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Research Article

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High Gain Cavity Backed SIW Array Antenna for Microwave Communications

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Abstract
A high gain 4-element Cavity Backed Substrate Integrated Waveguide (CBSIW) based antenna is proposed in this paper. The combination of low loss SIW cavities with quarter wave transformer based transmission line power divider can enhance the gain and power efficiency of the CBSIW antenna. A bow-tie shaped slot is located on rectangular shaped SIW cavity with optimum dimensions to form each element. The feed network is constructed with two quarter wave T-junction power dividers connected back-to-back to accomplish the impedance matching and optimum power distribution to the elements. The proposed CBSIW antenna exhibits a high gain of 21.9dBi with 82% of efficiency on low cost FR4 epoxy substrate. The measured results agree with simulated results obtained from commercial HFSS full-wave electromagnetic solver.

Keywords: Cavity Backed Substrate Integrated Waveguide (CBSIW), 4-element array, T-Junction, Quarter Wave Transformer, Power Divider, Gain, Ansys HFSS software.

1. INTRODUCTION
To be able to integrate entire microwave system in a single substrate with extremely low losses makes the Substrate Integrated Waveguide (SIW) system an attractive choice for developing microwave communication systems. Moreover, SIW structures maintain the majority of the benefits of conventional rectangular waveguide with self-consistent electrical shielding [1]. Cavity backed SIW (CBSIW) is an impressive candidate in SIW family to erect microwave antennas consisting high gain, high power handling capabilities and low surface wave losses with improved efficiency. The conventional high directive microstrip antennas suffer with large and complex feed structure requirements with extraneous radiation and ohmic losses from feeds and junctions [2]. In this perspective, to achieve the highly directive radiation requirements of emerging technologies including IoT, 5G, microwave and mm-wave communications, CBSIW array antenna can be a smart preference[3,4].The applicability of these promising features to future microwave IoT, 5G technologies has been presented in [5,6]. The implementations of several SIW antenna designs using innovative materials have been proposed in [7].

Enhancement of gain with optimum efficiency has been an essential concern in development of highly directive smart microwave radiators. Several Gain enhancement strategies in the design ofSIW have been proposed formerly. A single layered 4X4 cavity backed SIW array is proposed with wideband T-junction and obtained unidirectional radiation pattern with minimized cross polarization in [8]. The high gain characteristics were achieved by inserting a metallic via-brick into the SIW cavity in [9]. Metallic posts are incorporated in the cavity to excite TM220 mode to generate high-order cavity resonance in [10]. A 16x16 SIW array design for high gain with suppressed SLL is proposed in [11]. A circularly polarized 4x4 array on SIW technology is presented in [12]. A dual polarized 8x8 SIW antenna operating at 60GHz is designed with triple layer in [13].A dual mode SIW ring slot is uses to unveil the TE102 mode in the cavity [14]. A high gain dual polarized CBSIW shorted annular patch antenna is proposed for X-band operation in [15]. An SIW antenna consisting of 8 radiating slots and excited by two separated SIW feeding network to excite higher order TE430 and TE340 modes is presented in [16]. The diagonal TE120 and TE210 modes are excited in a differential dual polarized CBSIW in [17]. A narrow SIW cavity with high length-to-width ratio is used to generate a hybrid mode distribution of fields in the cavity in [18]. A novel differential high gain CBSIW antenna of H-shaped slot with high-quality common mode suppression is developed for X-band applications in [19]. A periodic strip loaded reconfigurable SIW leaky wave antenna excited with a tapered line transition is proposed in [20]. Aiming the higher bandwidth with optimum gain a wideband 4-element cavity backed SIW array is proposed in [21].

The present paper demonstrates the design and analysis of a novel high gain 4-element CBSIW array antenna fed with quarter wave T-junction power divider. A bow-tie shaped slot with optimized dimensions is positioned on each cavity. An efficient T-junction quarter wave line feed network is used to achieve optimum power distribution along with better impedance matching to all the SIW cavities. The CBSIW array is designed and simulated using Ansys HFSS software and the results are validated with measured ones.

