

Design of a Stacked Dual-Patch Antenna with 3D Printed Thick Quasi-Air Substrates and a Cavity Wall for Wideband Applications

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Featured Application: This article is related to a stacked dual-patch antenna with 3D printed thick quasi-air substrates.

Abstract: In this paper, we propose a stacked dual-patch antenna with 3D printed thick quasi-air substrates and a cavity wall for wideband applications. To achieve the theoretical maximum bandwidth of the patch antenna, the quality factor of the system needs to be minimized. To achieve this, the area of the conductive radiator should be enlarged, while the permittivity of the substrate within the patch must be reduced close to 1. To realize a patch antenna with this maximum bandwidth, the stacked dual-patch configuration is employed to obtain an extended conductive radiator area. In addition, square-pipe resin frames manufactured using a 3D printing method are applied to the proposed antenna to implement a quasi-air substrate structure that has a low permittivity value close to 1. The proposed stacked dual-patch antenna with a quasi-air substrate has a broad bandwidth of 20.7%. The results demonstrate that by using the proposed antenna structure, broadband characteristics close to the fundamental bandwidth limit of the patch antenna can be achieved.

Keywords: dual-patch antennas; broadband antennas; quasi-air substrates; 3D printing methods



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1. Introduction

Microstrip patch antennas have been widely adopted in various applications such as mobile communications, radar systems, and global navigation satellite systems, considering their advantages of being lightweight, low-profile, and low-cost [1–4]. These patch antennas consist of a radiator printed on a thin substrate, a feed pin, and a ground, so they typically have narrow bandwidth characteristics [5,6]. Therefore, increasing the bandwidth of patch antennas has been a primary concern and is a very challenging goal that should be achieved for their use in a variety of applications. In general, methods to improve the bandwidth of a patch antenna include optimizing the radiator shape for high radiated power or optimizing the substrate material to lower the quality factor of the system [7,8]. To date, there have been many studies conducted to optimize the radiator shape; for example, they include E-shaped patches [9], U-slotted patches [10], and L-shaped patches [11]. Since antenna bandwidth is proportional to the area of the conductive radiator, research on increasing the bandwidth using a stacked dual-patch antenna with a coupled-fed structure has been reported [12,13]. Various methods for optimizing the substrate material have also been studied, and recently, increasing the bandwidth by bringing the permittivity of the substrate closer to 1 was attempted [5,10]. By reducing the permittivity of the substrate, the quality factor of the system can be decreased efficiently, and the bandwidth can be increased [10]. To simultaneously improve the durability and bandwidth of the antenna,

a quasi-air substrate structure can be fabricated using 3D printing methods that has the advantages of being easy to manufacture, inexpensive, and robust [14–16].

In this paper, we propose a stacked dual-patch antenna with 3D printed thick quasi-air substrates and a cavity wall for wideband applications. In order to achieve the theoretical maximum bandwidth of the patch antenna, the quality factor of the system needs to be minimized. To realize this, the area of the conductive radiator should be enlarged, while the permittivity of the substrate within the patch must be reduced close to 1. To realize a patch antenna with this maximum bandwidth, a stacked dual-patch configuration is employed to obtain an extended conductive radiator area. This stacked dual-patch configuration consists of a directly fed lower patch and a coupled-fed upper patch, which can efficiently improve the antenna bandwidth. To further broaden the antenna bandwidth, thick quasi-air substrates with low permittivity close to 1 are employed between the two radiators and the ground plate. To simultaneously improve the durability and bandwidth of the antenna, the quasi-air substrate structure is fabricated using 3D printing methods because of their ease of manufacturing, low cost, and robustness. Square-pipe resin frames are built for the quasi-air substrate using the stereolithography apparatus (SLA) method [17] that can provide high-durability structures with low manufacturing tolerances. In addition, to increase the front-to-back ratio and suppress the leakage electric fields of the patch antenna, a metal cavity wall is placed around the square-pipe resin frames which is manufactured using the selective laser melting (SLM) method [18]. The stacked dual-patch antenna, the square-pipe resin frames, and the ground plate are then assembled with a metal cavity wall to form a complete antenna structure. To verify the antenna's feasibility, indicators of the antenna's performance such as reflection coefficients, bore-sight gains, and radiation patterns are measured in a full anechoic chamber. The results demonstrate that by using the proposed antenna structure, broadband characteristics close to the fundamental bandwidth limit of the patch antenna can be achieved, and at the same time, the durability of the antenna is improved for various applications.

