Integration of Miniaturized Patch Antennas with High Dielectric-Constant Multilayer Packages and Soft-and-Hard Surfaces (SHS)

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Abstract

The soft-and-hard surface (SHS) is employed to suppress the surface wave generated by a patch antenna integrated with high dielectric-constant LTCC multilayer packages. Two antenna structures are investigated to demonstrate the potential capability of the SHS in surface-wave suppression. The first is a stacked patch antenna on a large-size substrate. It is shown that using SHS can increase the gain at broadside of the patch antenna by almost 10 dB. The second antenna structure is a circularly polarized (CP) patch antenna designed for GPS applications. It is found that the SHS can reduce the backside radiation of the CP antenna on a small-size substrate by more than 14 dB. An observation to near-field distributions shows that the SHS can effectively block the surface-wave propagation on the substrate, therefore alleviating the electromagnetic coupling to the RF circuits

I. Introduction

The explosive growth of wireless communication systems has led to an increasing demand for integrating an antenna with a compact low-cost RF front end [1]. Patch antennas have a planar structure, suitable for integration on a multilayered material, such as multilayer organic (MLO) [2] or low temperature co-fired (LTCC) [3] materials. The LTCC multilayer technology is becoming more and more popular for its flexibility in realizing an arbitrary number of layers with easy-to-integrate circuit components like via-holes, thick film resistors, cavity-buried or top-mounted simultaneous multi-threading (SMT) components, or even chip devices. Typically LTCC materials possess a high dielectric constant. On one hand, this helps to miniaturize the antenna size due to the shorter wavelengths in such high dielectric-constant materials and the resonant nature of the patch radiator. On the other hand, however, patch antennas directly fabricated on such high dielectric-constant substrates suffer from surface-wave effects that can severally degrade the performance of the antenna and therefore of the integrated RF front-end module. The excitation of surface waves not only contaminates the radiation pattern (containing dips near the maximum and significant sidelobes) and reduces the efficiency of the radiator, but also can cause unwanted coupling between the active devices within the module.

In recent years, a number of techniques have been developed to suppress the surface waves generated by patch antennas on high dielectric-constant substrates [4]-[6]. The most popular method is to construct a complete band gap structure surrounding the patch antenna to prevent energy from being trapped in the substrate [4], [5]. Unfortunately, to form a band gap in the substrate via period holes requires considerable area, which may make it impractical for some applications. Typically, to form a band gap at least three periods are required with a period being on the order of a wavelength. Another approach considered has been to lower the effective dielectric constant of substrate under the patch to allow for more effective radiation [6]. The drawback of this approach is that the resulting patch antenna has to be larger than a patch on the unperturbed substrate, losing the advantage of using high dielectric substrate for reducing antenna size.

In this paper, we investigate the feasibility of suppressing surface waves using soft and hard surfaces (SHS) [7]. It is well know that the power-density flux along a soft surface is zero (i.e. the Poynting vector is zero) for any polarization of electric field. Therefore, if the surface of a high dielectric-constant substrate is covered with a soft surface, the surface waves could not propagate from a patch. As a result, there would be no diffraction/scattering from the substrate's edges, thus reducing the backlobe level and increasing the gain. The classical way to realize a soft surface is to corrugate an ideal conductor with transverse rectangular grooves that have a slot depth of a quarter wavelength. However, such a realization of SHS has a high manufacturing cost and results in a bulky structure. The techniques of conductor-corrugated SHS have been widely used in horn antennas [8] and other antennas [9]. In the LTCC technology, the corrugated structure can be easily realized in LTCC using arrays of metal vias (with a single manufacturing process). Two antenna structures will be investigated: one for increasing the gain of a patch antenna on a large-size LTCC substrate and the other for reducing the backside radiation of a CP antenna for GPS applications. It will be shown that the gain can be increased by about 10 dB for the antenna on a large-size substrate while the backlobe level for the CP antenna can be reduced by more than 14 dB.