This paper is prearranged as follows. Section II describes design methodology and sufficient conditions that are to be followed for theconstruction of cavity backed SIW array. Section III describes the structure and design parameters of two layer SIW.
architecture of proposed antenna. Section IV demonstrates the observations from the simulated and measured results and finally Section V is conclusion.

2. DESIGN METHODOLOGY

The design process of proposed SIW array requires various steps in calculating design parameters for cavity elements as well as feed network. The preliminary dimensions of the SIW Cavity depend on cutoff frequency $f_c$ and the dielectric constant $\varepsilon_r$ of the substrate material used. The basic CBSIW can be constructed by systematically incorporating cylindrical conducting vias connecting the upper and bottom layers forming rectangular cavity like structure. The diameter and spacing between the adjacent vias influence the energy leakage from the longitudinal walls of the SIW.

Fig.1. Isometric View of the Rectangular cavity

Fig.2. Equivalent SIW Rectangular Cavity

The basic SIW construction follows proper mathematical formulation and design guidelines proposed in [22]. The total design flow is represented as follows.

Step 1: Calculate the dimensions of the SIW cavity following the design guidelines and Resonance frequency $f_{mnp}$

$$f_{mnp} = \frac{1}{2\pi\sqrt{\mu\varepsilon}} \sqrt{\left(\frac{m\pi}{L_{eff}}\right)^2 + \left(\frac{n\pi}{W_{eff}}\right)^2 + \left(\frac{p\pi}{h}\right)^2}$$  \hspace{1cm} (1)

Where $m, n$ and $p$ are number of half-wave variations along length, width and height respectively. And
\[ L_{\text{eff}} = L_c - 1.08 \frac{d^2}{s} + 0.1 \frac{d^2}{L_c} \]  \hspace{1cm} (2)

\[ W_{\text{eff}} = W_c - 1.08 \frac{d^2}{s} + 0.1 \frac{d^2}{W_c} \]  \hspace{1cm} (3)

Where \( L_{\text{eff}} \) and \( W_{\text{eff}} \) are effective length and width of the SIW, whereas \( L_c \) and \( W_c \) are original length and width of the cavity respectively. The cutoff frequency of the SIW cavity can be obtained by

\[ f_c = \frac{c_0}{2W_{\text{eff}} \sqrt{\varepsilon_r}} \]  \hspace{1cm} (4)

Where \( c_0 \) represents the velocity of light in freespace.

Here \( d \) is the diameter of the each via and \( s \) is the spacing between two adjacent vias. The necessary condition that needs to be followed to avoid the leakages from the side wall is

\[ \frac{d}{s} \geq 0.5 \text{ and } \frac{d}{\lambda_0} \leq 0.1 \]  \hspace{1cm} (5)

**Step 2:** Construct the cavity for desired mode of operation using specified dimensions \( L_{\text{eff}}, W_{\text{eff}}, s \) and \( d \).

**Step 3:** Study the modes of SIW cavity and identify the desired modes by viewing its field pattern.

**Step 4:** Place the bow-tie shaped radiating slots on the cavity and optimize the location and dimensions of it.

**Step 5:** Calculate the dimensions of the quarter wave T-junction power divider [23] using equation 6 for given dielectric constant \( \varepsilon_r \), height \( h \) and thickness \( t \) of the copper layer of the substrate and frequency of operation.

**Step 6:** Construct the feed network with two quarter wave T-junction power dividers connected back-to-back to accomplish the impedance matching and optimum power distribution to the elements.

**Step 7:** Depending upon the desired mode pattern, connect the feed strategically at optimized locations of the cavity.