2. Design and Measurement of a Stacked Dual-Patch Antenna with Thick Quasi-Air Substrates

Figure 1 illustrates the geometry of the stacked dual-patch antenna with thick quasi-air substrates and a cavity wall. To achieve the theoretical maximum bandwidth of the patch antenna, the quality factor of the system should be minimized. In this study, two techniques are employed when designing the antenna components to reduce the quality factor of the system: one is to enlarge the area of the conductive radiator as much as possible, and the other is to reduce the permittivity of the substrate within the patch to close to 1. To enlarge the conductive radiator and realize a patch antenna with this maximum bandwidth, we applied the stacked dual-patch configuration to the proposed antenna design. This stacked dual-patch configuration consists of the lower and upper rectangular patches. The width and length of the lower patch are w_1 and l_1 , respectively, and this lower patch is directly connected to the SMA connector, as shown in Figure 1a. The upper patch, with a width w_2 and a length l_2 , is coupled-fed from the lower patch. Thus, the proposed antenna with two radiators can achieve broadband characteristics due to the broadened area of the conductive radiators. To further broaden the antenna bandwidth, thick quasi-air substrates with low permittivity close to 1 are employed between the two radiators and the ground plate. Typically, the quasi-air substrates are implemented using Rohacell ($\epsilon_r = 1.08$) [5,19], but patch antennas fabricated with this material are soft and vulnerable to heat, so their durability is relatively poor. To simultaneously improve the durability and bandwidth of the antenna, square-pipe resin frames ($\epsilon_r = 2.9$) are fabricated using a 3D printing method for implementing the quasi-air substrate structure. The square-pipe resin frame also consists of lower and upper frames, and the thicknesses of the lower and upper square-pipe resin frames are h_1 and h_2 , respectively. Thus, the proposed quasi-air substrate has a low dielectric constant of 1.8. To increase the front-to-back ratio and suppress the leakage electric fields of the patch antenna, a metal cavity wall is placed around the square-

pipe resin frame, as shown in Figure 1b. The geometrical parameters of the proposed antenna with the stacked dual-loop design are optimized using the FEKO electromagnetic simulator [20] and the genetic algorithm (GA) [21]. The optimum parameters are listed in Table 1. These geometrical parameters of the proposed antenna were determined in the following process: First, the initial values were obtained from the basic theory for the patch antenna [8]. For example, an antenna's length is half of a wavelength (50 mm), and the thickness of the antenna is determined by less than 1/10 of a wavelength (10 mm). Next, these values are applied as the input to the GA, and the optimum design parameters are obtained through the GA. In this optimization process, a cost function is determined simply as 1/antenna bandwidth.