II. Theory

The ideal SHS conditions can be characterized by the following symmetric boundary conditions for the electric and magnetic fields [10]

$$\hat{h} \cdot \vec{E} = 0 \,, \; \hat{h} \cdot \vec{H} = 0 \tag{1}$$

where $\hat{h}$ is a unit vector tangential to the surface. This boundary is called "ideal" since the complex Poynting vector $\vec{S} = \frac{1}{2} \vec{E} \times \vec{H}^*$ has no component normal to the boundary on the surface. This can be seen through the expansion

$$\begin{aligned}\hat{n}\cdot(\vec{E}\times\vec{H}^*) &= [\hat{h}\times(\hat{n}\times\hat{h})]\cdot(\vec{E}\times\vec{H}^*)\\ &= (\hat{h}\cdot\vec{E})[(\hat{n}\times\hat{h})\cdot\vec{H}^*]-[(\hat{n}\times\hat{h})\cdot\vec{E}](\hat{h}\cdot H)^* \qquad (2)\\ &= 0\end{aligned}$$

where $\hat{n}$ is the unit vector normal to the SHS. In the similar way, it can be proved that the complex Poynting vector has a zero component in the direction (say $\hat{s}$) transverse to $\hat{v}$ on the SHS. This means that the SHS in direction $\hat{s}$ can be considered being a soft surface, a concept originated from acoustics. We will take advantage of the characteristics of the soft surface to block the surface waves propagating outward along the high dielectric-constant substrate, thus alleviating the diffraction at the edge of the substrate. Shown in Fig. 1, a patch antenna with arbitrary configuration lies on a finite substrate with a dielectric constant of ε_r and is surrounded with an SHS that is formed as a soft surface in the outward direction. As a result, it would be difficult for surface waves to propagate from the microstrip patch to the substrate edge. Such an SHS can be realized using a number of via rings whose height h must be equal to $\lambda_0/(4\sqrt{\varepsilon_r})$ where λ_0 is the free-space wavelength. Based on this basic configuration, we will in the next two sections investigate two antenna structures. One is a patch antenna on a large-size substrate and the other is a CP antenna.

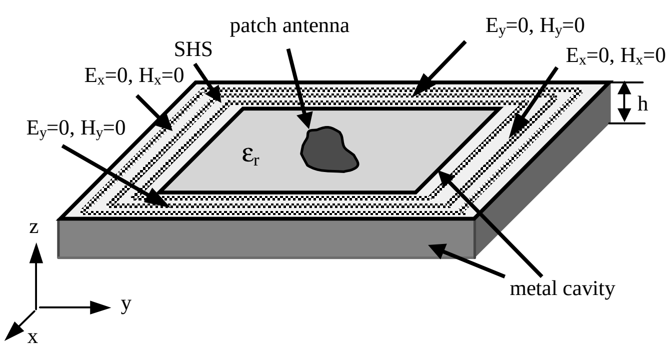


Fig. 1. Patch antenna surrounded by a soft-and-hard surface

III. Patch antenna on a large-size substrate

Consider a 0.75 mm × 0.75 mm square patch antenna laid on the center of a 7 mm × 7 mm dielectric substrate. The dielectric substrate used is Asahi's LTCC044 which has a dielectric constant of 5.4 and a layer thickness of 0.1 mm. The total thickness is 5 layers. In order to realize a quarter wavelength thickness, the design frequency is chosen to be 64.55 GHz. Three LTCC layers are used as the total thickness for the patch antenna. To achieve a desirable impedance match, a stacked patch configuration is adopted [11]. The heights of the lower and upper patches are respectively 1 and 3 layers. The stacked patch antenna is fed at the center edge to the lower patch. Five square via rings are used to construct the SHS. The diameter of the via is 0.13 mm and the spacing between two adjacent vias is 0.5 mm. The main parameters for the SHS and the stacked patch antenna are illustrated in Fig. 2.

The SHS-surrounded patch antenna is simulated using the TLM (Transmission-Line Method) based software Micro-Stripes 5.6. For comparison, we also simulated the same patch antenna without SHS (on a 7 mm × 7 mm × 0.3 mm dielectric substrate). The radiation patterns for the patch antennas with and without SHS are compared in Fig. 3. We can see that the directivity drop in the radiation pattern (caused by the surface wave) for the antenna without SHS is significantly improved by introducing the SHS. It is found that the gain improvement at broadside (z direction) is about 10 dB. It is also observed that the improvement in the backside lobes is better than 10 dB.

