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Design of a broadband planar cavity-backed circular patch antenna

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ABSTRACT

This paper presents a design of a low-profile cavity-backed circular patch antenna for broadband applications. By using substrate integrated waveguide (SIW) based cavity and feeding mechanism, a planar cavity-backed patch antenna is realized. The proposed study demonstrates that a wide impedance bandwidth can be achieved by employing a rectangular SIW-based cavity underneath the conventional circular patch. Additionally, to generate circular polarization (CP), the patch has been reduced diagonally and shorted by a via-probe. Finally, a CP SIW-based antenna is designed and operating for a wide impedance bandwidth of 23.10% below −10 dB criteria, ranging from 9.09 GHz to 11.40 GHz and axial-ratio (AR) bandwidth of 270 MHz (10.30–10.57 GHz). The proposed design is fabricated by means of a printed circuit board (PCB) procedure. The simulated results are validated with the experimental one which agrees well with each other in the terms of S_{11}, antenna gain, AR and radiation patterns. Moreover, the proposed design exhibits unidirectional radiation characteristics with the measured peak gain of 6.6 dBic while maintaining planar integration.

1. Introduction

Over recent years, the deployment of cavity-backed antennas (CBAs) have been tremendously progressed in the satellite communication due to their high gain, stabilized unidirectional radiation characteristics and resistance to unanticipated electromagnetic interferences in the atmosphere. Generally, the conventional type CBAs are espoused with a bulky metallic cavity to discard backside radiation. This inhibits the operation of such antennas in modern compact wireless systems, where essentially lightweight, low-profile, and planar integration is preferred [1,2]. To satisfy these requirements for the modern wireless communication system, a relatively new technique has been emerged named ‘substrate integrated waveguide’ (SIW) technology for the development of planar CBA structures. It was firstly implemented in [3], where a planar SIW-cavity is developed by embedding the chains of metallic vias in the dielectric substrate. Thus, the technology incorporates the realization of a planar version of volumetric conventional backing cavity antennas. The SIW-based CBAs offer the merits of its conventional equivalent, such as high quality (Q) factor and low-loss transmission, and also easy to manufacture using the standard printed-circuit-board (PCB) process [4,5]. Hence, this leads the mass productivity.

A variety of SIW-based CBAs have been designed and investigated for different wireless applications [6–15]. A pair of circularly polarized (CP) SIW CBAs are proposed in each [7] and [8], where the cross-shaped slot and half-mode SIW (HMSIW) is used to generate CP. However, these mentioned antenna structures exhibit limited impedance bandwidth due to the loading effect of high Q – factor SIW cavity and resonating slot characteristics. Many methods have been addressed in the previously reported work to eradicate the inherent limited bandwidth of SIW-based CBAs.

An SIW-based CBA is validated in [9], where, a conventional bowtie slot is used to generate two narrowly spaced hybrid resonant modes and the bandwidth was improved up to 9.4%. In [10], HMSIW cavity-backed U-slot antenna with CP is investigated and impedance bandwidth of 11.6% was realized. A linearly polarized multilayered SIW antenna was suggested in [11] with an impedance bandwidth of 10.9% and gain up to 7.7 dBi. Broadband antennas with CP presented in [12] and [13], provide the impedance bandwidth of 18.74 and 23.3% respectively. Though the most of the mentioned antennas show good electrical performances, merely a few of them are proficient in operating a broadband impedance bandwidth.

In this paper, the SIW technique is implemented to develop a planar cavity-backed patch antenna for broadband applications. The proposed design is a combination of the cavity-backed resonator, conventional circular patch and SIW feeding network. The SIW-cavity has an upper open-ended rectangular aperture and a perturbed circular patch that radiates the energy into the free space with the generation of CP. The feeding mechanism of the mounted patch includes a coupling of an upper cladding of the SIW and a shorted via-probe, which confirm the wideband impedance matching characteristics. In conclusion, the proposed design exhibits an impedance bandwidth and axial-ratio (AR)