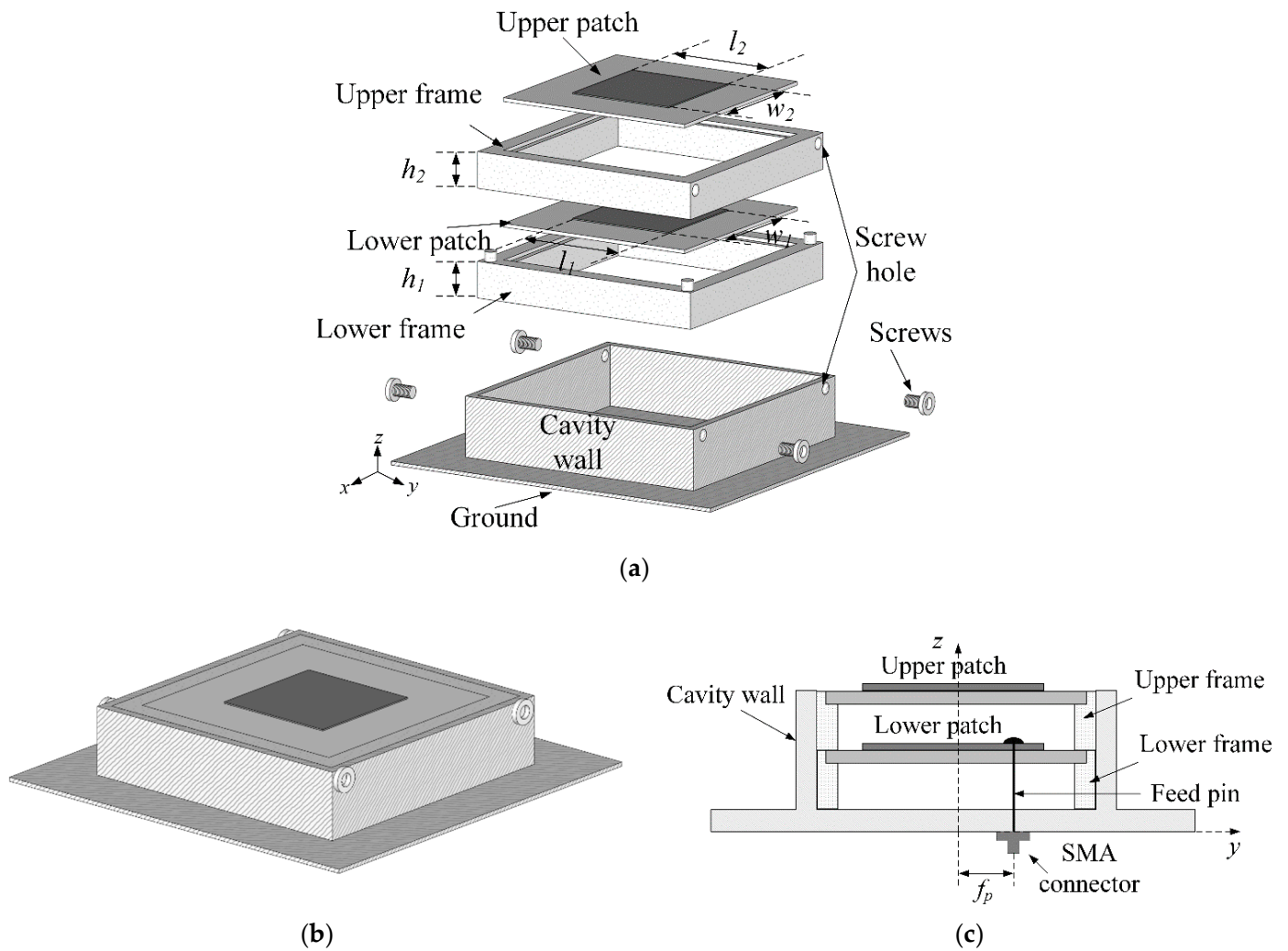


Figure 1. Geometry of the proposed antenna: (a) isometric view of each antenna component; (b) isometric view of the assembled antenna; (c) side view of the assembled antenna.

Table 1. Geometrical parameters of the proposed antenna.

Parameters	Value	Parameters	Value
w_1	28.4 mm	w_2	27 mm
l_1	40.3 mm	l_2	26.7 mm
h_1	2.4 mm	h_2	10.2 mm
f_p	19.3 mm		

Figure 2 shows photographs of the fabricated antenna with thick quasi-air substrates and the cavity wall. The fabrication of the proposed antenna is carried out using the

following procedures: First, two conductive radiators for the patch are printed on an RF-35 substrate ($\epsilon_r = 3.5$, $\tan \delta = 0.0018$, thickness = 0.5 mm) using photolithography and etching techniques. Next, two square-pipe resin frames are built to realize the thick quasi-air substrates using the SLA 3D printing method [17] that can provide high-durability structures with low manufacturing tolerances. The metal cavity wall with the ground plate is then manufactured using the SLM 3D printing method [18] that can provide full-metal body structures with low manufacturing tolerances at a low cost. Finally, the stacked dual-patch antenna, the square-pipe resin frames, and the ground plate are assembled with a metal cavity wall to form a complete antenna structure. To verify the antenna's feasibility, indicators of the antenna's performance such as reflection coefficients, bore-sight gains, and radiation patterns are measured in a full anechoic chamber.