The frequency responses for the directivity gain (on z direction) and for the return loss of the antenna are shown in Fig. 4. It is seen that the gain for the antenna with SHS keeps near 10 dBi over a frequency range of 60-67 GHz while the gain is only 0 dBi if without SHS. The -10-dB return-loss bandwidth for the antenna with SHS is narrower (about 3.5%) than that without SHS. It is worth mentioning that the addition of an SHS to the patch antenna does not considerably affect the efficiency of the antenna. It is found that for the dielectric substrate with a loss tangent of 0.0015 and the metal with a conductivity of 3.7×10^7 S/m (Ag), the efficiencies of the patch antenna with SHS is calculated to be 89% among which 47% of loss comes from the substrate and 53% from the metal.

To demonstrate the surface-wave suppression achieved by the SHS, the near-field distributions are also compared in Fig. 5. We can see a much weaker electric-field distribution outside the SHS as compared to that without SHS, helpful in alleviating the electromagnetic coupling to other RF components.

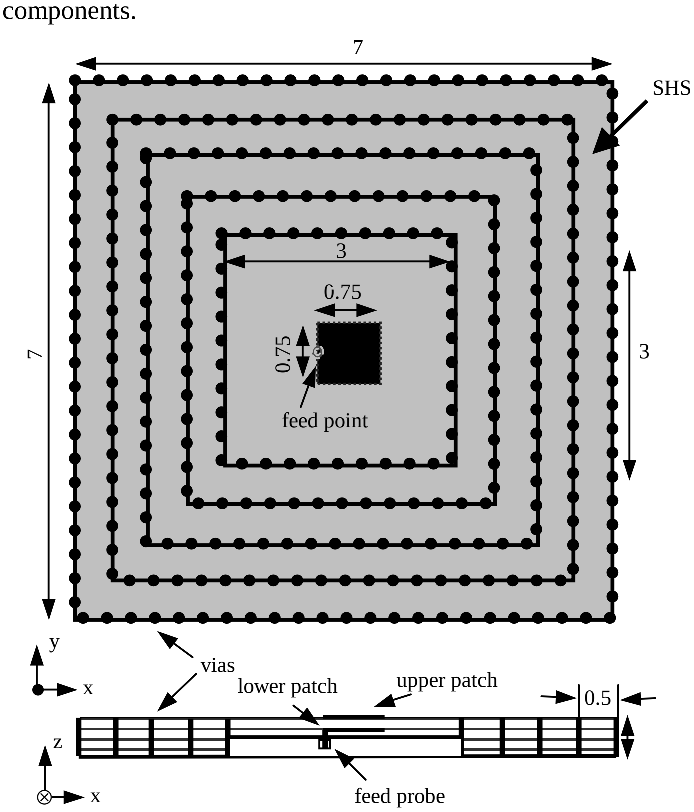


Fig. 2. Patch antenna surrounded by an SHS on a large-size substrate

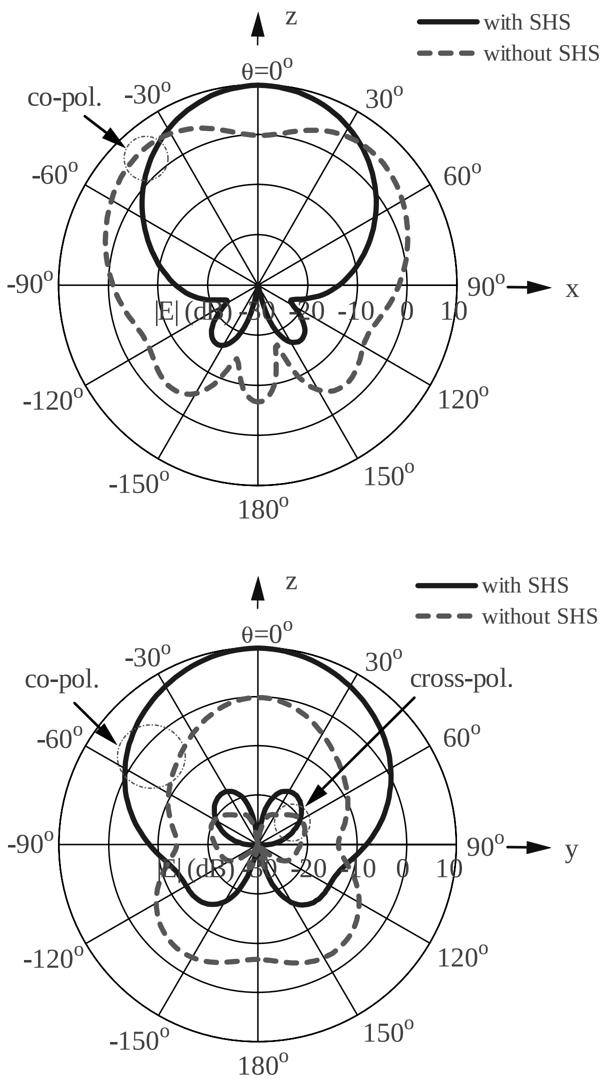


