Physically Connected Stacked Patch Antenna Design with 100% Bandwidth

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Abstract—Typically, stacked patch antennas are parasitically coupled and provide larger bandwidth than a single patch antenna. Here, we show a stacked patch antenna design where square patches with semi-circular cutouts are physically connected to each other. This arrangement provides 100% bandwidth from 23.9–72.2 GHz with consistent high gain (5 dBi or more) across the entire bandwidth. In another variation, a single patch loaded with a superstrate provides 83.5% bandwidth from 25.6–62.3 GHz. The mechanism of bandwidth enhancement is explained through electromagnetic simulations. Measured reflection coefficient, radiation patterns and gain results confirm the extremely wideband performance of the design.

Index Terms—Wideband patch antenna, dielectric superstrate, stacked patch antenna.

I. INTRODUCTION

NEW wireless telecommunication technologies are moving to millimeter-wave bands and require very wideband antennas to cater to next-generation high-data-rate applications. Therefore, the future 5G Local Multipoint Distribution Service (LMDS) band is promising to operate in the 27.5-31.3 GHz band [1]. The next-generation wireless local area network (WLAN) and wireless personal area network (WPAN) will exploit the 60 GHz spectrum [2]. Among a wide variety of ultra-wideband antennas [3], broadband patch antennas are attractive for telecommunication systems as they have omnidirectional radiation patterns.

Many designs of broadband patch antennas have been reported in literature [4-16]. Stacked patch antennas with bandwidths (BW) up to 20% are reported in [4]. In references [12] and [16], a stacked patch antenna design has been introduced which demonstrates a maximum BW of 27%. This design employs angled circular cutouts in square metallic radiating elements to achieve a wide BW. However, the central pin of the coaxial cable has electric contact only with the bottom patch. In another design, a U-slot microstrip antenna with an E-shaped stacked patch achieves an impedance BW of 59.7% [7], while a rectangular stacked patch antenna with a dielectric superstrate demonstrates a BW of 69% [5]. In [8], a rose leaf-shaped microstrip antenna with a capacitively coupled rectangular feed shows an impedance BW of about 69%, while in [10], a broadband L-strip-fed printed microstrip antenna

achieves a BW of 74%. A probe-fed stacked square patch slotted wideband microstrip antenna with an impedance BW of 76.25% is presented in [6]. The design in [6] has misaligned square slotted patches with shorting walls. A stacked patch antenna with a folded patch feed and a BW of 90% is presented in [9]. This strip-loaded slotted microstrip antenna is fed by an L-strip feed line to achieve impedance matching for the higher-order modes of the patch antenna in addition to the existing resonances. A design for a probe-fed shorted asymmetric E-shaped patch antenna with 110% BW is presented in [11]. A 112% BW square patch antenna with four capacitively coupled feeds is presented in [13]. In references [14] and [15], metamaterial-based patch antennas with 129% and 134% BWs are presented.

From the above literature review, we can see that patch antenna designs from [11, 13-15] have impedance BWs of more than 100%. However, the issue with these designs is that they do not provide consistent high gain across the band, and at some frequency points, their gains drop below 2 dBi. This means that the real working BWs of these designs are less than 100%. To overcome this issue, we present a stacked patch antenna design where the stacked patches are physically connected through the coaxial cable pin (instead of the typical capacitive coupling). By virtue of this approach, to the authors' best knowledge, this design for the first time provides a consistent gain of 5 dBi or more across the entire 100% BW.

II. DESIGN OF A SINGLE PATCH ANTENNA ELEMENT WITH A SUPERSTRATE

Let us consider a single-element patch antenna with a metallic radiating element in the form of a square plate of length $L_I = 2.65$ mm that has angled circular cutouts of radii $R_I = 0.95$ mm (Fig. 1) [17]. The radiating element is implemented on a Rogers RO4533 substrate, which has a permittivity of 3.3, loss tangent of 0.0025, thickness of 0.76 mm, and a radius of 5 mm. The bottom side of the substrate is metallized and thus acts as the ground plane for the patch antenna. The patch was excited by a 50- Ω coaxial cable, which was located at a distance of 0.78 mm from the center of the patch (along the X-axis). The outer ground of the coaxial cable has been connected to the patch ground plane.