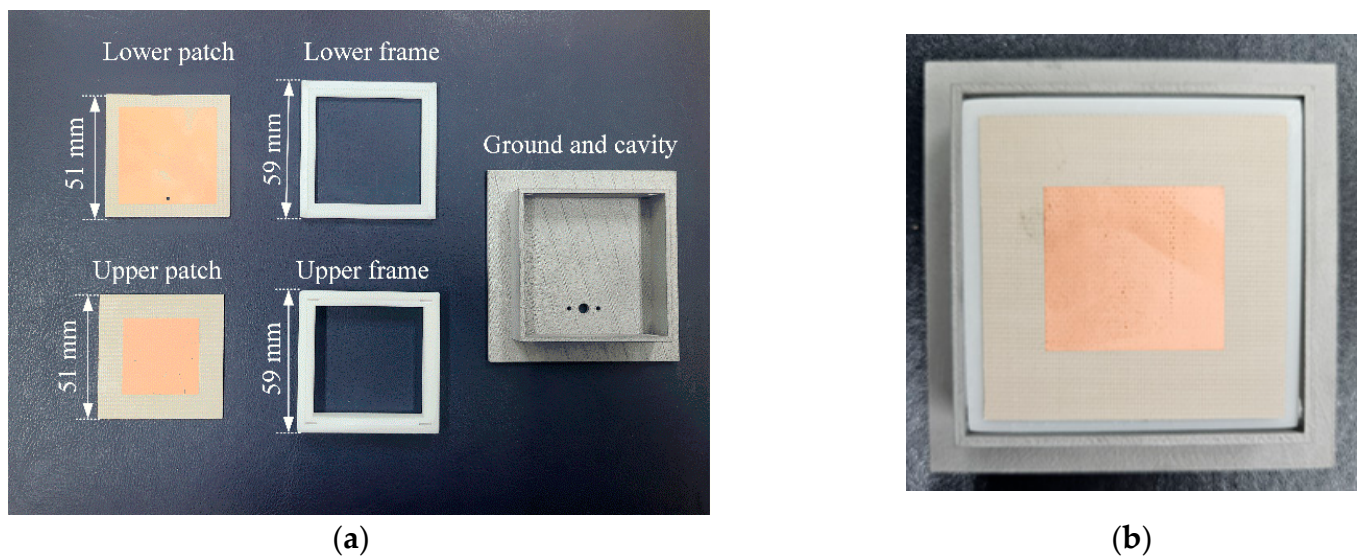


Figure 2. Photographs of the fabricated antenna: (a) each component of the antenna; (b) assembled antenna.

Figure 3 presents the reflection coefficient of the proposed antenna. The solid and dashed lines indicate measured and simulated results, respectively. The measured reflection coefficient has a bandwidth of 620 MHz (2.63 GHz to 3.25 GHz, $|\Gamma|_{\text{dB}} < -10$ dB), with a fractional bandwidth of 20.7%. This result is in good agreement with the simulated fractional bandwidth of 24%. In addition, the average reflection coefficients of the measurement and simulation are -14.9 dB and -14.2 dB, respectively.

Figure 4 illustrates the 2D radiation gain patterns (in a spherical coordinate system) of the proposed antenna in the E-plane (zx-plane) and H-plane (zy-plane). At 3 GHz, the bore-sight gains of the measurement and simulation are 7.9 dBi and 8.9 dBi, respectively. In addition, the measured half-power beamwidths (HPBW) in the E- and H-planes are 48° and 55° , respectively, while the simulated HPBW are 56° and 52° .

