A High-Gain Microstrip Patch Antenna Using Multiple Dielectric Superstrates for WLAN Applications

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Abstract **─** This paper presents the design and characterization of a microstrip patch antenna with multiple superstrates for performance enhancement operating at the central frequency of 5.5 GHz for high-gain WLAN applications. The performance of the antenna in terms of reflection loss and the gain are investigated using multiple high dielectric constant superstrates of Taconic CER-10 (ε_r=10.2). Numerical results showed that the patch antenna has -10 dB impedance bandwidth of 2.54% which improves to 8.43% and 17.43% by employing a single and dual superstrate, respectively. The gain of the antenna increases from 6.1 dBi to 9.5 dBi using a single superstrate, which further enhances to 13.6 dBi by placing two optimized superstrates. Moreover, further increasing the number of superstrates did not significantly impact on the performance of the patch antenna. The final design of the antenna (patch antenna with two superstrates) is fabricated and measured. The measured results agree well with the simulated results. Due to the good impedance matching, high-gain and desired radiation patterns compared to the other superstrate antennas, this antenna is a good candidate for high-gain WLAN applications.

Index Terms **─** Fabry-Perot cavity antenna, gain enhancement, microstrip patch antenna, superstrate antenna, WLAN.

I. INTRODUCTION

The wireless communication revolution is bringing fundamental changes and updates to data networking, telecommunication, and is making integrated networks for future development. By freeing the user from the cord, personal communications networks, wireless local area networks, mobile radio networks, and cellular systems, harbor the promise of fully distributed wireless computing and communications, anywhere and anytime. Due to the development of information communication technology, the wireless network uses various frequency bands. The frequency bands are assigned based on the technology, purpose, network size, and requirements of the communication. For example, Wireless Local Area Networks (WLAN) bands work with maximum 250 m distance, with medium data rates and used in houses, small offices, factories or corporation areas.

On the other hand, WLAN is mainly used not only in industrial fields but also in every house, offices, and public places. Its usability and application range is expanding because it can be used conveniently regardless of location compared to a wired network. Being the key component of the communication systems, the design of the antennas having the desired characteristics has always been a challenge for the antenna engineers. Microstrip patch antennas offer advantages of low-cost, planar structure and easy design and have been studied thoroughly in the literature [1]. However, these antennas have low gain which limits the use of microstrip patch antennas in those applications which require high gain. These low gain antennas are not suitable for long-range communications and confined spaces like corridors, streets, tunnels, and highways. For the specific cases described above, high-gain and directional antennas with low back radiations are needed. Usually, microstrip antennas are coupled with extended hemispherical dielectric lenses to achieve high gain, especially at high frequencies [2, 3]. Lens-coupled antennas undergo the disadvantages of fabrication complexity and low radiation efficiencies [4]. On the other hand, Fabry-Perot cavities [5], and the metasurfaces/metamaterial [6-13] have also been used to increase the gain of antennas. However, the metasurfaces

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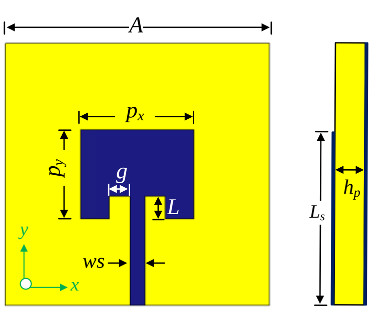
unit cells need optimization of complex design having huge design parameters. One of the famous and easy methods to increase the gain is the use of superstrates, in which one or multiple dielectrics and printed superstrates are placed over an optimized distance from the patch or basic radiator [14-29]. These superstrate antennas are getting significant attention of researchers both in microwave and millimeter waves owing to its intrinsic advantages of low complexity, high-gain, and conformal deployment ability.

