Assessing the Effect of Finite Conductivity on the Performance of Microstrip-Fed Patch Antennas*

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1 Abstract

The effect of finite conductivity on the performance of microstrip-fed patch antennas is examined. A zinc oxide film conductive patch material is modelled as an equivalent resistive surface using WIPL-D. The dielectric substrate and ground plane are finite in extent. The antenna radiation pattern and input impedance are used as figures of merit to assess different equivalent resistivities, corresponding to different thicknesses of the conductive zinc oxide layer. Results show that moderate thicknesses of zinc oxide are sufficient support acceptable patch antenna performance.

2 Introduction

Patch antennas offer an attractive design for airborne and spaceborne applications where size, weight, and conformability are prime requirements and only narrow bandwidths are needed [1]. In this paper we report on recent investigations into a patch antenna design using zinc oxide and quartz as the conducting and substrate materials, respectively, for novel microstrip-fed patch antenna. The major problem in the analysis is that of modelling the finite conductivity of ZnO, and the tradeoff between ZnO layer thickness and patch performance. Input impedance and radiation gain patterns are the relevant figures of merit for a patch antenna.

3 "Transparent" Patch Antenna

The US Air Force is interested in developing combined optical-radio frequency (RF) apertures. These promise to be better for airborne and spaceborne applications than separate optical and RF apertures. One method to achieve the dual-function aperture is to integrate an optically transparent RF antenna on the outer surface of the optical aperture. The obvious difficulty is that conventional metallic RF antennas obstruct light, and an equally obvious solution is to attempt to fabricate the RF antenna from optically transparent materials.

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A possible design is that of a microstrip-fed rectangular patch antenna, using quartz for the substrate material and zinc oxide (ZnO) for the conducting parts (ground plane, microstrip, and patch). The design is shown in Figure 1, and is designed to operate at approximately 5 GHz. The quartz substrate is 0.577 mm thick, and 60-by-60 mm in area. The finite ground plane covers the bottom surface of the substrate. The 19.3-by-15.2 mm patch is centered on the top of the substrate. The 1.04 mm wide microstrip feeds the long edge of the patch, 3.76 mm from the corner.

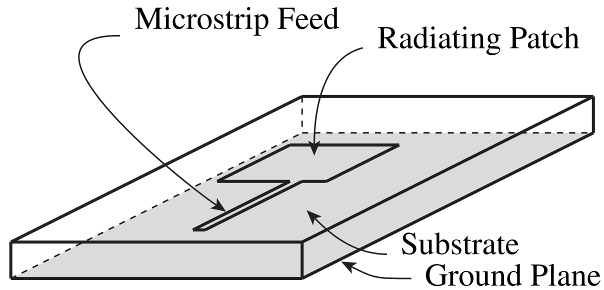


Figure 1: Microstrip patch antenna geometry. Patch, microstrip, and ground plane are sputtered zinc oxide; substrate is fused quartz. Substrate and ground plane are finite.

The major trade-off to be accomplished is to determine the best thickness of the ZnO layer. If it is made too thin, the patch, microstrip, and ground plane will not be sufficiently conductive. If it is made too thick, it will degrade the optical transparency and, hence, the performance of the optical sensor. An additional factor is the fabrication time to sputter the ZnO film on the quartz substrate, which is directly proportional to the film thickness.

4 Electromagnetic Modelling

We model the antenna using WIPL-D, which employs and solves the appropriate frequency-domain surface integral equation (SIE) using the moment method and entire-domain polynomial basis functions. We cast the problem in SIE form by modelling the ZnO film layers as infinitesimally thin resistive sheets, and the quartz substrate as a homogeneous, linear, isotropic dielectric.

Although quartz possesses a crystalline structure and is hence anisotropic, the degree of anisotropy is mild. Its permittivities parallel and perpendicular to the crystal axis are within approximately 10% of each other [2]. We thus model it as a simple isotropic material having a relative permittivity of 3.78 at 5 GHz [3].