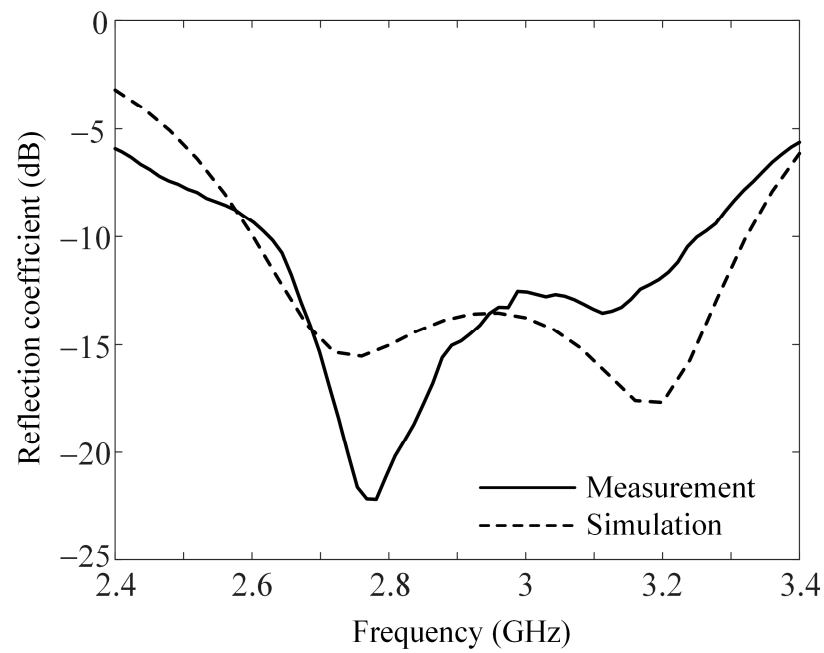


Figure 3. Reflection coefficient of the proposed antenna.