Fig. 3. Comparison of the radiation patterns between the patch antennas with and without SHS.

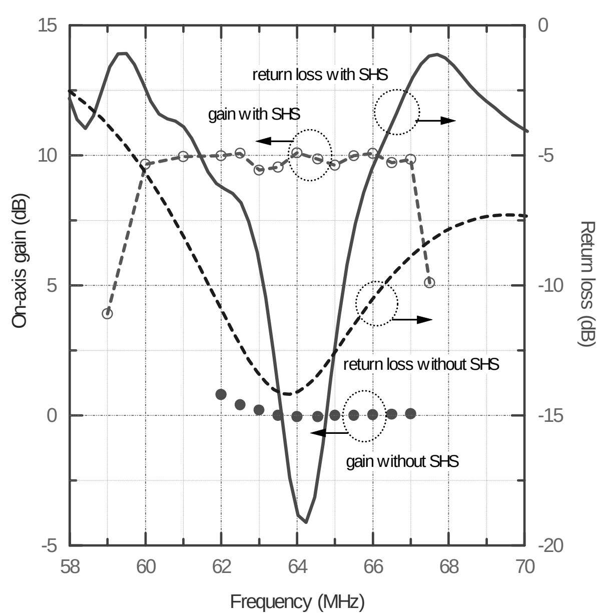


Fig. 4. Frequency responses of gain and return loss.

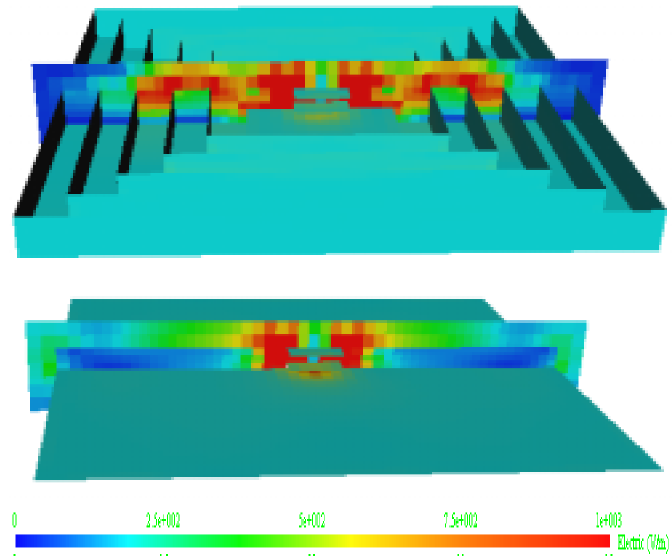


Fig. 5. Comparison of near-field distributions between the patch antennas with and without SHS.

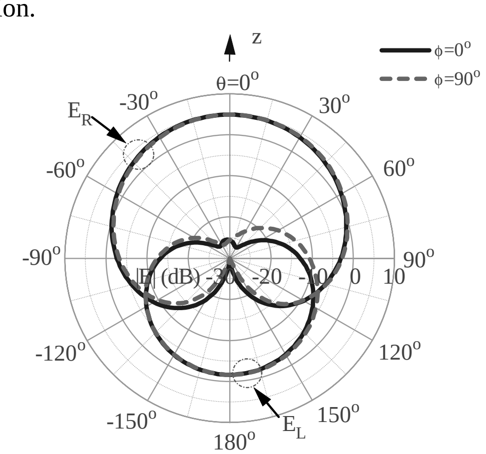
IV. CP patch antenna for GPS applications

For high-precision GPS applications, such as differential GPS, GPS-based spacecraft altitude determination or geometric surveying, the receiving antenna with a low-level backlobe radiation pattern is essential for the significant rejection of multipath signals. This property is particularly important for patch antennas because their backside radiation usually appears as a cross-polarized component. The multipath distortion results from the reflection of the GPS transmitted signal, which usually comes from the backside of the receiving antenna. As the GPS transmitted wave is right-hand circularly polarized (RHCP, or co-polarized), the directly reflected wave is left-hand circularly polarized (LHCP, or cross-polarized). Therefore, the patch antenna must have a lower cross-polarized component in the backside direction to eliminate the multipath effects.

