Bandwidth and Efficiency Enhancement of Cavity-Backed Slot Antenna Using a Substrate Removal

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***Abstract*—A technique for enhancement of bandwidth and efficiency of a cavity-backed slot antenna is proposed. The bandwidth of the cavity-backed slot antenna depends on the Q of the slot and the cavity. The proposed technique removes the substrate under the slot to decrease the capacitance of the slot. Because a half-wavelength slot is considered a parallel resonant circuit at resonant frequency, lowered capacitance increases the bandwidth of the antenna. Antenna efficiency also can be enhanced by the proposed technique. The dielectric loss, which is produced by the E-field across the slot, is effectively decreased by removing the substrate under the slot. Various simulation results of demonstration of the proposed technique are given. The proposed antenna, which was fabricated on a 2-mm-height FR-4 substrate, shows 6.2% higher antenna efficiency and 24% wider bandwidth compared to the conventional cavity-backed slot antenna, which has a whole substrate. The proposed technique is effective in enhancing the efficiency and bandwidth of a cavity-backed slot antenna.**

***Index Terms*—Antenna efficiency enhancement, cavity-backed slot antenna, wideband.**

I. Introduction

On THE surface of a highly lossy medium, such as a human body, antenna efficiency drops significantly because of dielectric losses in the lossy medium. A cavity-backed slot antenna, which has high radiation efficiency on the surface of the lossy medium, has several attractive features like a planar surface and high productivity. A cavity-backed slot antenna is a strong candidate for body area network (BAN) applications.

In many BAN applications, a low-profile antenna is highly favorable. In the case of a cavity-backed slot antenna, the height of the cavity can be lowered because the guided wavelength is maintained without reference to the height of the rectangular cavity. However, a low-height cavity causes serious drawbacks, such as a narrow bandwidth [1] and low antenna efficiency. As the generated E-field in the low cavity is stronger than that of the high cavity, the dielectric losses and conductor losses generated inside the cavity are larger than those of the high cavity.

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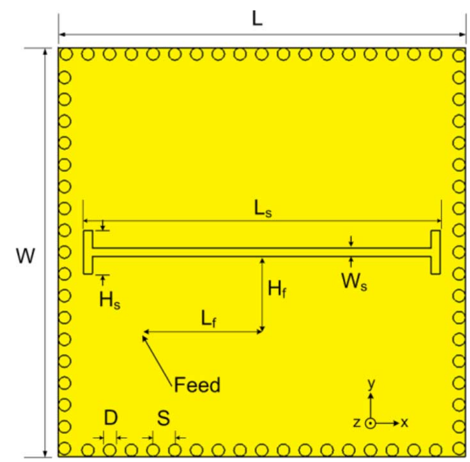

Fig. 1. Geometry of simulated and measured cavity-backed slot antenna. (Dimensions of the fabricated antenna, $W = 45, L = 55, L_s = 41, H_s = 1, W_s = 1, H_f = 9.5, L_f = 13, D = 0.7, S = 2.5$, all in the unit of millimeters.)

Various techniques are suggested to overcome the narrow bandwidth of the cavity-backed slot antenna. Hybrid substrate integrated waveguide (SIW) cavity modes are used to enhance the bandwidth of the SIW cavity-backed slot antenna [2]. In [3], dual slots are used to create dual resonance. By adjusting the length of each slot, two resonance frequencies can be moved to achieve the wideband characteristic. In [4], a second fictitious resonant frequency is introduced above the first resonant frequency by using the fictitious short circuit [5].

In this letter, a technique for the enhancement of the bandwidth and efficiency of the cavity-backed slot antenna is suggested. The proposed technique removes the substrate under the slot to decrease the Q of the slot. The simulation results for three different substrates are suggested to show the effect of the proposed technique. The measured results of the proposed antenna, which was fabricated on the 2-mm-height FR-4 substrate, shows 6.2% higher antenna efficiency and 24% wider bandwidth compared to those of the conventional cavity-backed slot antenna. The proposed technique is a novel method for enhancing the efficiency and bandwidth of a cavity-backed slot antenna.

