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Substrate integrated waveguide fed dual-frequency dual-linearly-polarized dielectric resonator antenna

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Research Paper

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In this paper, a single-feed dual-frequency dual-linearly-polarized dielectric resonator antenna is proposed which finds application in two- way internet satellite system and modern radar system. In order to achieve dual linear polarization at distinct frequencies, two rectangular dielectric resonators of same dimensions are excited in $TE^{x}_{\delta 11}$ and $TE^{y}_{1\delta 1}$ modes by a narrow longitudinal and transverse slot, respectively, etched on the top wall of the substrate integrated waveguide. The −10 dB impedance bandwidth of the proposed antenna is 6.76% for both the frequency bands. The antenna radiates along the broadside direction and the gain of the antenna varies from 5.37 to 6.24 dBi and 5.62–7.96 dBi across 8.14–8.71 GHz and 10.29–11.01 GHz, respectively.

Introduction

With the rapid development in the modern wireless communication technology, antennas having multi-band and diverse polarization characteristics are required for enhancing the capabilities of wireless systems [1,2]. The polarization diversity can be obtained in different ways such as (i) exciting the antenna with multi-port, thereby generating different polarizations in the same or distinct frequency bands [3–5] (ii) exciting the antenna using a single port, thereby generating multi-band behavior having different polarization at different frequency [2]. The diversified antenna can either be linearly polarized (LP) having horizontal/vertical polarization or circularly polarized (CP) having distinct sense (RHCP/LHCP) either at same or different frequencies. In certain situations, diversified antenna can be designed in such a way that it is linearly polarized at one frequency and circularly polarized at another frequency. Over the past few years, several printed dual-band dual-polarized antennas have been reported which include single-feed [1,2,6–8] and multiple-feed [9,10] designs.

The dielectric resonator antennas (DRAs) in contrast to conventional metal-based radiators, offer several alluring features such as high-radiation efficiency (due to lack of surface wave and conductor losses), low dissipation loss, relatively wider bandwidth, ease of excitation etc [11]. Being a volumetric radiator, it gives more design flexibility and versatility than the conventional microstrip antennas. Additionally, different modes with diverse radiation characteristics can be excited within a single dielectric resonator, which makes it an attractive candidate for diversity and multifunctional applications. In the past few years, several dual polarized DRAs have been reported for single band [4,5,12–14] and multi-band [15–17] operation using multi-port technique, where the two ports excite the distinct polarization. However, the use of single-feed or one port can reduce the system complexity and cost of the receiver front-end in lieu of conventional dual-port systems. The development of single-feed dual-band dual-polarized DRA is in early stage and few designs have been reported [18–22]. For example in [19], a probe cylindrical DRA fed by SIW cavity has also been proposed for dual-band dual-linearly-polarized applications, however, the radiation efficiency is quite low. In [20], dual-band and dual-sense omnidirectional circularly polarized antenna comprising of dielectric resonator and patch has been proposed. In [21], a hybrid Z-shaped DRA having LP and CP at different frequencies has been reported for WLAN, WiMAX and satellite communication. A dual-band dual-polarized (LP+CP) system has been designed for a wireless application using a hybrid approach where an inverted regular pentagon slot produces CP and DRA produces LP [22]. All the earlier reported designs of single-feed dual-band/multi-band dual-polarized DRA are below X-band.

A single-feed dual-band dual-linearly-polarized antenna can be designed by exciting a single DRA with two orthogonal slots which is the most common excitation technique. However, as the frequency increases, the size of DR decreases for a particular value of dielectric constant. Owing to the small size of DR at high frequency, it is quite difficult to accommodate two orthogonal slots beneath the DR which makes the excitation difficult. Due to this reason, in this paper, a SIW-fed dual-frequency dual-linearly-polarized DRA is proposed in X-band, where the orthogonal polarization at distinct frequency is achieved by exciting two rectangular DRs of the same dimensions using two orthogonal slots etched on top wall of SIW. The use of

SIW to feed the dielectric resonator eliminates the radiation losses of feeding network and makes it a highly efficient radiator, especially, at higher frequency [23]. The simulations are done using CST Microwave Studio and a prototype of the same is built for experimental verification. The proposed antenna can be scaled to higher frequency for millimeter wave applications such as next- generation 5G communication systems or it can easily be extended to a linear and 2D array using SIW- based power divider to achieve higher directivity.