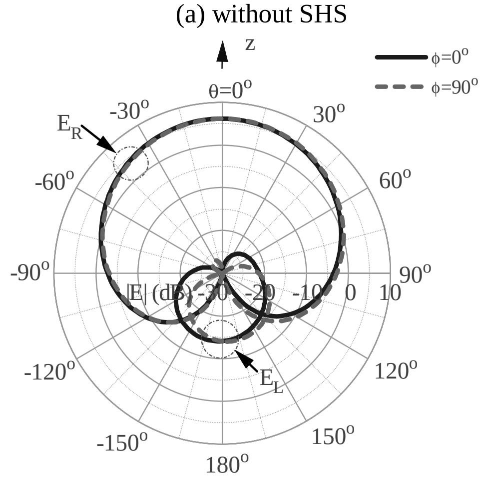
A simple way to reduce the backlobe level is to mount the patch antenna on a relatively large ground plane with respect to the size of the patch antenna (e.g., 6-7 times bigger for a 20-dB front-to-back ratio [12]). In some applications, such as laptops or mobile handheld terminals, however, there is not enough space left for a bigger ground plane. Hence, it becomes interesting to search for an alternative solution to suppress the backside radiation. Here we use an SHS surrounded configuration for the GPS patch antenna based on a high dielectric-constant LTCC material which is helpful in reducing the size of the antenna module as well as in guaranteeing the hemispherical coverage radiation pattern.

The antenna module is designed at the GPS civilian frequency (f_c=1575.42 MHz). The LTCC material used in the design is Kyocera's LTCC GL660 which has a high dielectric constant of ε_r=9.6. The layer thickness is chosen to be 0.5 mm. The SHS is realized using six square rings of metal vias. The via diameter is 0.2 mm and the via to via space in each ring is 2 mm. The distance between two adjacent rings is mm, thus leading to an SHS width of 10 mm. The dimensions of the outer and inner rings are respectively 70 mm and 50 mm. Since the length of the vias must be $\lambda_0/(4\sqrt{\varepsilon_r})$, we choose the total thickness of the antenna module as 32 layers. We also leave a cavity with a thickness of 11 layers beneath the patch antenna for burying the GPS RF front-end integrated circuit chipset (RFIC), thus leading a total thickness of 21 layers for the stacked patch. The stacked patch antenna is fed at the lower patch by a feed probe that is placed on the diagonal axis of a square area W×W. The length L and width W of the lower and upper patches (both have the same size) are adjusted to achieve the best circular polarization performance at f_c, which results in L=28.6 mm and W= 22.6 mm. The height of the lower is optimized to be 16 layers for a good input impedance match.

Fig. 6 shows the radiation patterns at f_c for the antennas without and with SHS for comparison. We can see that the backlobe level (LHCP, E_L) of the patch antenna with SHS is about -15 dBi, about 14 dB lower than that without SHS. The directivity gain (RHCP, E_R) is more than 0 dBi up to 15° elevation, much larger than the requirement of –5 dBi for maritime GPS applications [12]. Also the radiation pattern over the upper hemisphere (|θ|<90°) shows very low cross polarization and good symmetry with respect to the z direction.



(a) without SHS



(b) with SHS

Fig. 6. Radiation patterns for CP antennas without and with SHS.

V. Conclusions

It has been demonstrated that the LTCC multilayer technology can be applied to the realization of an SHS for surface-wave suppression, thus resulting in an increase in the gain and a reduction in the backside radiation of a patch antenna surrounded by the SHS. A patch antenna on a large-size substrate and a CP patch antenna are investigated. It is found that the gain can be increased by about 10 dB while the backside level can decrease by more than 14 dB. It is also shown through an observation to near-field distributions that the SHS can effectively block the surface-wave propagation on the substrate, therefore alleviating the electromagnetic coupling to the RF circuits.

Acknowledgments

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