The finite-thickness ZnO film layers are modelled as infinitesimally thin resistive layers located on the surface of the substrate. At 5 GHz, the conductivity and relative permittivity of ZnO are approximately 1.0×10^5 Siemens and 11, respectively. The skin depth, which measures the penetration of electromagnetic fields into a lossy material, of ZnO is given by [4]

$$\delta = \frac{1}{\omega\sqrt{\mu\varepsilon}\sqrt{\frac{1}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right]}} \tag{1}$$

Because, at 5 GHz, $\sigma \gg \omega\varepsilon$ and hence we can use the "good conductor" asymptotic form of Eq. (1),

$$\delta \approx \sqrt{\frac{2}{\omega\mu\sigma}} \approx 22\ \mu\text{m} \tag{2}$$

t (μm)	0.5	1.0	2.0
R_s ($\Omega/\Box$)	20	10	5

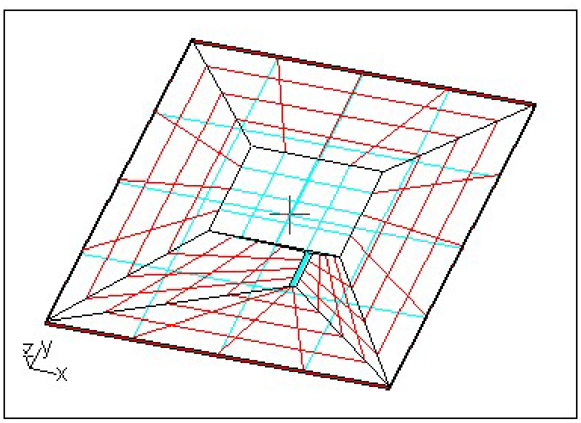
Table 1: Thickness and corresponding equivalent surface resistivities of ZnO layers at 5 GHz.

Using current sputtering technology, film thicknesses greater than about 5 μm are not practical, so we may assume that the film thickness is much smaller than the skin depth. Under this condition, we may further assume that the conduction current density is nearly constant through the film thickness. A thin layer carrying such a current density may be modelled as an infinitesimally thin resistive layer characterized by the surface resistance [5]

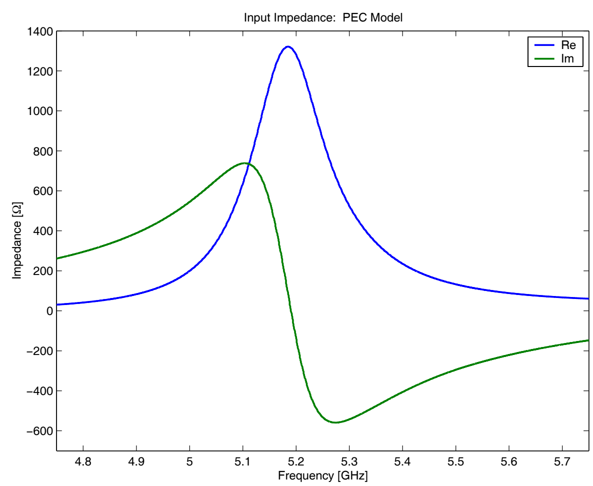
$$R_s = \frac{1}{\sigma t} \tag{3}$$

where t is the film thickness. Using Eq. (3), we can calculate the equivalent surface resistance of ZnO layer of various thicknesses at 5 GHz. Results are shown in Table 1.

5 WIPL-D Modelling



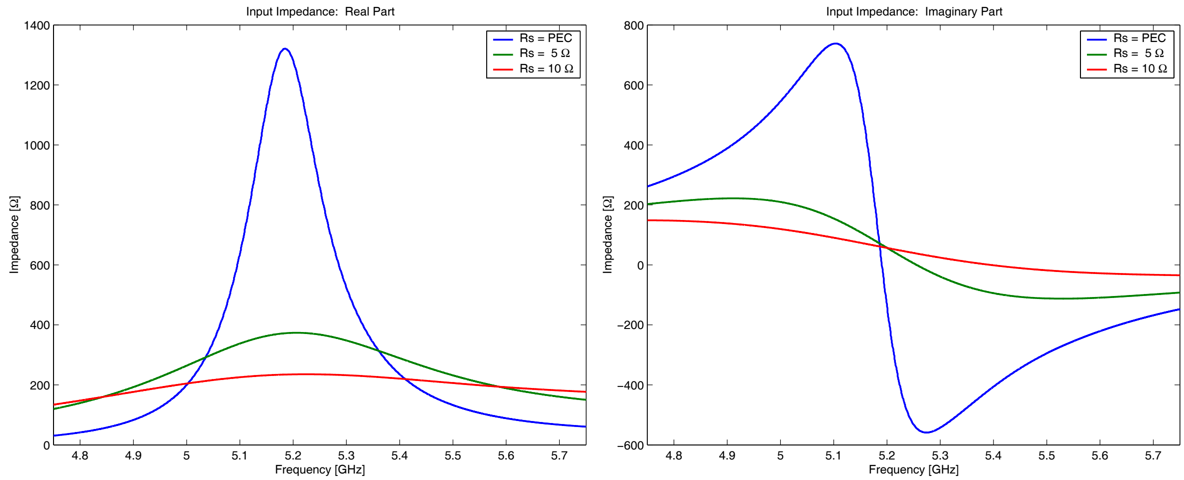
(a) WIPL-D "preview" of microstrip patch antenna model. Blue grids and red grids represent metallic and dielectric structures respectively.



