Matching Slot Role in Bandwidth Enhancement of SIW Cavity-Backed Slot Antenna

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Abstract— A substrate-integrated waveguide (SIW) cavity-backed antenna with two slots on top of the cavity has been proposed in this paper. The bowtie slot is the main radiator of the cavity and a rectangular slot close to the feed point has been etched (to add extra resonance to enhance the bandwidth of the antenna in the desired frequency range). Tuning the rectangular slot improved the fractional bandwidth to 8%. A 7.9 dBi peak gain and a steady beam over the entire bandwidth are achieved. The FTBR (front to back ratio) of the antenna is more than 20 dBi. A standard PCB producing process has been used in order to manufacture the proposed antenna on a single layer substrate.

Index Terms— bowtie, slot antenna, cavity-backed, matching slot, substrate-integrated waveguide (SIW).

I. INTRODUCTION

SIW technology was developed as an alternative to bulky metallic waveguides. Using this technique, a cavity can be implemented in thin planar substrates. This caused a huge size reduction in microwave circuits, which needed a bulky metallic waveguide. Although these waveguides suffer more loss compared with conventional metallic waveguides, they have an acceptable level of performance for a wide range of antenna applications [1-5] and miniaturized filters [6]. This technique enables fabrication of planar integrated rectangular and cylindrical cavities [1-7]. SIW cavity-backed antennas possess the good features of conventional cavity-backed antennas without their drawbacks like bulky cavity resonators and costly fabrication of metallic waveguides.

One of the most important disadvantages of SIW antennas is their coplanar waveguide (CPW) feed lines, which they are commonly fed by. The CPW feed may cause unwanted radiation, which can be easily neglected, but this unwanted radiation will increase cross polarization in more complex structures. As demonstrated in [2], the CPW feeding structure has somehow increased the unwanted feed radiation; however, the length of the CPW feed plays an important role in the determination of its quality factor [3]. Hence, it is not acceptable to shorten the length of the feed line to decrease the unwanted radiation. In [1], feeding and radiating slots are placed on opposite planes to prevent unwanted radiation from adding up to the main lobe. This can degrade the front to back ratio of the antenna because it increases the radiation feed in the reverse direction which is not desirable.

Other drawbacks of SIW cavity-backed antennas include their narrow bandwidth for their low-profile configuration and unique responding mechanism, and their high Q-factor [1]. Increasing substrate thickness is conventionally suggested to increase bandwidth of cavity-backed antennas. In [5], an inductive diaphragm using via arrays with diameters of 0.3

mm is inserted in the SIW feed. This leads to a more accurate fabrication but it is not cost-effective. In [10], excitation of hybrid modes is used to enhance the bandwidth of the antenna using a long slot.

In this paper, a SIW cavity-backed bowtie slot antenna is presented, as shown in Fig. 1. An extra resonant slot is implemented next to the feed point and in the area where electric fields are strong enough to excite the slot to enhance the bandwidth in the desired frequency range. The slot can be easily fabricated and is not sensitive to fabrication errors like the antenna presented in [9].

Fig. 1. Geometrical configuration of the proposed antenna

II. ANTENNA DESIGN

Based on the dimension of the cavity TE_{210} mode is excited in the cavity without any slots (Fig. 2). As mentioned in [10], different hybrid modes can be excited by etching a slot on the upper or lower ground plane of the cavity. Size and position of the slot determines if a single mode or combination of hybrid modes would be excited [10] and it can enhance the overall bandwidth of the antenna compared to an antenna with a simple $\lambda/2$ slot in the middle of the cavity [1].

Fig. 2. Electric field profiles of the cavity at 10 GHz.

A high-frequency structure simulator (HFSS) is used in order to simulate and optimize the slot size and position. SIW antennas can be modelled by conventional rectangular waveguide structures [8]. By this method, via arrays may be modelled by a finite conductivity rectangular wall in the simulation environment. While this is not a precise method, it can be used in the early stages of simulation in order to understand the overall achieved results. Using walls instead of via arrays can reduce the duration of the simulation. This method can become quite useful in the initial steps of simulation and optimization of more complex structures like multi-layer low temperature co-fired ceramic (LTCC) filters and antennas. In order to receive accurate simulation results of a structure, a final simulation step is needed where rectangular walls are again turned back to via arrays.

In the first design step, an equivalent width of the SIW cavity is chosen from an accurate empirical equation as mentioned in [8]:

$$w_{eff} = w - 1.08 \cdot \frac{d^2}{s} + 0.1 \cdot \frac{d^2}{w} \quad (1)$$

An antenna with the single bowtie on the upper ground plane is called Ant.1 and is used to show the effect of matching slot on bandwidth improvement. Figure.3 presents prototypes for both Ant.1 and Ant.2. Return loss of Ant. 1 and Ant.2 are depicted in Fig. 4 and it can be obviously seen that Ant.1 has a low Q-factor resonance with fractional bandwidth of 4% at 10.05 GHz. Adding the rectangular slot, another resonance appears and improves the fractional bandwidth up to 8%.

Fig. 3. Prototypes of Ant.1 and Ant.2.

Fig. 4. Measured and simulated S11 of the proposed antennas.

The main advantage of SIW structures, compared to conventional cavity-backed antennas, is that their low profile can be fabricated on a single substrate. The rectangular cavity resonator of an SIW antenna is formed by four walls made of via arrays (Fig. 1).