Let us investigate the influence of the diameter d of the central

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Fig. 1. A single element patch antenna.

pin of the feeding coaxial cable on the reflection coefficient (S_{11}) of the patch antenna. As we can see further, for the considered shape of the radiating patch, d had a strong effect on S_{11} . The diameter varied from 0.1 to 0.5 mm. The outer diameter of the coaxial connector was varied proportionally to d in simulations to obtain a 50- Ω wave impedance. A single-element patch antenna was simulated using Ansoft HFSS software for the dimensions mentioned above. Fig. 2 plots the simulated S_{11} of the single-element patch antenna. From this

Fig. 2. S_{11} of the patch antenna with various values of d .

figure, we can see that for the thin pin of the coaxial cable, the patch antenna only had a single resonance at the frequency of 34 GHz with a BW of 10%. The resonance shifted to higher frequencies and the BW increased when the diameter of the coaxial cables increased. When $d = 0.5$ mm, S_{11} was less than -10 dB for the frequencies of 39–68 GHz and had four resonances at frequencies of 42, 48, 58 and 64 GHz.

One of the methods to increase the gain, efficiency and BW of a patch antenna is the use of superstrates [18]. The effect of BW increase and change of resonance frequency of a square patch antenna has been studied for metamaterial superstrates [19, 20] and dielectric superstrates [5, 21]. To improve the BW of the single-element patch antenna with $d = 0.5$ mm, we covered the antenna with a dielectric superstrate, which was based on a Rogers RO4533 substrate with radius of 5 mm and thickness t . Fig. 3 shows the simulated S_{11} of the patch antenna without the superstrate and with a dielectric superstrate with varying thicknesses of 0.3, 0.6, 0.76 and 0.9 mm. From this figure we can see that the dielectric superstrate changed the frequency of each of the resonances of the single-element patch antenna. The widest working frequency band of 26.4–62 GHz (the BW is 80.5%) was obtained when $t = 0.76$ mm.

Fig. 3. S_{11} of the patch antenna with various values of t .

A single-element patch antenna with the dimensions described above and a dielectric superstrate with $t = 0.76$ mm was fabricated and measured (Fig. 4). As a feed connector, we used a standard 50- Ω SMA (manufacturer: Amphenol SV Microwave, part number: 3321-60001).

Fig. 4. (a) A photo of the fabricated single element patch antenna with dielectric superstrate and (b) a view of the patch antenna with dielectric superstrate.

Fig. 5 plots the measured and simulated S_{11} of the patch antenna with a dielectric superstrate. From this figure we can see that the measured S_{11} of the patch antenna was less than -10 dB for the frequencies 25.6–62.3 GHz (the BW was 83.5%). The broadband operational mode was provided by four resonances, which corresponded to measured (simulated) frequencies of 28 (31), 44 (46), 52 (54) and 58 (59) GHz.

Fig. 6 plots the measured and simulated meridional (E_θ) and

Fig. 5. S_{11} of the patch antenna with dielectric superstrate.

azimuthal (E_ϕ) components of the radiation patterns and peak gain of the patch antenna with the dielectric superstrate. The angle θ in the figure was measured from the Z-axis.

From Fig. 6, we can see that the radiation patterns have an asymmetrical shape in the XZ-plane, which was due to the

Fig. 6. Radiation patterns of the patch antenna with dielectric superstrate: (a) XZ-plane, 30 GHz; (b) YZ-plane, 30 GHz; (c) XZ-plane, 45 GHz; (d) YZ-plane, 45 GHz; (e) XZ-plane, 60 GHz; (f) YZ-plane, 60 GHz.

excitation of the patch by the coaxial cable with a thick pin. Generally, there is a good agreement between the simulated and measured radiation patterns, but the slight differences can be due to the influence of the feeding cable used in the measurements. It was expected to see a null for E_θ in the Z-axis direction and a symmetrical shape for E_θ and E_ϕ in the YZ-plane, as this is the trend for the radiation patterns for TM₂₀ and TM₂₁ modes of a circular patch antenna [4], which is quite close to our proposed antenna geometry as well. It can be clearly seen in Fig. 7 that the measured peak gain (the peak gain is the maximum gain over all the directions of the far-field infinite sphere) and the simulated total efficiency varies from 5.1 to 7.8 dBi (a variation of less than 3 dB) and from 0.66 to 0.94 respectively for the entire working frequency band. The lower measured gain value (~5 dBi) around 40-50 GHz band is due to the relatively lower directivity of the antenna from the resonant modes excited in this band as compared to relatively higher gain values (~7.5 dBi) for other bands.