**Step 8:** Simulate the entire construction of the antenna on HFSS platform.

**Step 9:** Fabricate the prototype for measurements.

### 3. CBSIW ANTENNA STRUCTURE

The CBSIW array fed with back to back connected quarter wave T-junction power divider transmission line has been designed with all the pre-calculated dimensions following the methodology in section II. The designed antenna architecture is shown in fig.4. The FR4 epoxy substrate with dielectric constant \( \varepsilon_r = 4.4 \), loss tangent \( \tan \delta = 0.02 \) with thickness \( h = 1.6 \text{mm} \) is chosen for realizing the proposed antenna structure.
Fig.3. Proposed CBSIW antenna

Fig.4. Geometry of the proposed design

Table 1: Optimized dimensions of the proposed antenna

| Parameter | Description                                      | Size (mm) |
|-----------|--------------------------------------------------|-----------|
| $L$       | Length of the Substrate                         | 59        |
| $W$       | Width of the Substrate                          | 56        |
| $l_1$     | Spacing between the cavity elements             | 28        |
| $l_2$     | Length of the primary transmission line         | 14.94     |
| $w_1$     | Width of the power divider arm                  | 24        |
| $w_2$     | Width of the quarter wave transformer           | 5.22      |
| $w_0$     | Gap between the slot and power divider          | 15.5      |
| $l_s$     | Length of the bow-tie slot                      | 10        |
| $w_s$     | Width of the bow-tie slot                       | 2.5       |
| $w$       | Width of the each cavity element                | 17        |
| $d$       | Diameter of the via                             | 1.5       |
| $h$       | Thickness of the substrate                      | 1.6       |
| $s$       | Spacing between adjacent vias                   | 2         |
Fig. 5. Schematic of the power divider

\[ w_q = \frac{7.48 \times h}{e^{\frac{Z_0}{Z_0} \sqrt{\frac{\varepsilon_r + 1.41}{87}}}} - 1.25 \times t \]  \hspace{1cm} (6)

Where \( \lambda_t, Z_0, W_q, h, \varepsilon_r, \) and \( t \) are guided wavelength of the waveguide, characteristic impedance of the antenna, width of the microstrip line, thickness of the substrate, dielectric constant of the substrate and thickness of the copper layer respectively.

Fig. 6. Design and simulation of proposed antenna in HFSS platform.
3.1 Rectangular SIW Cavities

The proposed CBSIW antenna consists of four rectangular shaped cavities each centered with bow-tie shaped slots with optimized dimensions. The location of the slot is optimized to achieve perfect impedance matching with the power divider network and standard antenna impedance for higher efficiency. Each cavity is constructed by incorporating cylindrical shaped metallic vias systematically inserted through the substrate layer to form rectangular elements. The spacing between the elements is optimized to accomplish higher gain with better efficiency. The dimensions of diameter of the via and the spacing between the adjacent vias are pre-calculated by following necessary conditions by following the equation 5 to avoid leakages from the side walls. The quarter wave transformer-based power divider arm is inserted into each cavity using insert feed system to couple the energy to the CBSIW resonator element. The architectural geometry of the dielectric filled rectangular SIW cavity array is shown in Figure 4.

3.2 Power Divider network

The power divider network of the proposed antenna is designed as the combination of two quarter wave transformer [24] based T-shaped power dividing networks connected back to back to couple the energy to the cavities. The basic schematic of the power divider network is shown in Figure 5. The applied power is equally distributed to the four waveguide segments through the power divider channels to couple with the slots. The width of the microstrip line is calculated by using equation 6. The primary excitation to the power divider is applied with standard coaxial feeding method. The inter element spacing and the relative phase distribution to the each CBSIW element will control the direction of the maximum radiation and the gain characteristics of the antenna. The optimized dimensions of the proposed power divider network and cavity resonator are listed in Table 1.

4. RESULTS AND DISCUSSION

The proposed CBSIW antenna is designed and simulated on Finite element method based full wave Ansys HFSS analysis software. All the geometrical dimensions are optimized to achieve higher gain in the required direction of radiation. The design and simulation of the 4-element antenna on HFSS platform is shown in Figure 6. The antenna prototype is fabricated on a copper coated double sided glass FR4 epoxy PCB board. The antenna is tested with a vector network analyzer and observed the reflection and VSWR characteristics. The validation of gain and radiation pattern characteristics is measured in anechoic chamber over the given operating frequency. The fabricated prototype and its validation are shown in Figure 6. The comparison of measured and simulated reflection characteristics are shown in Figures 7.