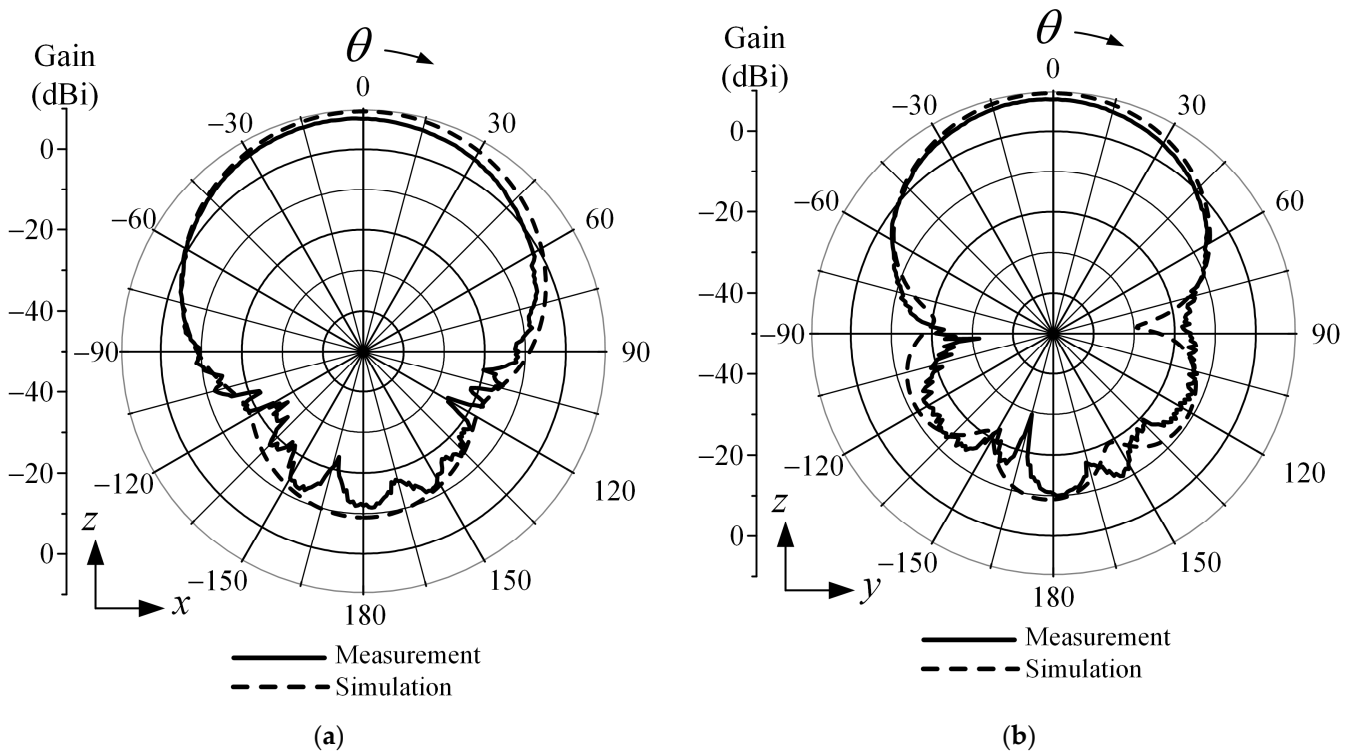


Figure 4. Radiation pattern of the proposed antenna: (a) zx -plane; (b) zy -plane.

3. Analysis and Comparison with Fundamental Bandwidth Limit

Figure 5 presents the theoretical maximum bandwidth of the patch antenna according to the permittivity of the substrates. The bandwidth of the patch antenna can be calculated using the following equation [6,8]:

$$BW = \frac{VSWR - 1}{Q\sqrt{VSWR}} \quad (1)$$

where Q is the quality factor of the antenna. When the surface wave power of the patch antenna is much smaller than the radiated power, the expression for the bandwidth of the patch antenna can be approximated as follows [6,8]:

$$BW = \frac{16}{3\sqrt{2}} \frac{c_1 p}{e_r} \left(\frac{1}{\varepsilon_r} \right) \left(\frac{h}{\lambda_0} \right) \left(\frac{W}{L} \right) \quad (2)$$

where e_r is the radiation efficiency of the patch antenna, and h is the total thickness of the substrate. p means the ratio of the power radiated by the patch to that radiated by an equivalent Hertzian dipole of the same moment. This p factor can be approximately 1.0 when the patch antenna has a small size [8]. W and L are the width and length of the conductive resonator of the patch antenna, and c_1 is expressed as follows [6,8]:

$$c_1 = 1 - \frac{1}{n^2} + \frac{2/5}{n^4} \quad (3)$$

where n is $\sqrt{\varepsilon\mu}$, and ε and μ are the permittivity and the permeability of the antenna substrates (the upper and lower substrate layers in the proposed antenna), respectively. According to Equations (1) and (2), in order to achieve the theoretical maximum bandwidth of the patch antenna, the quality factor of the system should be minimized. To do so, the area of the conductive radiator and the thickness of the substrate should be enlarged. In addition, the permittivity of the substrate in the patch should be minimized. The results in Figure 3 are then compared with the theoretical maximum bandwidth calculated using Equation (2). The solid and dashed lines represent the theoretical maximum bandwidth of the patch antenna for which the thicknesses of the substrates are $h = 0.05\lambda$ and $h = 0.13\lambda$, respectively. In this result, p and e_r are assumed to be 1 and 0.85, respectively, and the ratio of W and L is 1. The maximum bandwidth of the dual patch (dotted and dash-dotted lines) is assumed to be twice that of the single patch (solid and dashed lines), considering their two resonators. Therefore, the theoretical maximum bandwidth of the dual patch with the quasi-air substrate ($\varepsilon_r = 1.8$) is calculated to be 26%. In fact, the bandwidth of the simulation model for the proposed dual-patch antenna has a bandwidth of 21%. In addition, the fundamental bandwidth limits of the antennas with the RF-35 and FR-4 substrates are 15.5% and 13.3%, respectively. These results demonstrate that by using the proposed antenna structure, broadband characteristics close to the fundamental bandwidth limit of the patch antenna can be achieved, and at the same time, the durability of the antenna is improved for various applications.