II. Principles of Operation

A. Effect of the Substrate Removal

Fig. 1 shows the geometry of a cavity-backed slot antenna. The half-wavelength slot is located at the center of the cavity

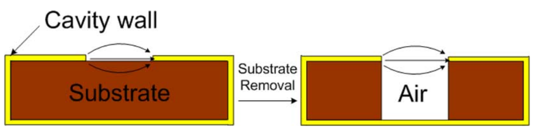

Fig. 2. Proposed substrate removal technique for the enhancement of bandwidth and efficiency of a cavity-backed slot antenna.

surface. The bandwidth of the cavity-backed slot antenna depends on the Q of the slot and the cavity. By lowering the Q of the slot, the antenna bandwidth can be increased.

The half-wavelength slot can be expressed by the parallel resonant circuit. The Q of the parallel resonant circuit is well known as

$$Q = \omega_0 RC \tag{1}$$

where ω_0 is the resonant frequency and R, C are the resistance and capacitance of resonant circuit, respectively. Hence, the Q of the slot antenna can be lowered by decreasing the capacitance of the slot. By decreasing the Q of the slot, the bandwidth of a cavity-backed slot antenna can be enhanced.

Fig. 2 shows the proposed technique for the decreasing capacitance of the slot. In a conventional cavity-backed slot antenna, the space under the slot is filled with a substrate that has a higher relative permittivity than that of air. The proposed technique removes the substrate under the slot to decrease the effective permittivity of the slot. By removing the substrate under the slot, the capacitance of slot can be lowered, which causes a decrease in slot Q.

Lowered capacitance increases the resonance frequency of the resonator. The inductance of the slot should be increased for the compensation of the decreased capacitance. The inductance of the slot can be easily increased by using the longer slot. However, the compensated longer slot may exceed the size of the cavity, which causes an increase in the size of the antenna.

In the proposed antenna structure, an I-shaped slot is used for the inductive loading of the slot. The protruded lengths of each end of the slot determine the increased inductance of the slot [6]. By using the I-shaped slot, decreased capacitance can be compensated without increasing the size of the cavity.

The proposed technique also enhances the efficiency of the cavity-backed slot antenna. In the operation of the slot antenna, an E-field is generated across the slot. However, the E-field, which penetrates the lossy substrate under the slot, causes dielectric losses. This dielectric loss causes a drop in efficiency of the cavity-backed slot antenna. In the proposed structure, the dielectric losses under the slot decrease considerably because the substrate under the slot is removed. The antenna efficiency is enhanced very effectively on cheap substrates that have high loss tangent. The reduced dielectric loss slightly increases the Q of the resonator. However, this effect on antenna Q can be compensated by the decreased capacitance.

The proposed technique enhances the bandwidth and efficiency of the antenna simultaneously, which are the two main requirements of the antenna.

TABLE I
DIMENSIONS OF SIMULATED CAVITY-BACKED SLOT ANTENNA. ALL DIMENSIONS ARE IN MILLIMETERS

Substrate	L	W	L_s	W_s	H_s [a]
RT5880	63	55	57	1	4.8
FR-4	45	39	42	1	8.8
RT6010	30	25	28	1	9.6

[a]Dimension when the height of the substrate is 1 mm, In other substrate heights, H_s is slightly changed for the resonance at 2.45 GHz

III. SIMULATION RESULTS

A. Effect of the Substrate Removal in Various Substrates

The proposed technique is applied to a conventional cavity-backed slot antenna on three different substrates and compared to conventional cavity-backed slot antennas that have a whole substrate. Duroid 6010 ($\varepsilon_r = 10.2, \tan\delta = 0.0023$) and FR-4 ($\varepsilon_r = 4.3, \tan\delta = 0.015$) are selected to observe the effect of the proposed technique in high-relative-permittivity substrate and lossy substrate, respectively. Duroid 5880 ($\varepsilon_r = 2.2, \tan\delta = 0.0009$) is selected for the reference substrate. Three different cavity heights (1, 2, and 3 mm) are simulated in each substrate. For BAN applications, the antenna is simulated on the body surface, which have a homogeneous electric properties $\varepsilon_r = 35.15, \sigma = 1.16$ S/m. The distance from the body surface to the cavity bottom is fixed at 0.5 mm.