In this paper, we proposed a microstrip patch antenna with multiple dielectric superstrates to enhance performance, especially the broadside gain at 5.5 GHz for high-gain WLAN applications. The results show that the impedance bandwidth and gain of the patch antenna is increased using a single superstrate, which is further increased using two superstrates. All the antenna designs (patch antenna, a patch antenna with one superstrate, patch antenna with two superstrates, and patch antenna with three superstrates) are simulated using the finite integration time-domain commercial simulator CST Microwave Studio. A transient time-domain solver with a hexahedral mesh type with an accuracy level of -45 dB is used in the simulation setup. This solver enables the complete far-field characterization of the antennas at broadband frequencies at one simulation run. To ensure the accuracy of the numerical results, the maximum mesh type is set as one-twentieth of a free space wavelength at 5.5 GHz.

II. ANTENNA DESIGN

The geometry of the microstrip patch antenna is shown in Fig. 1. The antenna is consisting of a full ground plane and a microstrip patch, both of which are patterned on Taconic TLY5 (ε_r = 2.2, $tan\delta$ = 0.0009) due to its low loss tangent and stable dielectric constant values at high frequencies. The patch is fed by a 50-ohm microstrip feed line. The optimized parameters of the patch antenna are: A = 50 mm, h_p = 1.6 mm, p_x = 19 mm, p_y = 18 mm, g = 4.25 mm, L = 3 mm, ws = 1.5 mm, and Ls = 44 mm.



(a) (b)

Fig. 1. Geometry of patch antenna: (a) front view and (b) side view.

The microstrip patch antenna is then coupled with a high dielectric constant superstrate to increase the broadside gain. Conventionally, an electrically thick superstrate is utilized to focus the radiated field in the broadside direction. Therefore, a planar slab of high dielectric Taconic substrate (ε_r = 10.2, $tan\delta$ = 0.0035) having a thickness of h_s = 1.6 mm is placed at an optimized distance of h_a = 4 mm from the antenna, as shown in Fig. 2. In this stage, only the parameters of the superstrate (h_a and h_s) are tuned for optimum performance, while all other parameters are kept unchanged.

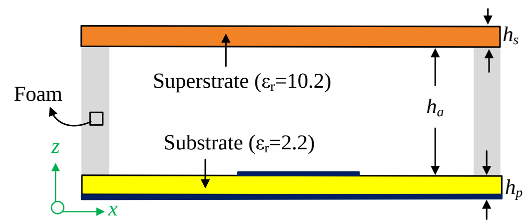


Fig. 2. Side view of the patch antenna with a single superstrate.

As the air gap is an important parameter in the design of such antennas. The antenna impedance and gain characteristics for the different values of superstrate height (h_a) from the patch antenna are shown in Fig. 3. The superstrate height greatly impacted on antenna performance. The gain and impedance of the antenna is improved when the superstrate height is increased from 2 mm to 4 mm, however, further increasing the height decreases the gain. Moreover, the impedance bandwidth is shifted to the higher frequencies for the increment in the air gap.

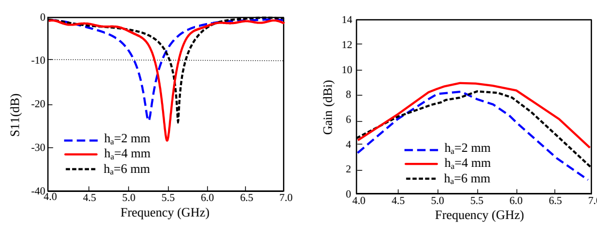


Fig. 3. Characteristics of patch antenna with single superstrate for different values of superstrate height (h_a): (a) $|S_{11}|$ and (b) broadside gain.

The patch antenna with single superstrate antenna is then modified by adding another identical superstrate for further gain enhancement to make the antenna suitable for high-gain WLAN applications, as shown in Fig. 4. A few antenna parameters are changed to reoptimized the antenna for two superstrates. The reoptimized parameters are: h_{s1} = 1.6 mm, h_a = 7 mm, and h_{a1} = 10 mm, while all other parameters remain the same.