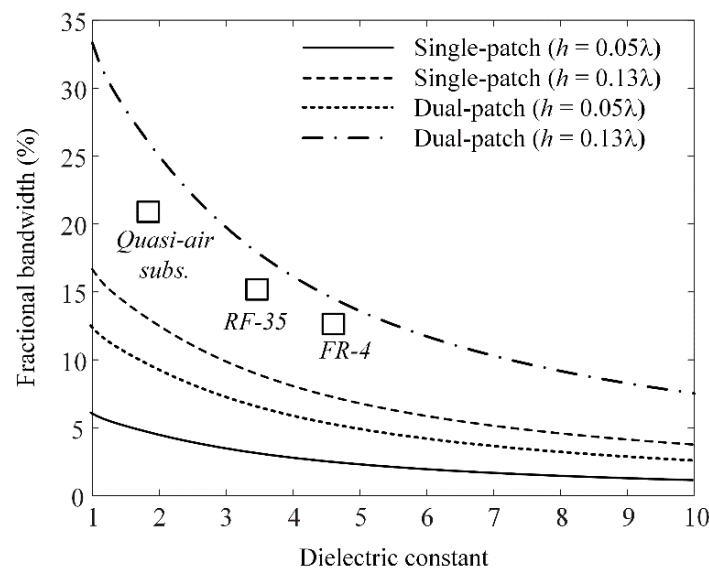


Figure 5. Fundamental bandwidth limit of the patch antenna according to the dielectric constant.

Figure 6 represents the fundamental bandwidth limit of the dual-patch antenna ($h = 0.13\lambda$) according to the antenna's efficiency [6,8]. As can be seen in this figure, when there is no reduction in bandwidth due to the antenna's efficiency ($e_r = 1$), the fractional bandwidth of the antenna with the quasi-air substrate is 30.8%. On the other hand, when the antenna's efficiency is reduced to 0.6, the bandwidth is also reduced to 18.5%.

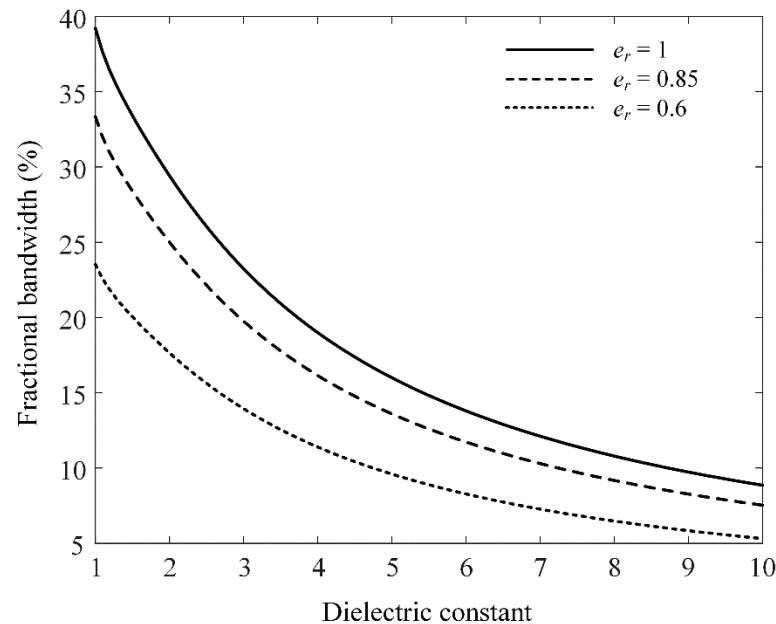


Figure 6. Fundamental bandwidth limit of the patch antenna according to the antenna efficiency.

