A Study on the Efficiency of Transparent Patch Antennas Designed from Conductive Oxide Films

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***Abstract*— A study on the efficiency of transparent patch antennas designed from indium tin oxide (ITO) films is presented to provide design guidelines for patch type transparent antennas. The trade-offs between optical transparency and antenna efficiency is analyzed by considering typical material properties of ITO films. It is shown that the efficiency of a patch antenna designed from ITO films is determined by the electron mobility of ITO films, operational frequency, and the substrate material. The study shows that with today's material processing methods, it is feasible to achieve at least 30% efficiency of an ITO antenna with 90% optical transparency for operational frequency higher than 5 GHz. While progress in material science may improve the antenna performance, the highly transparent patch antenna with 30% efficiency may be employed in array design for practical implementations.**

Keywords- Transparent antennas; patch antennas; indium tin oxide; conductive films

I. INTRODUCTION

Optically transparent antennas have been drawing increased interest in recent years. One method to design such antennas is to use transparent conductive oxide such as indium tin oxide (ITO) films because of their reasonable trade-offs between optical transparency and conductivity. We found that most reported development of ITO antennas is monopole geometry [1]-[3] whereas not much has been done for patch antennas. Transparent patch antennas are important in application where a ground parallel to the antenna surface is unavoidable. An example is integration of transparent antenna with solar cells for small satellite applications for reduced satellite payload, where the solar cells are typically mounted on a metal panel [4]. In such an application, a monopole antenna is not an appropriate choice. Saberin performed a study on ITO patch antennas and analyzed antenna efficiency on a glass substrate [5]. As the dielectric constant of the glass is fairly high for an effective antenna design, it is necessary to perform a more detailed study by considering different substrates. In addition, most ITO antennas have a transparency of less than 80% [5], which is not sufficient for applications where a higher transparency such as 90% is needed. This paper is aimed to present an analysis on the efficiency of patch antennas made from ITO films and to predict design guidelines for a 90% ITO antenna.

II. BASIC PROPERTIES OF AN ITO FILM

Efficiency of a patch antenna is primarily determined by the conductivity of the patch and substrate. Therefore, it is important to assess the material parameters that affect the conductivity and transparency of an ITO film. ITO is indium oxide doped with tin oxide. Electrical conductivity and optical transparency of an ITO film are highly dependent on the material properties, which are mostly decided during doping and deposition process. It is found that high conductivity is balanced against high transparency in the visible spectrum [5]-[7].

For an ITO film to be considered as a conductor, the operational frequency has to be below the plasma frequency of the film [5]-[7]. The plasma frequency, which is also a limiting factor for optical transparency, is determined from free electron density N_e of ITO, electron charge q, effective mass of an electron m^*, and electron relaxation/scattering time τ [5]-[7]. For an ITO film to be transparent in visible spectrum and conductive in microwave band, the plasma frequency needs to be carefully designed.

The optical transparency, or the transmission coefficient, of the ITO film can be approximated by (1), where t is the film thickness, and δ is the skin depth for visible light [6]. The skin depth δ can be obtained using (2), where Z_∞ is equal to $377/\varepsilon_\infty^{1/2}\Omega$, and ω_l is the frequency of visible light [7].

$$T(t) \approx e^{-\frac{2t}{\delta}} \,. \tag{1}$$

$$\delta \approx \frac{2m^*\omega_l^2\tau}{Z_\infty q^2 N_e} \,. \tag{2}$$

From (1) and (2), it is obvious that higher transparency requires thinner film with higher skin depth at visible frequencies.

The electrical conductivity can be derived from the surface resistance of an ITO film. The surface resistance is computed from

$$R_s = 1/(N_e q \mu_e t), \tag{3}$$

where μ_e is the electron mobility [5]-[7]. At a microwave frequency ω, the electrical conductivity is related to the skin depth, which can be approximated from

$$\delta \approx \sqrt{2/(\omega\mu\sigma)} \ . \tag{4}$$

For higher conductivity, a thicker film with higher N_e and μ_e is needed. In addition, the thickness of the film t needs to be much higher than the skin depth δ at the microwave frequencies. To maximize both optical transparency and electrical conductivity, N_e can only be at its maximum 1.5×10^{21} cm^{-3} [5]-[7], and μ_e should be as high as possible. According to the literature [6], [7], high quality ITO films with μ_e up to $50\mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1}$ are available from current material technology.