![Fabricated prototype (a) Front view (b) Back view (c) Antenna validation](image-url)
4.1 Reflection Characteristics

![Reflection Characteristics](image)

Fig. 7 Reflection characteristics of the proposed antennas

4.2 Radiation Pattern and Gain characteristics

![Radiation Pattern](image)

Fig. 8 Radiation pattern at 6GHz
Fig. 9 3D Radiation Patterns

(a) 5.8GHz

(b) 5.9GHz

(c) 6GHz

(d) 6.2GHz

Fig. 10 Measured Gain and Efficiency
The simulated as well as measured return loss ($S_{11}$) characteristics illustrate that the proposed antenna resonates at 6GHz with bandwidth range from 5.7GHz to 6.4GHz with respect to the -10dB level of $S_{11}$ with minimum return loss of -20dB. The 2D and 3D radiation patterns shown in Figure 8 and 9 illustrate that the CBSIW antenna array produces a broad side radiation pattern with maximum gain of 19.749dB with nearly 82% of efficiency. The measured gain and efficiency variations over the given range of frequencies are illustrated in the graph shown in Figure 10. The performance comparison of the proposed CBSIW antenna with standard literature is presented in Table 2.

| CBSIW antenna References | Substrate material | Frequency (GHz) | Gain (dBi) | Number of elements | Number of layers | Return loss (dB) | Efficiency (%) |
|--------------------------|--------------------|----------------|------------|--------------------|------------------|----------------|----------------|
| [8]                      | Rogers 5880        | 60             | 19.6       | 16                 | 4 layer          | -25            | 54.5           |
| [9]                      | Rogers 5880        | 6.62           | 20.1       | 16                 | Single           | -20            | 83             |
| [10]                     | RO 4003            | 10.15          | 6.9        | 4                  | Double           | -20            | 83             |
| [11]                     | Rogers-Duroid 5880 | 20.5           | 29         | 256                | Single           | -35            | --             |
| [12]                     | Rogers-Duroid 5880 | 20.5           | 25.9       | 256                | Double           | -32            | --             |
| [13]                     | Rogers 5880        | 60             | 24.45      | 64                 | 3 layer          | -23            | 72.5           |
| [14]                     | Rogers 5880        | 18.3           | 7          | Single             | Single           | -28            | --             |
| [15]                     | Rogers 5880        | 11.5           | 10.6       | Single             | Double           | -30            | --             |
| [16]                     | Rogers 5880        | 10.78          | 12.9       | 4                  | 3 layer          | -30            | --             |
| [17]                     | RT/Duroid 5880     | 8.74           | 7.4        | 4                  | Single           | -29            | 90             |
| [18]                     | RT/Duroid 5880     | 9.5            | 9.62       | Single             | Single           | -45            | --             |
| [19]                     | RT/Duroid 5880     | 10.5           | 8.7        | Single             | Single           | -38            | --             |
| [20]                     | RT/Duroid 5880     | 10.07          | 14.58      | Single             | Single           | -48            | --             |
| Proposed Antenna         | FR4 Epoxy          | 6              | 21.9       | 4                  | Single           | -20.2          | 82             |

5. CONCLUSION

A novel high gain 4-element SIW cavity backed array antenna is presented paper. The proposed antenna array is the combination of four SIW cavities with bow-tie shaped slots and twoback to back connected T-shaped quarter wave transformer based microstrip lines. The feeding system provides superior impedance matching and optimum power distribution to the elements. The proposed antenna is designed using commercial Ansys HFSS full wave electromagnetic solver and fabricated on a single layer low cost FR4 epoxy substrate. The presented simulated and measured results show that the proposed antenna exhibits higher gain of 21.9dBi at an operating frequency of 6GHz with 82% of efficiency. Due to the observed high gain and efficiency over optimum range of frequencies the present antenna is well suited for embedding in different IoT, lower 5G microwave communication applications.

Declarations

Neither the entire paper nor any part of its content has been published or has been accepted for publication elsewhere. It has not been submitted to any other journal.

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