Problem formulation, antenna design, analysis

Problem formulation

The main aim of this work is to design single feed dual-frequency dual-linearly-polarized DRA. In order to design the antenna, two rectangular DRs of similar dimension are excited by a narrow longitudinal and transverse slot, situated on the broad wall of SIW. However, before describing the design process of the proposed antenna, the resonant modes of an isolated rectangular dielectric resonator (RDR) are first briefly described.

An isolated RDR of relative permittivity ϵ_{rd} and dimensions W (along x-axis), L (along y-axis) and B=2H (along z-axis) would support TE^x, TE^y and TE^z, modes [11]. With $L > W > B$, the resonant frequency of $TE^x_{\delta 11}$ mode is lower than $TE^y_{1\delta 1}$ mode. Using the dielectric waveguide model, the resonant frequency of $TE^x_{\delta 11}$ mode can be calculated by solving the following transcendental equation [11]

$$k_x \tan\left(\frac{k_x W}{2}\right) = \sqrt{(\epsilon_{rd} - 1)k_0^2 - k_x^2}, \tag{1}$$

and

$$k_y = \frac{m\pi}{L} \quad \text{and} \quad k_z = \frac{n\pi}{B} \quad \text{where} \quad m = n = 1, \tag{2}$$

where, k_x, k_y, and k_z are the wavenumbers along the x-, y-, and z-directions and are related as

$$k_x^2 + k_y^2 + k_z^2 = \epsilon_{rd} k_0^2, \tag{3}$$

where, k_0 denotes the free space wavenumber. The resonant frequency of $TE^y_{1\delta 1}$ mode can be calculated in the same way as above. Based on the above equations, different RDRA dimensions are possible for a particular value of dielectric constant such that both the modes resonates in X-band. Some of the possible dimensions are given in Table 1. For the present design, we have chosen $W =$ 7 mm, $L = 10$ mm, and $H = 3.81$ mm.

Table 1. Possible RDRA dimensions for $\epsilon_{rd} = 10.2$

W (mm)	L (mm)	H (mm)	f_L (GHz)	f_U (GHz)
7	10	3.81	8.90	9.77
5	10	5.08	8.37	11.08
5	7	6.35	9.40	11.15
12	16	2.54	10.18	10.33