Table 2 shows comparisons of the antenna's characteristics with other stacked coupled-fed antennas. As can be seen in this table, the antennas in [5,13] with air foam substrates have a broad bandwidth while having a relatively low profile. In addition, an antenna in [11] achieved broader bandwidth through a shorted patch and an L-shaped probe structure. However, these antennas fabricated with air foam are soft and vulnerable to heat, so their durability is relatively poor. On the other hand, the proposed antenna with 3D printed quasi-air substrates achieved a broad bandwidth while demonstrating high durability.

Table 2. Comparison with other stacked coupled-fed antennas.

Research	Substrate	Bandwidth	Antenna Height	Durability
[5]	Air foam ($\epsilon_r = 1.07$)	21%	0.085λ	Poor
[13]	Air foam ($\epsilon_r = 1.05$)	20%	0.085λ	Poor
[11]	Air foam ($\epsilon_r \approx 1$)	41%	0.094λ	Poor
Proposed	Quasi-air ($\epsilon_r = 1.8$)	21%	0.13λ	Good

Figure 7 shows the normalized electric field distributions of the antenna with and without the metal cavity at 3 GHz. As can be seen in Figure 7a, leakage electric fields that formed on the sides and back of the antenna are suppressed by the metal cavity structure. In contrast, without the metal cavity structure, a strong leakage electric field is observed around the antenna structure, as shown in Figure 7b.

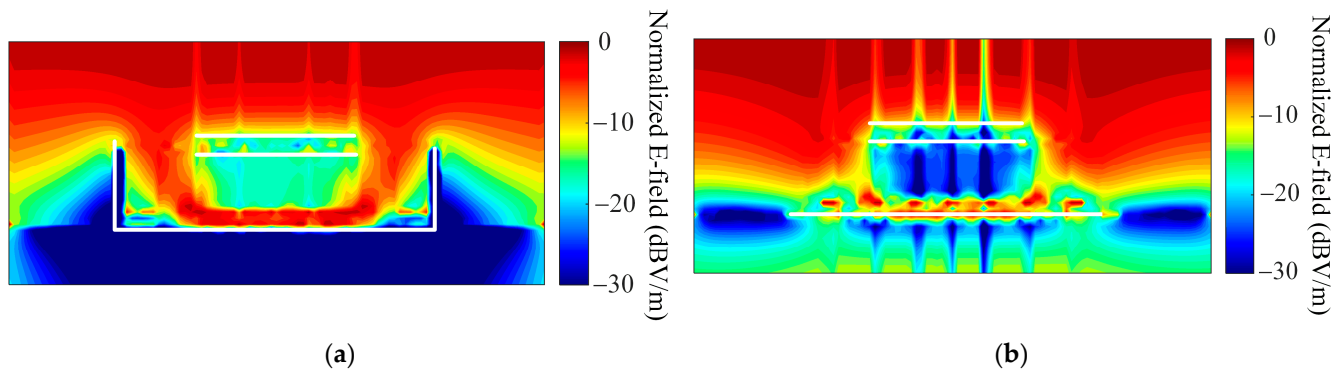


Figure 7. Near-field distributions with and without the cavity: (a) with the cavity; (b) without the cavity.

4. Conclusions

In this paper, we investigated a stacked dual-patch antenna with 3D printed thick quasi-air substrates and a cavity wall for wideband applications. In order to achieve the theoretical maximum bandwidth of the patch antenna, a stacked dual-patch configuration was employed to the proposed antenna to extend the area of the conductive radiator. In addition, the square-pipe resin frames manufactured using the 3D printing method were applied to the proposed antenna to implement a quasi-air substrate structure that has a low permittivity close to 1. Therefore, the proposed antenna had a broad bandwidth of 620 MHz with a fractional bandwidth of 20.7%. Then, the bore-sight gain of the proposed antenna is 7.9 dBi, and the HPBW in the E- and H-planes are 48° and 55° , respectively. The results demonstrate that by using the proposed antenna structure, broadband characteristics close to the fundamental bandwidth limit of the patch antenna can be achieved, and at the same time, the durability of the antenna can be improved for various applications such as military radar systems, mobile communication systems, and wireless transfer systems.

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