The antenna characteristics in terms of $|S_{11}|$ and broadside gain of the antenna for the various separations (h_{a1}) between the two superstrates is shown in Fig. 5. A separation of h_{a1} = 12.5 mm gave the best results for the resonance at the desired frequency of 5.5 GHz with the high-gain and wide impedance bandwidth. Similarly, the antenna was optimized for three identical superstrates, where a third superstrate layer was placed on the antenna with two superstrates. The reoptimized parameters for this antenna configuration are as: h_{s2} = 1.6 mm, h_a = 6.5 mm, h_{a1} = 12, and h_{a2} = 7 mm (h_{s2} and h_{a2} is thickness and air separation of the third superstrate, respectively).

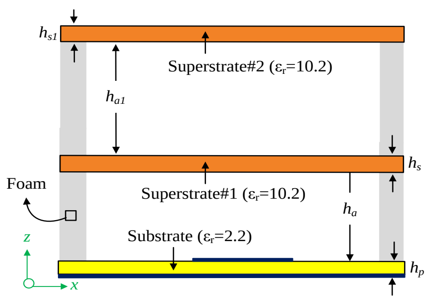


Fig. 4. Side view of the patch antenna with two superstrates.

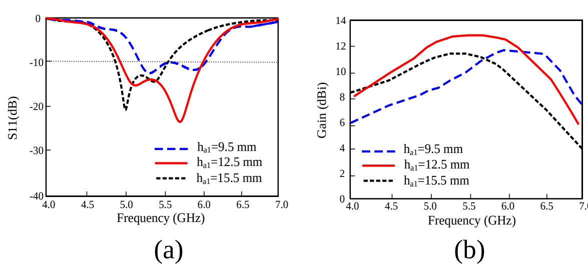


Fig. 5. Characteristics of patch antenna for the separation (h_{a1}) between two superstrates: (a) $|S_{11}|$ and (b) gain.

The antenna performance in terms of reflection loss and gain is compared for all cases of the patch antennas (a patch antenna with single superstrate, patch antenna with two superstrates, and patch antenna with three superstrates) is illustrated in Fig. 6. In summary, the overall performance especially impedance bandwidth and the gain of the patch antenna is improved using multiple superstrates. The antenna achieved the optimum performance for two superstrates. Further addition of the superstrates (three superstrates) did not improve the antenna performance. The detailed performance comparison of antennas for different superstrates is plotted in Table. 1. The antenna with two superstrates has a high-gain of 13.6 dBi and a wide impedance bandwidth from 4.8 - 6.1 GHz for $|S_{11}| < -10$dB covering the entire WLAN band. Compared to the patch antenna, the gain of the proposed antenna with two superstrates is increased 7.5 dBi, while impedance is increased almost four times.

The radiation patterns of the antenna at 5.5 GHz for three cases: antenna without substrate, antenna with one substrate, and antenna with two substrates are shown in Fig. 7. The radiation beam gets narrow with the addition of superstrates to increase the gain of the antenna. The half-power beamwidth of the patch antenna is around 70°, which decreases to 50° and 33° for the antenna with one superstrate and two superstrates, respectively.

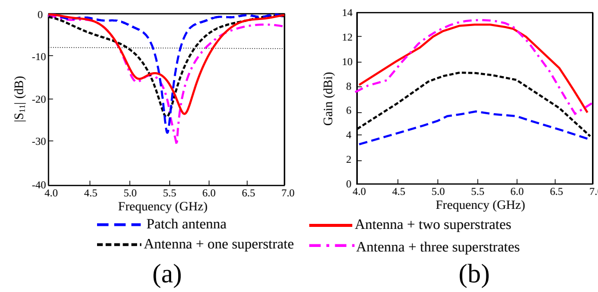


Fig. 6. The performance comparison for antennas with different configurations: (a) $|S_{11}|$ and (b) broadside gain.

