Various strategies for the miniaturization and integration of planar antennas with 3D LTCC multilayer modules are presented. First, the design of compact stacked patch antennas and the derivation of design rules in which only one parameter needs to be adjusted in order to achieve an optimal bandwidth performance are thoroughly reviewed. This design strategy has been used for WLAN applications. Secondly, the principle of soft-and-hard surface (SHS) is employed to suppress the backside radiation and substrate modes generated by a patch antenna integrated with high dielectric-constant LTCC multilayer packages. One benchmarking design incorporates a V-band stacked patch antenna on a large-size substrate, where SHS effectively blocks the surface-wave propagation on the substrate, therefore alleviating electromagnetic coupling to the RF circuits.

INTRODUCTION

The explosive growth of wireless communication systems has led to an increasing demand for the miniaturization and integration of antennas with compact low-cost RF front ends [1]. Patch antennas have a planar structure, suitable for integration on multilayered materials, such as multilayer organic (MLO) [2] or low temperature co-fired ceramic (LTCC) [3] materials. Especially, the LTCC multilayer technology is maybe the most commonly used multilayer RF technology, due to its maturity and to its flexibility in realizing an arbitrary number of layers with easy-to-integrate circuit components. Typically LTCC materials possess a high dielectric constant (above 5.5) which makes for more compact modules at the expense of a reduced bandwidth and a reduced efficiency (due to surface wave excitation which can degrade the performance of the antenna).

To address these design concerns, various techniques have been reported in the past in order to increase bandwidth and suppress surface waves using high-dielectric constant substrates [4,5,6]. The most common method of increasing bandwidth is the use of a stacked patch [4], but unfortunately, there are many parameters, such as the length and width of the patch, the substrate thickness, and the position of the feed point, that need to be adjusted to achieve an optimal bandwidth performance, thus, making the design process quite tedious since it is difficult to adjust every parameter. A popular method of suppressing surface waves is to use an electronic band gap (EBG) structure for the substrate material or a ground pattern of the patch antenna to prevent energy from being spread in the substrate [5], [6]. One disadvantage of EBGs is they lead to large module sizes that are not suitable for compact design and may lead to edge diffraction, which further contaminates the far-field radiation pattern.

In this paper, two design methods are presented. The first involves the efficient design of compact stacked-patch antennas based on LTCC multilayer structures. An optimal bandwidth performance can be achieved by changing the number of LTCC layers. Then, the derived design rules are applied to benchmarking WLAN applications. The second methodology focuses on a stacked patch antenna that incorporates a soft-and-hard surface (SHS) for the suppression of surface waves, hence reducing the unwanted backside radiation. It will be shown that a reduction of more than 10 dB can be obtained in the backside level when the SHS is employed.

DESIGN OF LTCC-BASED STACKED PATCH ANTENNAS

Antenna Structure and Design Strategy. The antenna structure for this design is shown in Fig. 1. It consists of two square patches (lower and upper) of length \( L \) that are stacked on a grounded LTCC substrate. The total thickness of the substrate is \( h \). This thickness can be divided into two smaller thicknesses, \( h_1 \), the distance between the lower patch and the ground plane, and \( h_2 \), the distance between the lower and upper patch, where \( h=h_1+h_2 \). A metal backed cavity is introduced for reducing signal crosstalk. The feed point is selected to match a 50 \( \Omega \) coaxial line. The LTCC multilayer material used in the design has a dielectric constant of 5.6 and a loss tangent of 0.0012. Each laminated layer has a thickness of 4 mils.

Numerical simulations were performed using the 3D fullwave TLM (transmission-line model) based software MicroStripes. In lieu of initial simulation results, a set of design rules was derived for the efficient
and accurate design of compact stacked patch antennas using LTCC multilayer technology. First, an initial value for the total design thickness of the substrate \((h_1 + h_2)\) is selected. This thickness is usually less than 0.05\(\lambda_0\) for a compact design. Second, the lower substrate thickness, \(h_1\) is chosen. Through analyzing the results of many simulations, a lower substrate thickness of \(h_1 = \frac{h}{4}\) is suggested, for an enhanced bandwidth. Next, the length \(L\) should be designed according to the appropriate resonant frequency \(f_c\) required for the application. Equation (1) is suggested for designing the length \(L\):

\[
L = \frac{c}{2f_c\sqrt{\varepsilon}}
\]

where \(c\) is the speed of light in free space. Then, the upper substrate thickness, \(h_2\) is selected. This value can be varied to give an optimal bandwidth. Lastly, the length \(L\) is adjusted slightly to cover the desired frequency band.