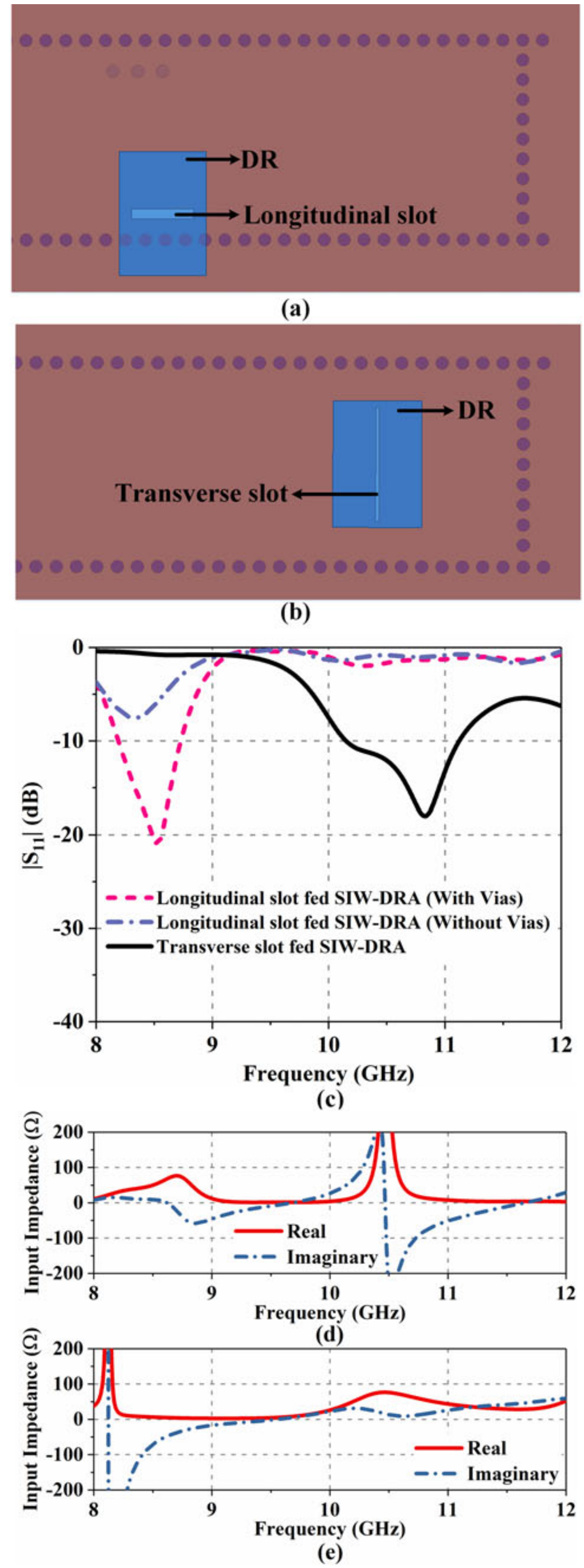

Fig. 1. Different antenna configurations and simulated response (a) SIW-fed DRA using longitudinal slot (b) SIW- fed DRA using transverse slot (c) Reflection coefficient (d) Input impedance plot for longitudinal slot-fed DRA (e) Input impedance plot for transverse slot-fed DRA.

Once the antenna dimensions are chosen, an appropriate feeding network is designed to facilitate the dual-frequency dual-polarized operation as described in the next section.

Antenna design and analysis

In order to design SIW- fed dual-frequency dual-linearly-polarized DRA, we first design two different configurations of SIW fed DRA. In the first configuration (refer Fig. 1(a)), DR is excited through a narrow longitudinal slot etched on the broad wall of the SIW and in the second configuration (refer Fig. 1 (b)), a narrow transverse slot is used to excite the rectangular DR. The DR under investigation is made of Rogers RT/Duroid 6010 of relative permittivity 10.2 and has dimensions $W \times L \times H$. The dimensions of the rectangular DR are chosen such that the operating frequency of both the configurations fall in X-band. The X-band SIW presented here is designed on Rogers RT/Duroid 5880 substrate of dielectric constant 2.2 and thickness 0.787 mm. The two rows of metallic vias are placed a_{SIW} distance apart which is calculated using the following equation [24]

$$a_{SIW} = W_{equi} + p(0.766e^{(0.4482d/p)} - 1.176e^{(-1.214d/p)}), \quad (4)$$

where p is the pitch between the vias, d is the diameter of vias and W_{equi} is the effective waveguide width determined as [24]

$$W_{equi} = \frac{c}{2f_c\sqrt{\epsilon_{rs}}}, \quad (5)$$

where ϵ_{rs} is the substrate permittivity. The diameter d and pitch p are chosen in order to maintain the minimum leakage of energy through sidewall of SIW [24] and the width of SIW (a_{SIW}) is chosen for the single fundamental TE_{10} mode propagation.