The length of the slot and the size of the cavity are adjusted to resonate the antenna at 2.45 GHz. Instead of the SIW structure, solid conductor wall cavity is used. The adjusted parameters are described in Table I. Discrete ports are used across the center of the slot to feed the antenna. For simplicity's sake, the port impedance is changed according to the input impedance of the antenna. Because the E-field across the slot is at maximum at the center of the slot and zero at the end of the slot, the input impedance of the antenna can by matched to 50 Ω by moving the location of the feeding point. The simulation is conducted using CST Microwave Studio.

Fig. 3 shows the simulated -10-dB bandwidth of each antenna. As expected, the cavity-backed slot antennas designed with proposed technique have wider bandwidths than those of conventional antennas. Because the Q of the slot is proportional to the relative permittivity of the substrate, the proposed technique is especially useful when the substrate has high relative permittivity. In the case of a cavity-backed slot antenna on the 2-mm-height Duroid 6010 substrate, bandwidth that is 46% wider is obtained.

Fig. 4 shows the simulated radiation efficiencies of each antenna. The radiation efficiencies of antennas designed with proposed technique are also increased in all substrate. The proposed technique is very effective when the substrate has a higher loss tangent. The cavity-backed slot antenna on the 2-mm-height FR-4 substrate shows a radiation efficiency enhancement of 7.1%. As the E-field across the slot generates the large dielectric loss in the lossy substrate, the proposed technique is effective on the highly lossy substrate. Because of the low-loss property, radiation efficiencies increased by proposed technique were very small on the Duroid 5880 substrate.

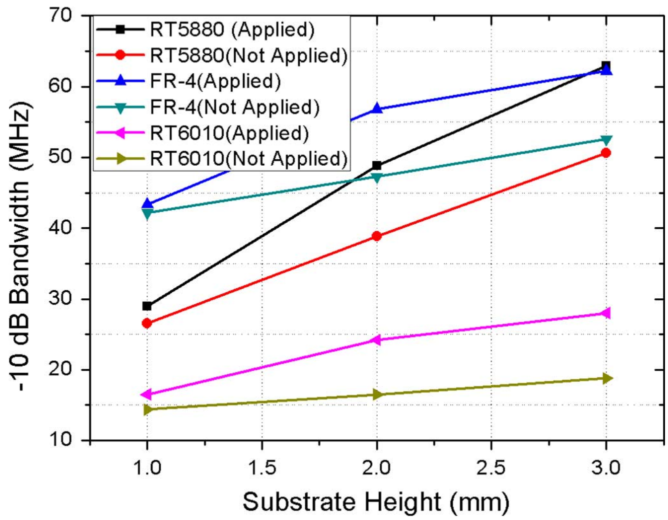

Fig. 3. Simulated −10-dB bandwidth of the cavity-backed slot antenna on different substrates.

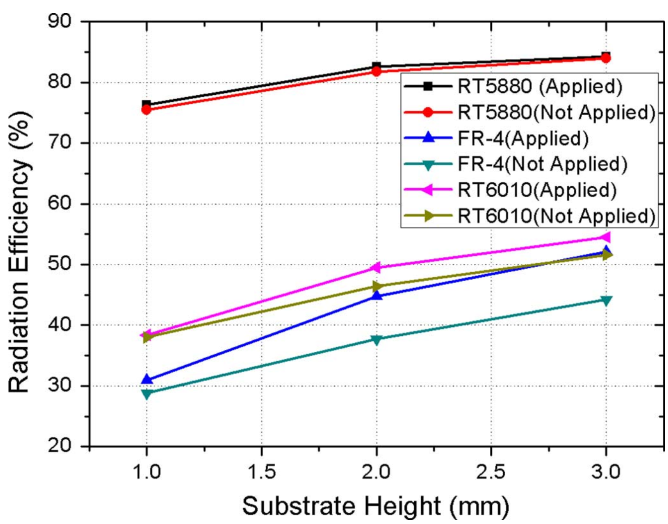

Fig. 4. Simulated radiation efficiency of the cavity-backed slot antenna on different substrates.