(b) Input impedance of microstrip patch antenna modeled with PEC components.

Figure 2: WIPL-D geometry and input impedance for PEC patch antenna.

All simulations were performed using a demo version of WIPL-D [6]. Note: the demo version is limited to a maximum of 700 unknown currents. As such, a "basic mode" was used in modeling the transparent patch antenna, as shown in Figure 2(a). The patch, microstrip, and finite ground plane consisted of infinitely thin composite metallic plates. Dielectric plates formed the outer boundaries of the quartz substrate. Current was provided at the feed end of the microstrip via the basic generator option set to an amplitude of one volt. Numerical experimentation showed the optimal length of the microstrip feed to be approximately 6.5 mm. Surface resistance, R_s, was simulated using distributed



(a) Real part of input impedance, $\Re(Z_{\text{in}})$.

(b) Imaginary part of input impedance, $\Im(Z_{\text{in}})$.

Figure 3: Input impedance comparison between PEC and transparent antenna models.

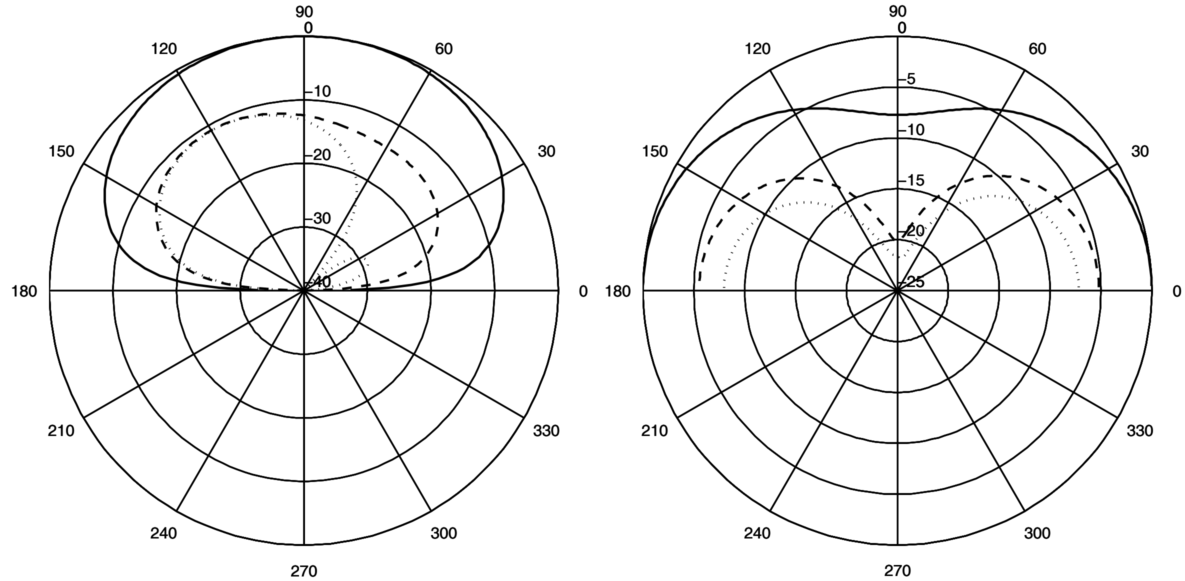
loading. Resistivities of 0 (PEC), 5, 10, and 20 $\Omega/\square$ were simulated. Frequency sweeps from 4.75 to 5.75 GHz with 41 steps were performed, resulting in 596 current unknowns.

