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Suppression of surface waves and radiation pattern improvement using SHS technology

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Abstract
To reduce the backside radiation due to surface wave propagation from a high dielectric substrate, the use of an SHS has been employed to the design of microstrip patch antennas. The SHS is realized by surrounding the patch with metal via rings whose height must be equal to $\lambda_0/(4\times\varepsilon_r\ 0.5)$. A reduced backside radiation of approximately 10 dB is achieved with the SHS in comparison to a similar design without the SHS at 64.55 GHz. Generally, a large ground plane can also be used to reduce backside radiation, but incorporating the soft surface ring to surround a patch antenna can significantly reduce the size of the antenna, therefore making for a more compact module.

Keywords: Surface wave, SHS Technology, Patch Antenna etc.

Introduction
As multilayer materials such as LTCC, LCP, and MLO are being utilized for the integration of antennas into SOP modules, there are some concerns that need to be addressed in order to maintain the performance of the antenna. One of the drawbacks of designing antennas on LTCC is the high dielectric constant of the substrate ($\varepsilon_r > 5$), which facilitates the propagation of surface waves, which may be a larger problem at higher frequencies (millimeter-wave range). Designing antennas on high dielectric constant substrates can severely degrade the performance of the antenna's radiation characteristics as well as reduce the efficiency of the radiator. Another disadvantage of the surface wave propagation due to antennas on high dielectric constant substrates is the unwanted coupling of energy between the antenna and other active devices on the module. Although placing the antenna at a distance of about three wavelengths (3λ) away from the active devices can reduce the crosstalk between devices, this approach is not feasible for maintaining a compact module. Additionally, the use of vertical integration capabilities associated with SOP technology has allowed the lateral size (length and width) of the substrate to be decreased considerably [1-3]. Despite this innovation, planar antennas that are designed on small-size substrates contribute to backside radiation below the ground of the structure. There is a need for a surface wave suppressing mechanism that can be integrated to the patch antenna to maximize the performance of the antenna and minimize the degradation of other devices on the module. The most common method of suppressing surface waves is the use of a periodic bandgap structure (PBG). Sometimes, integrating PBG structures into SOP-based devices may not be suitable for maintaining the compactness of the design because PBG structures can be quite large as a result of the rows of via holes needed to realize the bandgaps. A new implementation using the soft surface properties of a soft-and-hard surface (SHS) structure is applied to a patch antenna on LTCC multilayer substrates.

Theoretical analysis
The ideal SHS conditions can be characterized by the following symmetric boundary conditions for the electric and magnetic fields:

$$\hat{h}.\overline{H} = 0, \hat{h}.\overline{E} = 0 \qquad (1)$$

where $\hat{h}$ is a unit vector tangential to the surface.

This boundary is called "ideal" since the complex Poynting vector $\bar{s} = \frac{1}{2}\overline{E} \times \overline{H}$. has no component normal to the boundary on the surface. This can be seen through the expansion

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

where $\hat{n}$ is the unit vector normal to the SHS.
The antenna structure for this implementation is shown in figure.

SHS on LTC Process

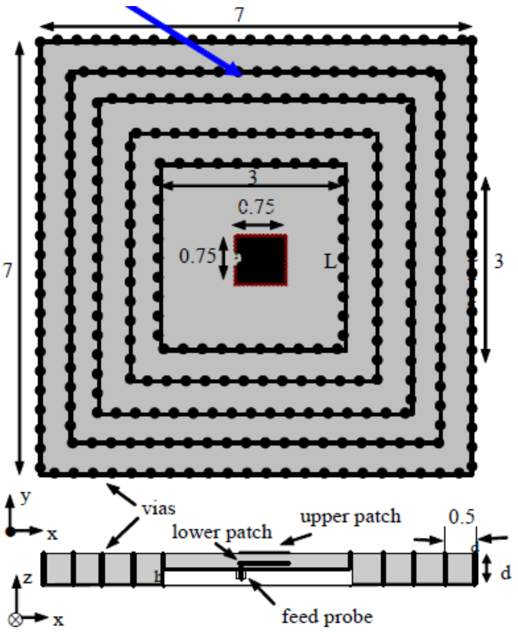

Fig 1: Stacked patch antenna surrounded by SHS structure

Investigation of improved one ring soft surface structure and its implementation to a patch antenna

An illustration of an antenna structure surrounded by a single soft surface ring is shown in Figure. Since the focus of this section is on the operation of the ring, a simple square patch antenna is used as the radiator for simplicity [4-6]. The ideal soft surface ring is shorted to ground along its outer edge with a continuous metal wall. The important parameters of the ring are its width, Ws, and length, Ls. It is seen in Figure that the ring can be modeled as a transmission-line where the impedance at the shorted edge is zero. Additionally, it is assumed that the inner edge of the ring can be modeled as an open circuit whose impedance is infinite.