B. Effect of the Removal Depth

The effect of the removal depth is simulated on the 2-mm-height FR-4 substrate. The simulated bandwidth and efficiency are shown in Fig. 5. The simulated results show that when the removal depth is deeper than the slot width (1 mm), the effect of the proposed technique is observed sufficiently. The E-field generated across the slot is strong near the slot and weak near the bottom of the cavity. Therefore, the substrate near the bottom of the cavity does not have a strong effect on the operation of the slot. Partially removing the substrate still has the effect of decreasing Q of the slot antenna.

IV. Measured Results

The proposed technique can be applied to the any type of cavity-backed slot antennas, cavities of which are filled with substrates. For the demonstration of the proposed technique,

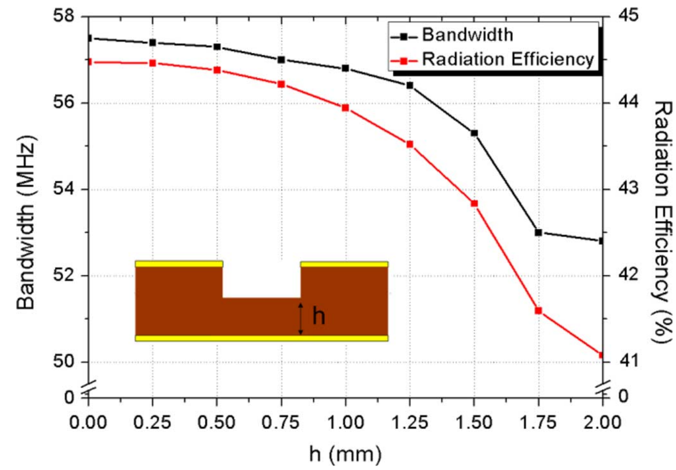

Fig. 5. Simulated −10-dB bandwidth with variations of removing depth.

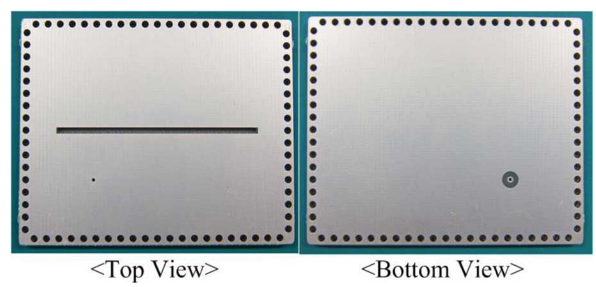

Fig. 6. Fabricated antenna.

a cavity-backed slot antenna was fabricated on a 2-mm-height FR-4 substrate and compared to the conventional cavity-backed slot antenna, which has a whole substrate. For a fair comparison, equal-size cavities were used in both antennas. Slot length was adjusted for the resonance of the antenna at 2.45 GHz. Instead of the solid conductor cavity, an SIW with via conditions $(D/S = 0.56, D/\lambda_0 = 0.011)$ was used to fabricate the antenna using a standard printed circuit board process [7]. At the feeding point, the center pin and the outer conductor of the coaxial cable were connected to the surface and bottom of the cavity, respectively, through the small hole using an SMA connector. The dimensions of the antenna are illustrated in Fig. 1. The fabricated antenna is shown in Fig. 6.

Fig. 7 shows the simulated and measured reflection coefficient of the designed antenna. Although the resonance of the conventional cavity-backed slot antenna is observed at a higher frequency than that of the simulated antenna, similar results were obtained. The difference between the simulated and measured results might have been caused by the electric property variation of the FR-4 substrate. The measured −10-dB fractional bandwidth of the fabricated antenna was 2.16%, which is 24 % wider than that of the conventional antenna.

The Bluetest reverberation system chamber was used to measure the efficiency of the proposed antenna, and the results were compared to the conventional antenna, as shown in Fig. 8. The measured antenna efficiency was about 3% lower than that of the simulated antenna. In the operating frequency, the efficiency