Table 1: Performance comparison of antennas with different number of superstrates

Antenna Configuration	$\|S_{11}\|$ Bandwidth	Max. Gain (dBi)
Patch	5.43 - 5.57 GHz (2.54%)	6.1
Patch + one substrate	5.0 - 5.7 GHz (13%)	9.5
Patch + two substrates	4.8 - 6.1 GHz (23.8%)	13.6
Patch + three substrates	4.8 - 5.91 GHz (20.7%)	13.7

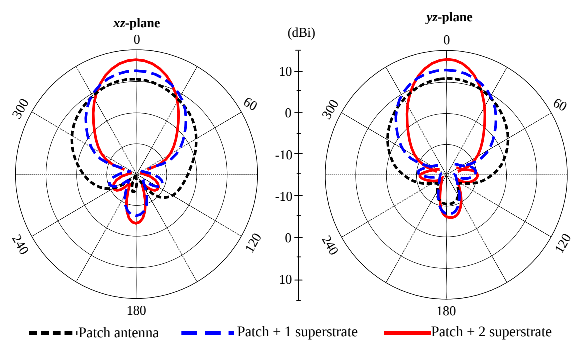


Fig. 7. Radiation patterns of the patch antenna for the different number of superstrates.

To explain the radiation mechanism of gain enhancement of the antennas using multiple superstrates, we computed the *E*-field of the antennas. The *E*-field for each antenna configuration in *xz*-plane is plotted at the central frequency of 5.5 GHz as depicted in Fig. 8. The superstrate layer acts as a lens to focus the *E*-filed to increase its intensity in broadside direction, thus the gain of the patch antenna is increased for the increasing layers of superstrates. Meanwhile, the *E*-field is almost the same for the antennas with two and three superstrates. Therefore, the gain did not increase for three superstrates even though the superstrates layers were increased.

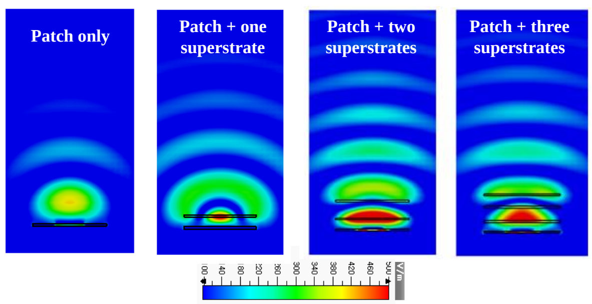


Fig. 8. *E*-filed of the antennas at *xz*-plane.

It is noted that in this study, we analyzed the performance of the patch antenna for the different numbers of superstrate layers, however, the size, thickness, and dielectric constant of the superstrate layers remained the same. The antenna with multiple superstrate layers, when the superstrate layers are different from each other would be the topic of a separate study in the near future.

III. MEASUREMENT RESULTS

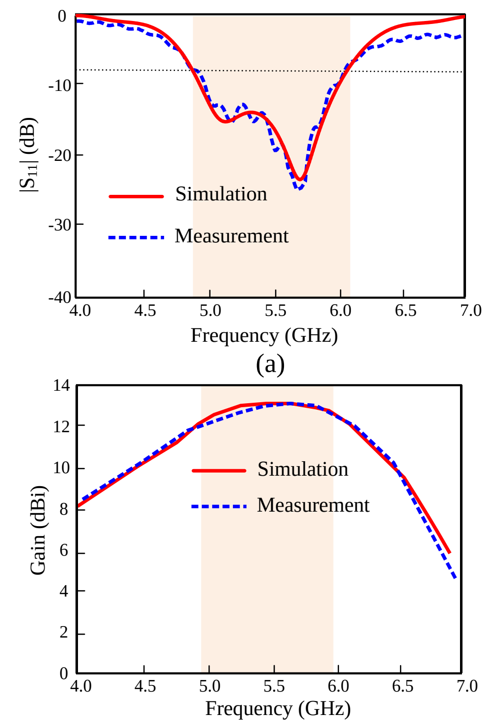
The proposed antenna design that is the antenna with two superstrates is fabricated to obtain the measurement results. A fabricated prototype of the proposed antenna is shown in Fig. 9.

(a) (b) (c)

Fig. 9. Fabricated prototype of the proposed antenna: (a) Front view of the patch, (b) back view of the patch, and (c) side view of patch antenna with two superstrates.