**Application to WLAN 5.8 GHz Band.** Following the proposed design rules, a design was simulated and measured at 5.8 GHz. The length \(L\) was 400 mils and the initial substrate thickness, \(h\), was 8 layers. Two layers were chosen for \(h_1\) and up to six layers for \(h_2\). A plot of the return loss versus frequency is shown in Fig. 2. Good agreement is seen between the simulated and measured results. An optimal impedance bandwidth of 3.5% is achieved. This bandwidth is broader than the required standard for this application.

**INTEGRATED STACKED PATCH ANTENNA USING SHS BASED ON LTCC MULTILAYER TECHNOLOGY**

**Antenna Structure and SHS Theory.** An ideal soft-and-hard surface (SHS) is characterized by the parallel stacking of alternating Perfect Electric (PEC) and Perfect Magnetic Conductors (PMC), that is \(\hat{h} \cdot E = 0\) and \(\hat{h} \cdot H = 0\) for adjacent regions, where \(\hat{h}\) is a unit vector tangential to the surface of the SHS. This type of surface can be realized in the form of co-centered metallized rings for planar (patch) antenna geometries (Fig. 3) and forces the power flow in the direction towards the SHS (component normal to the boundary on the surface) to be zero. Therefore, by surrounding all four sides of a rectangular (or square) antenna with alternating PEC/PMC regions, surface waves can be eliminated as they propagate away from the patch towards the edges of the substrate.

**Application to V-band at 64.55 GHz.** The benchmarking case had a resonant frequency of 64.55 GHz (V-band) and is applicable for millimeter-wave sensors. The rings were separated by 500 \(\mu\)m. The diameter of each via was 130 \(\mu\)m with a center-to-center spacing of 500 \(\mu\)m. The stacked patches were square in geometry with a length of 750 \(\mu\)m. The total surface area was 7mm x 7mm and the LTCC material had a dielectric constant, \(\varepsilon_r\), of 5.4 and a loss tangent of 0.0015. The total substrate thickness for this design was 500 \(\mu\)m. This consists of 5 LTCC layers that were 100 \(\mu\)m each. For the stacked configuration, there was one layer between the lower patch and the ground plane and three layers between the lower and upper patch. A requirement for an effective, surface wave suppressing SHS is that the substrate thickness maintains a height of \(\lambda_0/(4\sqrt{\varepsilon_r})\), where \(\lambda_0\) is the free space wavelength.

Simulations for the design were performed using MicroStripes. The radiation pattern is shown in Fig. 4 and it can be clearly seen that the strong backlobe radiation level in the conventional patch design without SHS (-2 dB at \(\theta=180^\circ\)) is significantly suppressed when the SHS is introduced (-14 dB at \(\theta=180^\circ\)). A reduction in the backlobe of more than 10 dB can be achieved in the SHS antenna design with five rings.

**CONCLUSION**

Miniaturized stacked-patch antennas have been designed and optimized in terms of bandwidth and radiation modifying only one parameter that takes full advantage of the 3D modules, the substrate thickness between the upper and lower patches. When applied to WLAN applications, a 3.5% impedance bandwidth is achieved. It has also been shown that surrounding a patch antenna with an SHS structure can have a significant effect on suppressing the surface waves and substrate modes as they propagate away from the patch. A backlobe reduction of more than 10 dB can be realized when utilizing an SHS surrounding a patch antenna, hence, making for a more compact antenna for integration with RF devices.
ACKNOWLEDGMENTS
The authors wish to acknowledge the support of the NSF CAREER #ECS-9984761, the NSF #ECS-0313951, the Georgia Electronic Design Center, and the Georgia Tech Packaging Research Center.

REFERENCES

---

**Fig. 1.** Stacked patch antenna on LTCC multilayer substrate.

**Fig. 2.** Return Loss versus frequency for stacked patch antenna for WLAN applications at 5.8 GHz.

**Fig. 3.** Stacked patch antenna surrounded by an SHS on LTCC multilayer substrate.

**Fig. 4.** Radiation pattern of antenna w/ and w/o SHS at 64.55 GHz.