radiation pattern of the HMSIW triangular antenna with and without the rectangular box-shaped DR structure. With DR loading, the radiation coming out from the HMSIW equilateral triangular antenna finds a higher permittivity region; hence the beam converges and enhancement of antenna gain occurs. Thus for this antenna an improvement in gain of 4.6 dBi is observed.

3 Conclusion

A HMSIW equilateral triangular antenna is taken which resonates at 5.28 GHz at the fundamental TE_{101} mode and at 9.57 GHz at the next higher TE_{202} mode. The antenna produces a gain of 5.7 dBi and 7.4 dBi for the two respective modes. This antenna when supported with a rectangular box-shaped dielectric resonator over its PMC wall resonates at the higher TE_{202} mode at 9.5 GHz producing a gain of 12 dBi. Thus an overall enhancement of 4.6 dBi gain is observed with the antenna-DR composite structure. This super high frequency X-band high gain antenna would find applications in weather radar systems, in radio location for land, airborne and naval radars and commercial wireless LAN. Thus the proposed antenna would be surely beneficial to be used as a good sensing element for a plethora of X-band microwave imaging and radar applications and lead to further research by researchers worldwide.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

- Deslandes D, Wu K (2003) Single-substrate integration technique of planar circuits and waveguide filters. *IEEE Trans Microw Theory Tech* 51:593–596
- Xu F, Wu K (2005) Guided-wave and leakage characteristics of substrate integrated waveguide. *IEEE Trans Microw Theory Tech* 53:66–73
- Deslandes D, Wu K (2006) Accurate modeling, wave mechanisms and design considerations of a substrate integrated waveguide. *IEEE Trans Microw Theory Tech* 54:2516–2526
- Lianlin L, Wenji Z, Fang L (2010) Derivation and discussion of the SAR migration algorithm within inverse scattering problem: theoretical analysis. *IEEE Trans Geosci Remote Sens* 48(1):415–422
- Kwon S, Lee S (2016) Recent advances in microwave imaging for breast cancer detection. *J. Biomed Imaging, Int*
- Wang Z, Lim EG, Tang Y, Leach M (2014) Medical applications of microwave imaging. *Sci World J* 2014:147016
- Smith D, Elsdon M, Leach M, Fernando M, Foti SJ (2006) 3D microwave imaging for medical and security applications. In: *IEEE international RF and microwave conference (RFM-2006)*, pp 233–237
- Banerjee S, Rana B, Parui SK, Chatterjee S, Dey N (2017) HMSIW based miniaturized sensing antennas for S- and C-band applications. *IEEE Sens Lett* 1(1):1–4
- Biswarup R, Parui SK (2017) Microstrip line fed wideband circularly-polarized dielectric resonator antenna array for microwave image sensing. *IEEE Sens Lett* 1(3):3500604
- Lai Q, Fumeaux Ch, Hong W, Vahldieck R (2009) Characterization of the propagation properties of the half-mode substrate integrated waveguide. *IEEE Trans Microw Theory Tech* 57:1996–2004
- Xu J, Hong W, Tang H, Kuai Z, Wu K (2008) Half-mode substrate integrated waveguide (HMSIW) leaky-wave antenna for millimeter wave applications. *IEEE Antennas Wirel Propag Lett* 7:85–88
- Lai QH, Hong W, Kuai ZQ, Zhang YS, Wu K (2009) Half-mode substrate integrated waveguide transverse slot array antennas. *IEEE Trans Antennas Propag* 57:1064–1072
- Zelinski GM, Thiele GA, Hastriter ML, Havrilla MJ, Terzouli AJ (2007) Half width leaky wave antennas. *IET Microw Antennas Propag* 1:341–348

14. Martinez-Ros AJ, Gomez-Tornero JL, Goussetis G (2012) Planar leaky-wave antenna with flexible control of the complex propagation constant. *IEEE Trans Antennas Propag* 60:1625–1630
 15. Banerjee S, Rana B, Parui SK (2016) Substrate integrated waveguide based triangular antenna arrays. *Microw Opt Technol Lett* 58(3):675–679
 16. Banerjee S, Rana B, Parui SK (2016) SIW based compact and dual-band equilateral triangular antennas. *J Electromagn Waves Appl* (Taylor & Francis) 30(5):637–650
 17. Petosa A, Ittipiboon A (2010) Dielectric resonator antenna: a historical review and the current state of the art. *IEEE Antennas Propag Mag* 52:91–116
 18. Tadjalil A, Sebak AR, Denidni TA (2006) Resonance frequencies and far field patterns of elliptical dielectric resonator antenna: analytical approach. *Prog Electromagn Res* 64:81–98
 19. Song Y, Sebak AR (2006) Radiation pattern of aperture coupled prolate hemispheroidal dielectric resonator antenna. *Prog Electromagn Res* 58:115–133
 20. Cheng J, Rui L, Alphones A, Bao X (2013) Quarter-mode substrate integrated waveguide and its application to antennas design. *IEEE Trans Antennas Propag* 61:2921–2928
 21. Sauer T (2006) *Numerical analysis*. Pearson Educ, Upper Saddle River
 22. Pozar DM (2005) *Microwave engineering*, 3rd edn. Wiley, New York
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