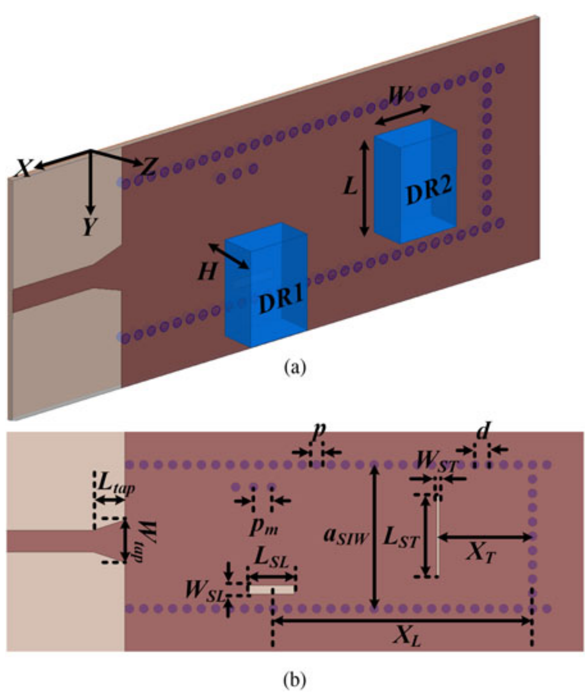

Fig. 2. Geometry of the proposed dual-frequency dual-polarized DRA (a) Isometric view (b) Top view without DR.

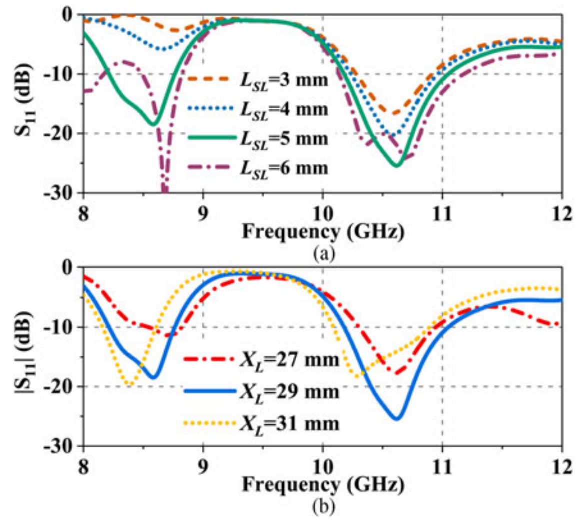

Fig. 3. Simulated reflection coefficient of dual-frequency dual-polarized DRA for different values of (a) longitudinal slot length L_{SL} (b) slot position X_L.

Figure 1(c) shows the reflection coefficient of the two configuration of SIW-fed DRA and the corresponding input impedance curve is depicted in Figs 1(d) and 1(e). The longitudinal slot excites the DRA in $TE^x_{\delta 11}$ mode whereas the transverse slot excite the DRA in $TE^y_{1\delta 1}$ mode. The theoretical resonant frequency calculated using (1)–(3) for $TE^x_{\delta 11}$ and $TE^y_{1\delta 1}$ mode is 8.90 GHz and 9.77 GHz, respectively whereas the simulated resonant frequency is 8.53 GHz and 10.74 GHz, respectively. The shift in the theoretical and simulated frequency is due to the fact that mathematical analysis considers infinite ground plane and it did not account the effect of slot [23]. In case of longitudinal slot excitation, extra vias are embedded near the slot. These vias helps in the impedance matching [25] which is clearly inferred from Fig. 1(c).

Next, in order to design dual-frequency dual-linearly-polarized antenna, both the longitudinal and transverse slot are accommodated on the broad wall of the same SIW as shown in Fig. 2. This configuration will excite two similar DRs at distinct frequency simultaneously to achieve dual-frequency dual-polarized response. The element *DR1* is excited by a narrow

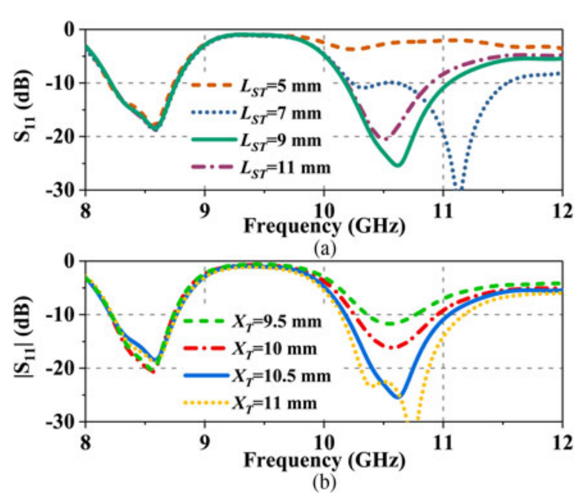

Fig. 4. Simulated reflection coefficient of dual-frequency dual-polarized DRA for different values of (a) transverse slot length L_{ST} (b) slot position X_T.