More robust models were attempted using combinations of various modeling techniques: single edging, double edging, imaging, enhancement options, and modeling a patch of finite thickness. Such techniques usually resulted in models which required more than the limit of 700 unknown currents, and WIPL-D would not run due to "input data overflow" errors. A significant reduction in the number of unknowns was accomplished by setting the current expansion option to "reduced," but results were less accurate than the basic model under these conditions. Each configuration was evaluated against a known reliable model, being a substrate composed of free space.

Each model was evaluated by comparing its results against those of a free space metallic plate model of the same geometry. Comparison of input impedance and resonant frequency were used as figures of merit. Two modifications were made in order to compare the transparent patch model to the reference metallic plate model. First, the relative permittivity of the dielectric plates was changed from 3.78 to 1.0. Subsequently, since the resonant frequency approximately scales inversely with the square root of the relative permittivity, the microstrip length was adjusted to obtain a reasonable impedance value at the new (scaled) resonant frequency (9.2 GHz). The Smith Chart feature along with impedance plots were used to determine the optimum microstrip length.

6 Results

Simulations were conducted on WIPL models of three transparent microstrip patch antennas ($R_s = 5,\ 10,\ 20\Omega/\square$) along with one non-transparent patch antenna. It was found that only the low surface resistivities employed could be applied to the patch and the ground plane, but not the microstrip. In addition, results for resistivities of more than 10 $\Omega/\square$ indicated that the antenna does not operate at all like a PEC patch.



(a) E_ϕ field component, E plane scan. (b) E_θ field component, H plane scan.

Figure 4: Microstrip patch antenna normalized radiation patterns. Angle is scan angle in degrees, radius denotes normalized gain in dB. Solid line is normalized gain of PEC antenna; dashed line used for $R_s = 5\,\Omega/\Box$; dotted line for $R_s = 10\,\Omega/\Box$.

Modeling the antenna's metallic components as perfect electric conductors led to a relatively high input impedance ($Z_{\text{in}} \approx 1300\,\Omega$) at resonance-using the point at which the imaginary impedance crosses through zero, see Figure 2(b). The broadside gain and bandwidth[1] for the PEC patch were approximately 3.6 dBi and 3%, respectively.

As shown in Figure 3, adding resistive surfaces shifted the resonant frequency and dramatically decreased the magnitude of input impedance. A surface resistivity of 5 $\Omega/\Box$ resulted in resonant frequency and input impedance of approximately 5.25 GHz and 370 Ω, respectively. A surface resistivity of 10 $\Omega/\Box$ resulted in resonant frequency and input impedance of 5.40 GHz and 230 Ω, respectively. No attempt was made to re-optimize the geometry of the antenna after adding surface resistivity.

At broadside, adding a surface resistivity of 5 $\Omega/\Box$ decreases the antenna gain by about 12 dB. A resistivity of 10 $\Omega/\Box$ decreases the gain an additional 2 dB. Normalized E-plane and H-plane gains are plotted in Figure 4. The E-plane pattern, Figure 4(a), is symmetric for the PEC patch, but becomes asymmetric for lossy patches. A null appears in the E-plane pattern for $R_s = 10\,\Omega/\Box$, a qualitative departure from the PEC pattern. The H-plane pattern, Figure 4(b), maintains approximate symmetry as R_s increases, but the overall gain degrades and the broadside gain, in particular, develops a more pronounced null as R_s increases. Also, we see the effect of the finite ground plane and substrate in the broadside dip in the H-plane pattern.

[1]Bandwidth is defined as the range of frequencies for which $|\arg Z_{\text{in}}| \leq 45°$.

7 Conclusion

A "transparent" microstrip-fed patch antenna is analyzed using the WIPL-D computational electromagnetics code. The antenna uses sputtered zinc oxide for the conductive portions of the antenna, which are modelled as resistive surfaces. Results show that zinc oxide film is a viable material with which to construct such an antenna, but results in changes to the input impedance and resonant frequency that must be taken into consideration since they are significantly different from the corresponding values for a patch antenna using metal. A zinc oxide film thickness of 2.0 μm is sufficient to achieve performance nearly equal to that of a PEC patch antenna.

8 Acknowledgments

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