Fig. 7. Peak gain and total efficiency of the patch antenna with dielectric superstrate.

III. THE MODIFIED STACKED PATCH ANTENNA DESIGN

The next improvement for the BW of the single patch antenna with dielectric superstrate was made possible by the creation of an additional fifth resonance. The additional resonance could be obtained by increasing the length of the central pin of the coaxial cable to the thickness of the superstrate (Fig. 8).

Fig. 8. A single element patch antenna with increased length of the central pin of the coaxial feed.

A simulated S_{11} of such a design is shown in Fig. 9. From this figure we can see that the additional fifth resonance

Fig. 9. S_{11} of the patch antenna with increased central pin of the coaxial feed.

appeared at the frequency of 71 GHz, and the working frequency band of the design was 25.5–73 GHz, but for frequencies of 39, 49 and 67 GHz, S_{11} was higher than -10 dB.

To match the design at these frequencies, we connected the increased pin of the coaxial feed with the second radiating element that had the same shape as the first radiating element, with dimensions $L_2 = 2.55$ mm and $R_2 = 0.95$ mm. The modified stacked patch antenna design with electrical contact between both of the radiating patches was fabricated and measured (shown in Fig. 10).

Fig. 10. (a) A photo of the fabricated stacked patch antenna with electrical contact between the central pin of a coaxial cable and both plates; and (b) a view of the modified stacked patch antenna.

Fig. 11 plots the measured and simulated S_{11} of the modified stacked patch antenna. From this figure we can see that the S_{11} of the patch antenna was less than -10 dB for frequencies of 23.9–72.2 GHz (the BW was 100.3%). The influence of the size of ground plane on S_{11} of the antenna has been investigated. Simulated results verify that the ground plane does not affect the BW of the antenna, as long as the radius of the ground plane is larger than the length L_1 of the patch antenna. In addition, the BW was provided by five resonances, which corresponded to measured (simulated) frequencies of 27 (30), 43 (45), 51 (55), 63 (63) and 68 (67) GHz. Simulated distributions of normalized

Fig. 11. S_{11} of the modified stacked patch antenna.

amplitude of surface electrical currents on the upper and bottom plates of the stacked patches for different resonance frequencies are shown in Fig. 12. From Fig. 12 we can see that for the frequency of 30 GHz, the maximum electrical current amplitude only existed on the edges of the bottom patch. Thus, the bottom plate was the main source of radiation for a frequency of 30 GHz. For higher resonance frequencies, both patches had a high amplitude of electrical currents on the edges, and thus both patches contributed to the overall radiation pattern. Fig. 12 shows that the current distributions were different for different frequencies, which indicates the excitation of different types of resonance modes.

Fig. 13 plots the measured and simulated radiation patterns and peak gain of the modified stacked patch antenna design. From this figure we can see that radiation patterns of the single

Fig. 12. Normalized current distribution on the metal plates of the modified stacked patch antenna for frequency of (a) 30 GHz, (b) 45 GHz, (c) 55 GHz, (d) 63 GHz, and (e) 67 GHz.

patch with a dielectric superstrate (Fig. 6 [a], [b]) and the stacked patch (Fig. 13 [a], [b]) have the same shape for a frequency of 30 GHz. This fact confirms the conclusion that the bottom plate creates the main contribution in radiation pattern for a frequency of 30 GHz. The measured peak gain and the simulated total efficiency of the modified stacked patch antenna (shown in Fig. 14) varies from 5.2 to 8.2 dBi (a 3 dB variation) and from 0.73 to 0.96 respectively for the entire working frequency band.

Fig. 13. Radiation patterns of the modified stacked patch antenna: (a) XZ-plane, 30 GHz; (b) YZ-plane, 30 GHz; (c) XZ-plane, 50 GHz; (d) YZ-plane, 50 GHz; (e) XZ-plane, 70 GHz; (f) YZ-plane, 70 GHz.

Fig. 14. Peak gain and total efficiency of the modified stacked patch antenna.

IV. CONCLUSION

Thus, a physically connected stacked patch antenna design with radiating patch plates of a square shape with angled circular

cutouts provides 100.3% BW and peak gain of more than 5 dBi inside the working band.

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