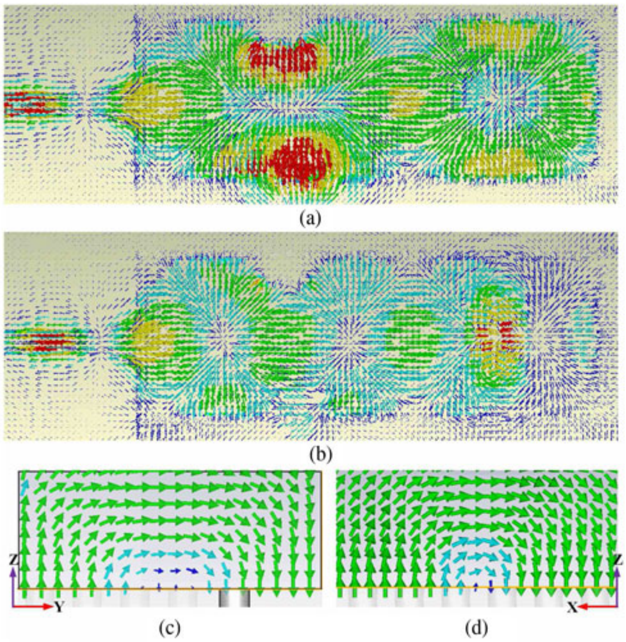

Fig. 5. (a) Current distribution in SIW at (a) 8.58 GHz (b) 10.62 GHz and Electric field distributions in the rectangular DR at (a) 8.58 GHz (*yz*-plane) (b) 10.62 GHz (*xz*-plane).

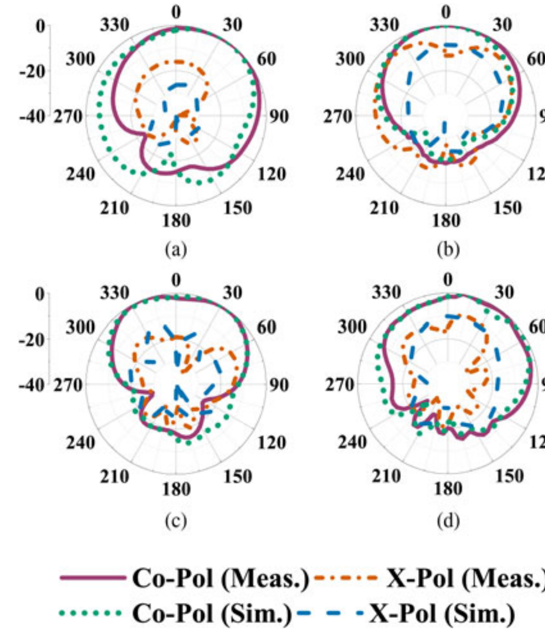

Fig. 7. Normalized radiation pattern of the proposed antenna (a) *yz*-plane (lower frequency) (b) *yz*-plane (upper frequency) (c) *xz*-plane (lower frequency) (d) *xz*-plane (upper frequency).

longitudinal slot of dimension $L_{ST} \times W_{ST}$ located at a distance of X_L from the shorting wall and the element *DR2* is excited by a narrow transverse slot of dimension $L_{SL} \times W_{SL}$ located at a distance of X_T from the shorting wall.

Figure 3 shows the effect of longitudinal slot length L_{SL} and its position X_L on the reflection coefficient. It is evident from the figure that the change in L_{SL} affects the matching of lower frequency band whereas the matching of upper frequency band is not affected much and S_{11} remains well below −10 dB for different values of L_{SL}. Similarly, the change in the value of X_L affects only the matching of the lower band. The similar variation in the response of the antenna is observed for different slot width. Figure 4 shows the effect of transverse slot length L_{ST} and its position X_T on the reflection coefficient of the antenna. It is observed from the figure that, changing the transverse slot length affects the matching of upper frequency band whereas the S_{11} remains well below −10 dB for lower frequency band. The change in the slot position X_T affects the matching of upper band whereas it hardly affects the lower band.