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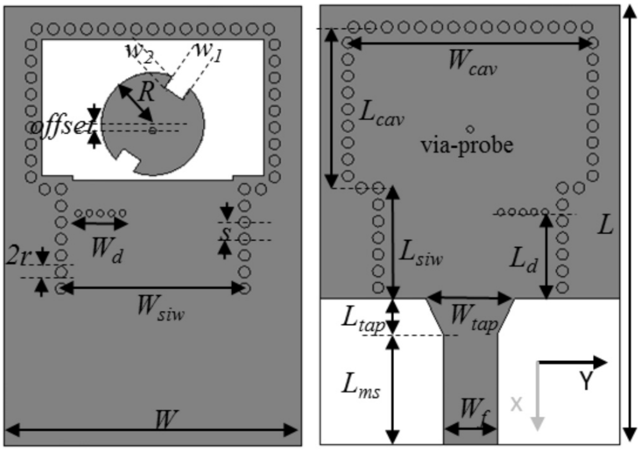

(a) Top (b) Bottom

Fig. 1. Configuration of the proposed SIW-based antenna ($W = 26.0$ mm, $L = 39.0$ mm, $r = 0.5$ mm, $s = 1.5$ mm, $W_d = 4.6$, $L_d = 7.8$ mm, $L_{ms} = 10.0$ mm, $L_{tap} = 3.2c$ mm, $W_{tap} = 8.0$ mm, $L_{cav} = 14.5$ mm, $W_{cav} = 22.0$ mm, $L_{siw} = 9.1$ mm, $W_{siw} = 16.6$ mm, $W_{tap} = 7.6$ mm, $w_1 = 1.9$ mm, $w_2 = 1.2$ mm, $R = 4.47$ mm, $W_f = 4.9$ mm).

bandwidth of 23.10% and 2.7%, respectively.

2. Antenna design procedure and principle of operation

As an SIW is a planar counterpart of the metallic rectangular waveguide, the PCB's top and bottom claddings form the broad walls of the SIW structure and periodic metalized via arrays are used to employ the narrow walls. The proposed SIW-based antenna is an assembly of a radiating element reduced (perturbed) the conventional circular patch with a shorted via-probe and a rectangular SIW-cavity as shown in Fig. 1. The reduced patch generates CP, and an SIW-cavity resonator provides high gain and suppresses the backside lobe radiation. The antenna is excited by an SIW-based rectangular waveguide feed, which provides better isolation from external interferences. This feed is integrated with a horizontal inductive diaphragm formed by linear via array which acts as a matching network for broadband impedance characteristics, as well as to excite right-handed-CP (RHCP) [12]. The SIW feed is extended by 50 Ω microstrip line for measurement and a tapered microstrip-to-SIW transition is adopted for smooth power transmission from the input source. Initially, the tapered length is chosen as a quarter of a guiding wavelength (λ_o) in the free space at 10 GHz, further it has been optimized to 3.48 mm. The microstripline is placed at the backside of the design which provides extra shielding from the spurious radiation. The total occupied dimensions of the antenna, including transition is in terms of λ_o is 0.86 λ_o × 1.3 λ_o × 0.05 λ_o. The proposed antenna assembly is designed on Rogers (RT/Duroid 5880, $\varepsilon_r = 2.2$ tan $\delta = 0.0009$@ 10 GHz) dielectric substrate with a thickness (h) 1.57 mm. Optimized geometrical parameter values are presented in Fig. 1. The optimization process is performed by using a commercial CST-MWS full-wave simulator.

The preliminary dimensions of the SIW structure can be calculated by considering it as a dielectric-filled conventional rectangular waveguide. The corresponding width of the SIW feed ($W_{siw} = 16.6$ mm) has been determined from the cutoff frequency (f_c) of 6.37 GHz of the fundamental TE_{110} mode by [5]. The physical parameters of metalized vias ($r = 0.5$ and $s = 1.5$) are adjusted such that it must satisfy the conditions $2r/s \geq 0.5$ and $2r/\lambda_0$ to ensure a minimal amount of leakage energy from via gaps along the narrow walls, where λ_o denotes the free space guiding wavelength [14].