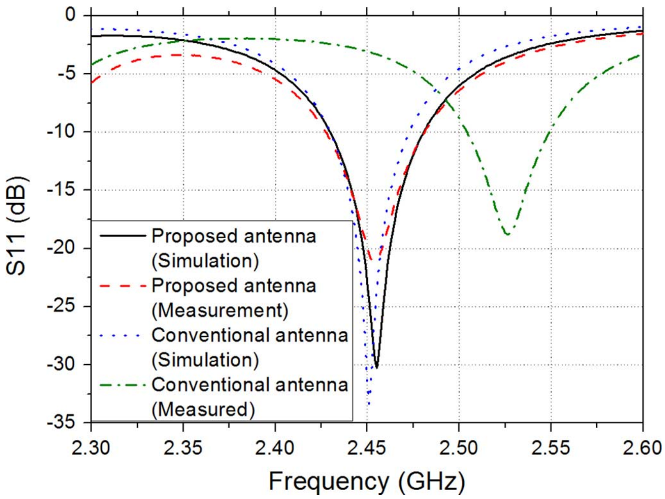

Fig. 7. Reflection coefficient of simulated and measured antenna.

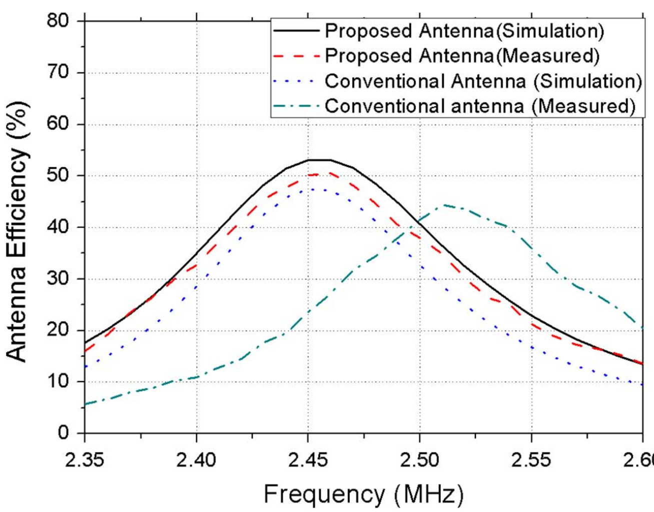

Fig. 8. Simulated and measured antenna efficiency.

of proposed antenna was 50.6%, which is 6.2% higher than that of the conventional antenna.

The radiation patterns of the fabricated antennas were measured in an anechoic chamber. Fig. 9 shows the measured radiation patterns of proposed and conventional cavity-backed slot antenna at 2.45 and 2.52 GHz, respectively. Because of the shifted resonance frequency of the fabricated conventional cavity-backed slot antenna, the radiation patterns of the fabricated conventional antenna are plotted at 2.52 GHz. They are compared in the E-plane (yz-plane) and H-plane (xz-plane). Although the bandwidth and efficiency are enhanced, the radiation patterns of the proposed antenna were similar to the

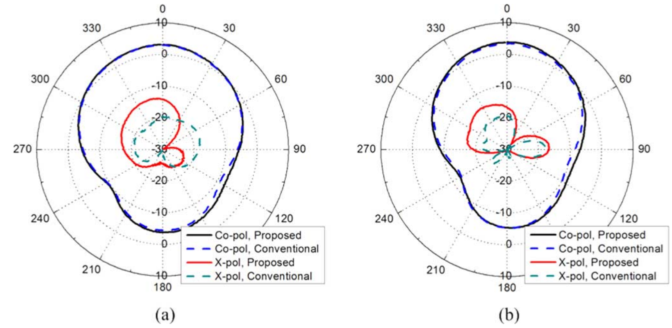

Fig. 9. Measured radiation patterns of the proposed and conventional cavity-backed slot antenna. (a) E-plane (yz-plane) (b) H-plane (xz-plane).

those of the conventional cavity-backed slot antenna. Because the proposed technique does not change the symmetric structure of the cavity-backed slot antenna, the radiation patterns of a cavity-backed slot antenna are maintained.

V. Conclusion

A technique for the enhancement of the bandwidth and efficiency of the cavity-backed slot antenna is proposed and demonstrated. The proposed technique can compensate for the drawbacks of the substrate, which have high relative permittivity or high loss tangent. The fabricated cavity-backed slot antenna designed using the proposed technique showed 24% wider bandwidth and 6.2% higher antenna efficiency compared to the conventional cavity-backed slot antenna. The proposed technique is useful in designing a highly efficient wideband cavity-backed slot antenna.

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