The above parametric study confirms that the element *DR1* is responsible for lower resonance whereas the element *DR2* is responsible for upper frequency.

Figures 5(a) and 5(b) shows the current distribution in SIW at 8.52 GHz and 10.62 GHz, respectively. It is observed that at both the frequency the current distribution resembles the current distribution of TE_{10} mode of the substrate integrate waveguide which helps in the excitation of DR through the narrow slots.

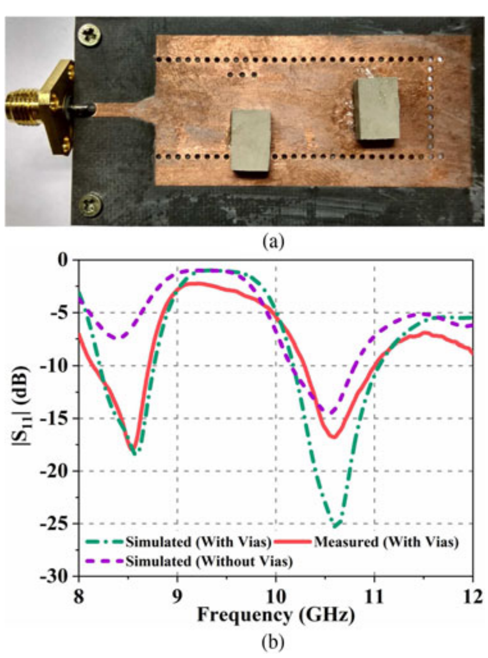

Fig. 6. (a) Fabricated prototype of the proposed antenna (b) Simulated and measured response of the proposed dual-frequency dual-polarized DRA.

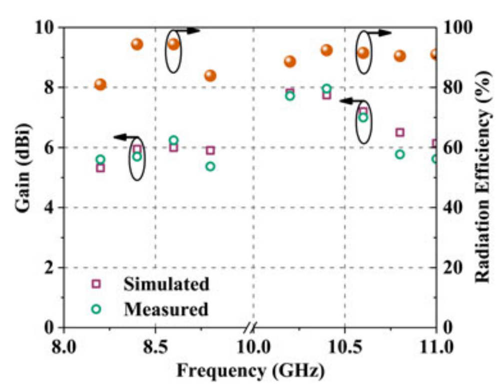

Fig. 8. Simulated and measured gain and simulated radiation efficiency of the proposed antenna.

Table 2. Comparison of the proposed antenna with the other single-fed dual-polarized dual-band DRAs

Ref	Antenna type	Polarization type	Bandwidth (%) BW_L/BW_U	Gain G_L/G_U	$\eta L/\eta U$ (%)	Design
[6]	Multilayer SIW-fed patch	LP+LP	7.3/7.76	8.5 dBi	87	Complex
[7]	Patch	LP+CP	4.56/2.15	2 dBiC/2.27 dBi	NA	Easy
[8]	SIW cavity backed slot antenna	LP+LP	7.2/8.74	5–5.3 dBi/3.2–4.4 dBi	NA	Complex
[18]	Cylindrical DRA	LP+CP	5.5/17.24	3.37/4.7 dBi	97	Easy
[19]	Cylindrical DRA	LP+LP	0.85/1.25	3.7/4.7 dBi	67/87	Easy
[20]	DRA+patch	CP+CP	2.64/18.03	1/1.4 dBiC[†a]	NA	Easy
[22]	CDRA+slot	LP+CP	18.31/23.14	5.5/6.2 dBi	NA	Easy
Proposed antenna	**SIW-fed rectangular DRA**	**LP+LP**	**6.76/6.76**	**5.37–6.24/ 5.62–7.96 dBi**	**91/94**	**Easy**

The bold values highlight the proposed antenna as compared to other related antennas. NA, not available.
[†a]Average gain.