The geometrical parameters of the SIW-cavity resonator are optimized, so that it can be applied in its dominant TE_{110} mode at 8.3 GHz as presented in Fig. 2. The SIW-cavity is a closed resonant structure has a characteristic of confining the leakage energy. The radius (R) of the circular patch operating at 10 GHz can be approximated by (1) and (2) [15], and finally optimized to 4.47 mm.

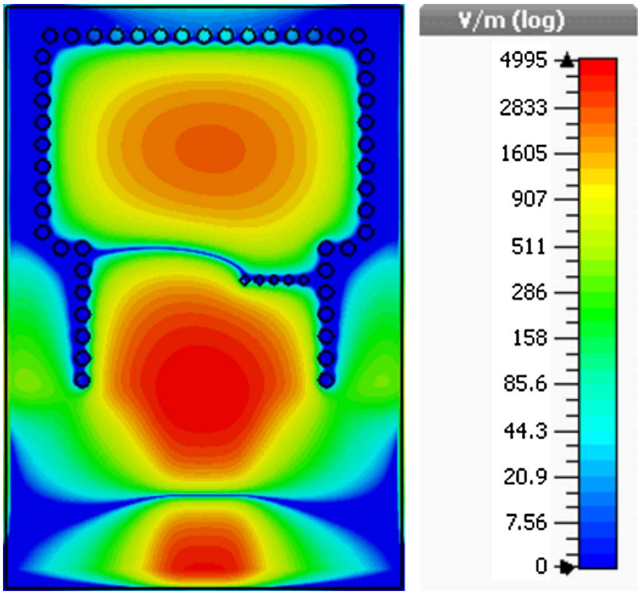

Fig. 2. Electric field distribution of SIW cavity resonator at 8.3 GHz (TE_{110} mode).

$$R = \frac{F}{\sqrt{\left\{1 + \frac{2h}{\pi\varepsilon_r F}\left[ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]\right\}}} \tag{1}$$

$$F = \frac{1.8412*c}{2\pi f_r\sqrt{\varepsilon_r}} \tag{2}$$

The reflection coefficient (S_{11}) and axial ratio (AR) performance of the proposed design, with and without perturbation on the circular patch antenna is depicted in Fig. 3. From the reflection coefficient of the perturbed circular patch, it seems that the antenna is demonstrating three resonances at the frequencies of 9.49, 10.58 and 11.01 GHz, which results broadening of impedance bandwidth up to 23.1%, ranging from 9.09 GHz to 11.40 GHz, suitable for X (8–12 GHz) band applications. Also, the input resistance and reactance curve certify the wideband matching conditions as shown in Fig. 4. It is conjectured that the first two resonances are due the separation into a dual resonant TM_{11} mode at nearby frequencies of a single TM_{11} mode, which is generated by defecting the conventional circular patch to obtain RHCP as shown in Fig. 3. This mechanism can be clearly understood with the help of electric-field distributions, which shows that the zero-potential

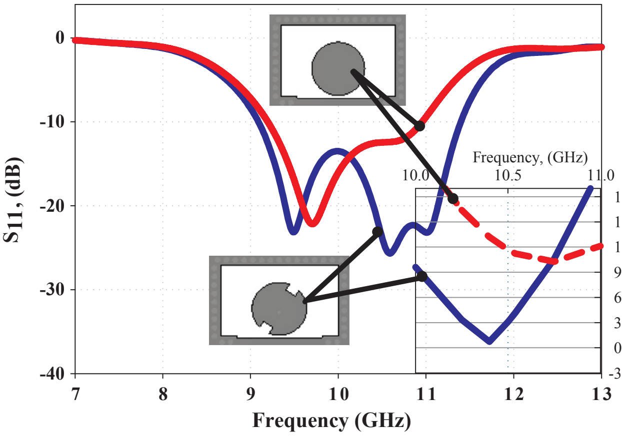

Fig. 3. The simulated reflection coefficients with and without perturbation on the circular patch.