In order to satisfy the equivalency between the SIW and the conventional metallic cavity, the following conditions have been considered in the design process: $d/d_p \geq 0.5$ and $d/\lambda_0 \leq 0.1$ (λ_0 is the free space wavelength). Under these circumstances, via diameter and distance between vias are fixed to: $d=1.5\text{mm}$ and $d_p=1.9\text{mm}$ for the proposed application. In the final design, two slots are etched on the top face of the cavity: a bowtie slot (etched in the area where electric fields are highest in value) and a rectangular slot (etched close to another peak of electric fields in the cavity). These slots add another resonance and act as matching elements as well by having an effect on the feed point of the cavity. For the purpose of measurement, a 50Ω microstrip line with a tapered transition is used to excite the cavity [11].

In order to enhance the bandwidth of Ant. 1, the matching slot technique is employed. A rectangular matching slot was etched close to the feed point. The antenna with both slots is called Ant. 2 and its final optimized geometrical parameters are presented in Table 1.

TABLE 1
GEOMETRICAL PARAMETERS OF THE PROPOSED ANTENNA

PARAMETER	value (mm)	PARAMETER	value (mm)
h	0.7874	W_{ms}	0.6
W_C	26.7	W_t	9
L_C	22.65	L_t	5
d_p	1.9	W_{feed}	2.4
d	1.5	L_{feed}	10
L_b	22	W	42
W_b	4.45	L	40
W_{in}	0.4	L_{ms}	9

By adding the matching slot, currents flowing around the rectangular slot interfere with currents flowing on the top face of the cavity. It acts as a sink for the residual power inside the cavity. As a consequence, two high Q-factor resonances would occur at 9.73 GHz and 10.21 GHz. The electric field profiles of the proposed antenna at these frequencies are presented in Fig.5 and the dominant excited mode in the cavity after

etching the slots is still TE_{210} .

Fig. 5. Electric field profiles of the antenna, (a) at 9.73 GHz and (b) at 10.21 GHz

Figure 4 makes a comparison between measured and simulated return loss of Ant. 2 as well and a parametric study for the rectangular slot is presented in Fig. 6 (to prove that the rectangular slot participates in changing the lower resonance at 9.73 GHz and improves the bandwidth by having an effect on the feeding mechanism). It is evident that rectangular slot changes lower the resonance frequency of the antenna and do not change the higher frequency resonance. For different dimensions of the rectangular slot, Q-factors of two resonances change and thus the bandwidth of the proposed antenna increases. Etching the matching slots increases the bandwidth from 4% to 8%, while there are two high Q-factor resonances about 500 MHz and 300 MHz apart at 9.73 GHz and 10.21 GHz respectively.

Fig. 6. Simulated S11 of the Ant. 2 versus matching slot dimensions.

III. ANTENNA MEASUREMENT

A prototype of the proposed antenna shown in Fig. 1 was fabricated on a RT/Duriod 5880 substrate with thickness of 31 mil, relative permittivity of 2.2, and loss tangent of 0.0009. The overall dimensions of the antenna are 42 mm × 40 mm × 31 mil and the cavity size is about 26.7 mm × 22.65 mm. The antenna was tested in an anechoic chamber using an Agilent 3115 horn antenna as the reference antenna. Return loss of the antenna was measured as well using a Rohde & Schwarz (ZVA 24) VNA. A picture of a prototype of Ant. 2 under test is presented in Fig. 7.

Fig. 7. A prototype of the fabricated antenna under test conditions.

The proposed antenna has a fractional bandwidth of 8% from 9.53 GHz to 10.3 GHz. As can be seen, there are two wide resonances in 9.73 GHz and 10.21 GHz. The center frequency is 9.915 GHz. Effects of the PCB procedure and finite conductivity of conductor films affects the antenna performance. This, in addition with the finite sized ground plane, is the main reason why high Q-factor resonances are not observed in the measurement results. Conventionally, to overcome the problem of poor ground plane effects, a thick conductor plate may be stuck to the ground plane to improve ground plane performance. For a SIW antenna, which is integrated with follow-up planar circuits, the ground plane will be naturally enlarged and often there is no need for any additional metal sticking.

Fig. 8 shows simulated gain and radiation efficiency. Peak gain is about 7.9 dBi and it occurs at 10.3 GHz. As can be seen from this figure, the proposed antenna has relatively high and steady gain over the bandwidth. Measured radiation patterns at 9.9, 10.2 and 10.6 GHz are presented in Fig. 9. Cross polarization is always kept below -16 dBi and can be neglected. These radiation patterns show that over the entire operational bandwidth, cross polarization in the E-plane (x-z plane) is far below cross polarization in the H-plane (y-z plane). As the unwanted feed radiation is greatly suppressed, front to back ratio (FTBR) is always better than 20 dB over the bandwidth. Half power beam widths at different frequencies are presented in Table 2. It is noticeable that the proposed antenna has a wide and steady beam over the operating bandwidth.

Fig. 8. Simulated gain and efficiency of Ant. 2.

Fig. 9. Measured radiation patterns for E-plane and H-plane at (a) 9.9 GHz, (b) 10.2 GHz and (c) 10.6 GHz.

TABLE 2
HALF POWER BEAMWIDTHS

	H-plane	E-plane
9.9 GHz	62°	93°
10.2 GHz	62°	93°
10.6 GHz	72°	60°

IV. CONCLUSION

A SIW cavity-backed bowtie slot antenna with two slots on the upper ground plane is presented. Both slots are resonant slots and are placed close to the area in which electric fields are highest in value inside the cavity. A simple rectangular slot is acting as a matching slot as well because it is placed close to

the feeding point of the cavity and can affect the energy coupling into the cavity. It has been demonstrated that bandwidth enhancement can be achieved by adding the rectangular slot close to the feed point and area in which electric currents are at a maximum. The antenna has relatively high gain (7-8 dBi), which does not change significantly over the whole frequency range of the antenna. The proposed antenna has a wide beam with low cross polarization and satisfies our presumption of high radiation efficiency.

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