To gain insight into the resonant modes responsible for radiation, the simulated modal *E*-field distribution at 8.58 GHz and 10.62 GHz are portrayed in Figs 5(c) and 5(d). From the figure, it is evident that $TE^x_{\delta 11}$ mode is excited at 8.58 GHz whereas $TE^y_{1\delta 1}$ is excited at 10.62 GHz. With reference to the coordinate system shown in Fig. 2, the longitudinal slot excites *DR1* in $TE^x_{\delta 11}$ mode, generating linear vertical polarization at the lower frequency whereas the transverse slot excites *DR2* in $TE^y_{1\delta 1}$ mode, thereby producing linear horizontal polarization at the upper frequency.

Antenna fabrication and experimental results

To validate the proposed design, a prototype of DRA is built using Rogers RT/Duroid 6010 of dielectric constant 10.2 with design parameters: L = 10 mm, W = 7 mm, H = 3.81 mm, p = 1.6 mm, d = 1 mm, $a_{SIW} = 16.12\,mm$, $L_{ST} = 9\,mm$, $W_{ST} = 0.25\,mm$, $L_{SL} = 5\,mm$, $W_{SL} = 1\,mm$, $X_L = 29\,mm$, $X_T = 10.5\,mm$, $p_m = 2\,mm$. The rectangular DRs of desired dimension are cut from Rogers RT/Duroid 6010 ($\epsilon_{rd} = 10.2$) having thickness of 1.27 mm with the help of abrasive waterjet machine. The pieces are then glued together using commercially available adhesive to get the desired height. The measurement of the reflection coefficient is carried out using Aglient E5071C vector network analyzer. Figure 6 depicts the comparison between the simulated and measured reflection coefficient of the proposed SIW fed dual-frequency dual-linearly-polarized DRA. The measured resonant frequencies of two modes are 8.54 GHz and 10.60 GHz, which fairly agree with the simulated values of 8.58 GHz and 10.62 GHz. The simulated and measured impedance bandwidth (for S_{11}<−10 dB) of lower band is 6.48% (8.21–8.76 GHz) and 6.76% (8.14–8.71 GHz), respectively and the corresponding data for the upper band is 8.2% (10.17–11.04 GHz) and 6.76% (10.29–11.01 GHz), respectively. A little deviation between the simulated and measured results can be attributed to fabrication imperfection, alignment of DR, the inevitable air gap between the DR and the feeding structure. Though a very thin layer of glue is used but it might affect the measurement as well.

Figure 7 shows the comparison between the simulated and measured normalized radiation pattern of the proposed antenna at two operating frequencies. The proposed antenna radiates along the broadside direction with cross polarization level better than −10 dB in both *xz*- and *yz*-plane. The simulated and measured gain of antenna ranges from 5.32 to 6.00 dBi and 5.37–6.24 dBi, respectively at lower band whereas in upper band it varies from 6.14 to 7.82 dBi in simulation and 5.62–7.96 dBi in measurement as shown in Fig. 8. The radiation efficiency of the antenna is 94% at lower operating frequency and 91% at upper operating frequency.

A very few DR- based single feed dual-frequency dual-linearly-polarized antennas were available in the open literature. Table 2 shows the comparison of the proposed antenna with some other related antennas.

Conclusion

A novel substrate integrated waveguide fed dual-frequency dual-polarized rectangular DRA has been proposed. The polarization diversity at distinct frequency has been achieved by exciting two rectangular dielectric resonators of same dimension in $TE^x_{\delta 11}$ and $TE^y_{1\delta 1}$ mode through narrow longitudinal and transverse slot, respectively etched over the substrate integrated waveguide. The $TE^x_{\delta 11}$ mode generates linear vertical polarization at lower frequency while the $TE^y_{1\delta 1}$ mode produces linear horizontal polarization at higher frequency. The −10 dB impedance bandwidth of the proposed antenna is 6.76% in each band. The antenna exhibits broadside radiation at both the operating frequency with cross-polarization level better than −10 dB in both the planes. The gain of antenna varies from 5.37 to 6.24 dBi in lower band and 5.62–7.96 dBi in the upper band. The proposed antenna could be suitable for two-way satellite internet systems, modern radar systems. Moreover, it can be scaled to higher frequency for millimeter wave applications such as next generation 5G communication system.

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