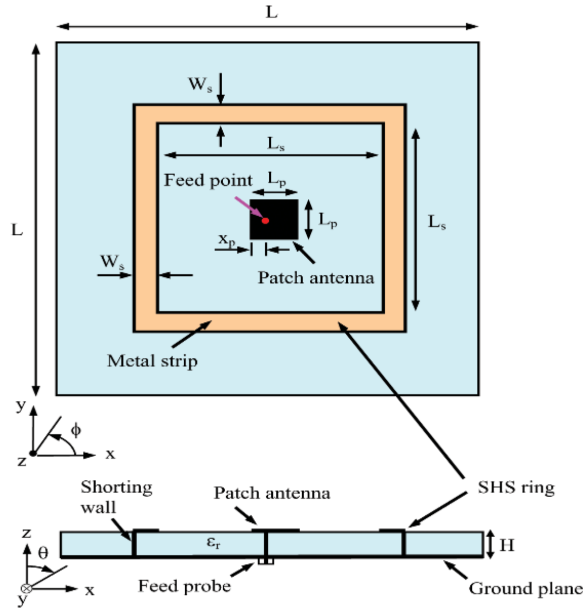

Fig 2: Patch antenna surrounded by a single soft surface ring

Therefore, to effectively transform a short circuit to an open circuit, the width, $W_{s'}$ must be approximately equal to a guided quarter-wavelength,

$$W_s^* = \left| \frac{C}{4\int \sqrt{\varepsilon_r}} \right| \tag{3}$$

Where c is the speed of light (≈3*10^8 m/s), f^0 is the operating frequency, and ε_r is the dielectric constant of the medium. Taking into account the fringing fields, Ws can be more accurately expressed as

$$W_s = \frac{C}{4\int 0 \sqrt{eff}} - \Delta W_S \tag{4}$$

Equations for the fringing field width, ΔWs, and the effective dielectric constant, ε_{eff}, can be obtained in as

$$\Delta W_s = H \cdot \left[0.882 + \frac{0.164(\varepsilon_r - 1)}{\varepsilon_r^2} + \frac{\varepsilon_r + 1}{\pi\varepsilon_r} \times \left\{ 0.758 + \ln\left(\frac{2W_s^*}{H} + 1.88 \right) \right\} \right] \tag{5}$$

and

$$\varepsilon_{eff} = \left[\frac{\varepsilon_r + 1}{2} \frac{\varepsilon_r - 1}{2} F(W_s^* / H) \right] \tag{6}$$

Where F(Ws*/H) = $(1+6H/W_s^*)^{-½}$ and H is the thickness of the substrate. The design value for Ws is optimized by simulation for a maximum directivity in the broadside ($\theta=0^0$) direction.
The optimal value for Ls in given as

$$L_S \approx \lambda_0 + L_P. \tag{7}$$

In addition, it has been shown via simulation that adding more rings does not improve the radiation pattern performance and contributes to an increase in the size of the structure.

Sensitivity analysis and optimization using design of experiments and monte carlo simulation

The performance of RF and microwave systems is severely affected by tolerances in the fabrication process, especially for small circuit dimensions at microwave frequencies. Therefore, it is important to analyze the performance of the system (in this case, the antenna) by examining the most critical factors that affect the performance of the soft surface ring. The performance is modeled with transfer functions developed from a methodology based on the integrated use of statistical tools, deterministic simulations, and measurements [7-10].

The factorial designs are used in experiments involving several factors where the goal is the study of the joint effects of the factors on a response. First, the variables that affect this design are chosen to be the length, Ls, and width, Ws, of the soft surface ring. The analysis intervals for the two variables are presented in Table 1.

Table 1: Ranges for the soft surface ring input variables

	Ls(mm)	**Ws(mm)**
"–" level	12	0.5
"+" level	36	4.5
Center Point	24	2.5

The statistical analysis of the first order models shows which effects and interactions between the factors are significant for each of the three figures of merit, and those that are not significant are eliminated from the final models [11-15]. In this case, curvature has not been detected and the first order models, which are investigated for the normality and equal variance assumptions, are presented below:

$$D = 6.72 - 0.29\left(\frac{L_S - 24}{12} \right) + 0.09\left(\frac{W_s - 2.5}{2} \right) - \left(\frac{L_S - 24}{12} \right)\left[0.33\left(\frac{W_s - 2.5}{2} \right) \right] \tag{8}$$

$$F / B = 9.96 - 0.80\left(\frac{L_S - 24}{12} \right) + 0.55\left(\frac{W_s - 2.5}{2} \right) - \left(\frac{L_S - 24}{12} \right)\left[0.85\left(\frac{W_s - 2.5}{2} \right) \right] \tag{9}$$

$$MRLP = 9.76 - 0.59\left(\frac{L_S - 24}{12} \right) \tag{10}$$

Next, the structure is optimized based on the models for the following goals: maximum directivity, maximum F/B ratio and a minimum MRLP. Table 2 shows the results of the Monte Carlo simulation.

Table 2: Predicted performance of the outputs of the soft surface ring design

	D(dBi)	F/B (dB)	MRLP (dB)
Nominal	7.07	11.2	–9.2
USL	n/a	n/a	–8.756
LSL	6.709	9.919	n/a
Cp	n/a	n/a	n/a
Cpk	1.57	1.52	1.58

Conclusion

To reduce the backside radiation due to surface wave propagation from a high dielectric substrate, the use of an SHS has been employed to the design of microstrip patch antennas. The SHS is realized by surrounding the patch with metal via rings whose height must be equal to λ_0/ (4×ε_r0.5). A reduced backside radiation of approximately 10 dB is achieved with the SHS in comparison to a similar design without the SHS at 64.55 GHz. This design can also achieve a gain enhancement of 10 dB at broadside (z-direction). The SHS has a broad coverage and a low cross-polarization level. An improved design of an antenna surrounded by one soft surface ring has shown the same potential in suppressing surface waves and edge diffraction effects and in reducing backside radiation. With this implementation, a 5 dB improvement in the gain and an 8 dB improvement in the F/B ratio can be observed in comparison to a simple antenna design without the soft surface ring. Generally, a large ground plane can also be used to reduce backside radiation, but incorporating the soft surface ring to surround a patch antenna can significantly reduce the size of the antenna, therefore making for a more compact module.

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