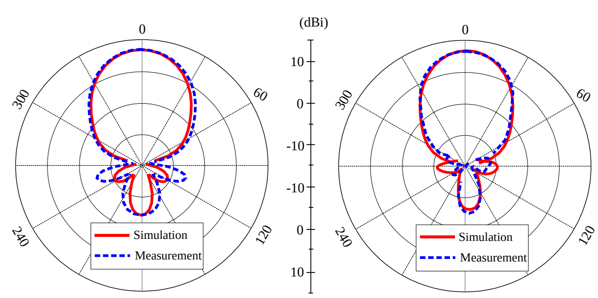
The simulated and the measured impedance $|S_{11}|$ and gain characteristics of the proposed antenna are shown in Fig. 10. Simulation and measured results showed that the antenna has an improved 10 dB impedance bandwidth from 4.8 - 6.1 GHz (23.8%). In addition, the antenna achieved a higher gain of 13.6 dBi due to the enhanced beam collimation of multiple superstrates.

The measured and simulation radiation patterns of the antenna at 5.5 GHz at *xz*-plane (*E*-plane) and *yz*-plane (*H*-plane) are shown in Fig. 11. The antenna produced a symmetrical directional radiation pattern with low side and back lobe levels at both principal planes. The beam-width became narrow to increase gain and directivity. With the aforementioned features of wide bandwidth, high gain, and directive radiation patterns, the antenna is a good candidate for the high-gain WLAN applications at confined places including building corridors, tunnels, and streets.



(a) (b)

Fig. 10. Characteristics of patch antenna with two superstrates: (a) $|S_{11}|$ and (b) broadside gain.



(a) (b)

Fig. 11. The radiation pattern of the antenna with two superstrates: (a) *xz*-plane and (b) *yz*-plane.

Finally, the antenna performance is compared with the other superstrate antennas [18-25] in Table 2. In general, it can be concluded that the proposed antenna is offering wider bandwidth and high gain with the additional advantage of smaller size compared to most of the reference antennas, which verifies the worth of the proposed design. Among the reference antennas, only the designs presented in [19] and [21-22] has the advantages of smaller overall size, however, these antennas have narrow bandwidth and low-gain. Although the antenna with two printed superstrate [24] offers a high gain of 15 dBi, it has the disadvantages of complex superstrate design as well as high antenna profile and narrow bandwidth. Thus, the proposed antenna is offering the advantages of simple design, smaller size, wide-bandwidth, and high-gain.

Table 2: Performance comparison of the proposed antenna with other superstrate antennas

Ref. Antenna	**Antenna Overall Size (λ_0^3)**	**$\lvert S_{11}\rvert$ BW (%)**	**Max. Gain (dBi)**
[18]	5.28 × 5.28 × 0.6	5.28	11.95
[19]	0.67 × 0.5 × 0.53	3.14	10.3
[20]	2.06 × 2.06 × 0.83	3.0	12.8
[21]	0.88 × 0.88 × 0.07	15	8.4
[22]	0.67 × 0.67 × 0.14	3.14	7
[23]	1.6 × 1.2 × 0.8	3.7	12.86
[24]	2.5 × 2.5 × 1.44	8.2	15
[25]	1.93 × 1.93 × 0.61	2.7	6.8
Proposed	**0.91 × 0.91× 0.36**	**23.8**	**13.6**

IV. CONCLUSION

A patch antenna with multiple superstrates is designed at the central frequency of 5.5 GHz for WLAN applications. All antenna designs (patch antenna, a patch antenna with single superstrate, patch antenna with two superstrates, and patch antenna with three superstrates) are analyzed numerically to explain the design procedure and performance enhancement. Simulation and measured results confirm that the antenna performance (gain and $|S_{11}|$) is improved by coupling patch antenna with one superstrate which further improves using two superstrates. The antenna shows the optimum performance for the two superstrates, further increasing the number of superstrates did not increase the antenna performance. Owing to its wide bandwidth (23.8%) high-gain (13.6 dBi) and desired radiation patterns the proposed antenna (antenna with two superstrates) may find its usability in high-gain WLAN applications.

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