III. ANALSYS AND DISCUSSIONS

In this study, we considered a rectangular patch antenna constructed from an ITO film and a copper ground plane. A typical thickness (2 mm) and loss tangent (0.0057) of a plexiglass is assumed. The reason for these considerations is that most solar panels of small satellites use a copper layer as base, and plexiglass is convenient for laboratory validation when needed. In all of the following studies, the size of the ground plane is set to be large enough such as the antenna properties do not change anymore after increasing the dimension of the ground plane.

A. Effect of Electron Mobility

Since the electron mobility μ_e of an ITO film is the only variable of material parameters that can affect both transparency and conductivity in the same manner, it is reasonable to expect a higher μ_e value produces an ITO film with better electric and optical quality.

Using (1), (2), and the relationship between μ_e and τ [7], we computed the relation between the electron mobility, thickness of the ITO film, and the optical transparency. The computed results are presented in Fig. 1. The surface resistance of the ITO film for different electron mobility and optical transparency was computed from (3) and plotted in Fig. 2. It is clear from Fig. 1 and Fig. 2 that at a given transparency, higher electron mobility allows higher thickness of the ITO film, which helps reduce the surface resistance and hence the loss.

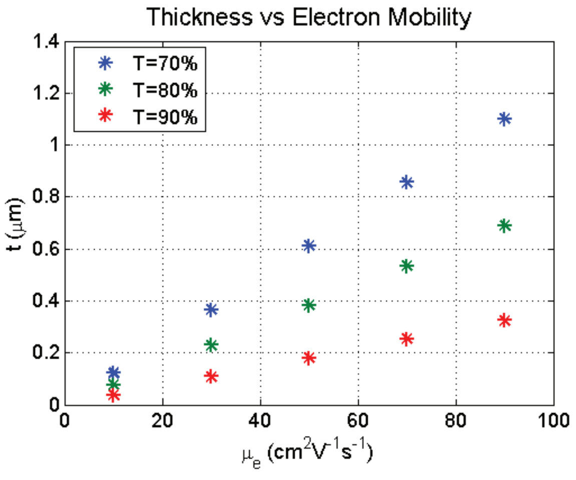

Figure 1. Effect of Electron Mobility on ITO Film Thickness

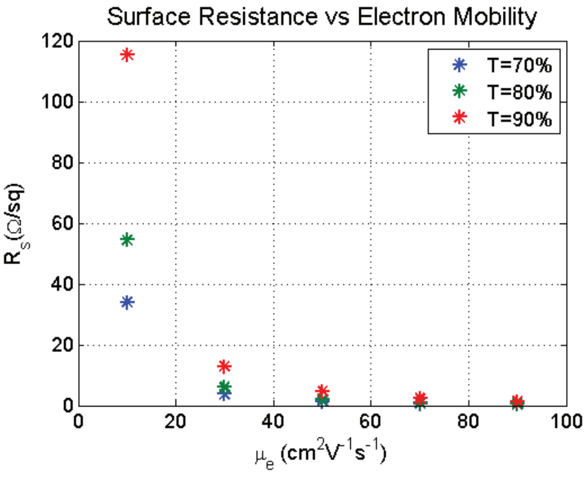

Figure 2. Effect of Electron Mobility on Surface Resistance

To examine how the electron mobility μ_e affects the antenna's radiation efficiency, 3 sets of patch antennas with different transparencies were studied using Ansoft's HFSS. The operation frequency of these antennas is set to be 2.5 GHz. The thickness of the ITO film is extracted from Fig. 1, and the permittivity of the substrate is set to 2. The results are plotted in Fig. 3. As expected, higher electron mobility results in higher antenna efficiency. Also, for the same electron mobility, higher transparency implies lower efficiency. The current material development shows that the maximum mobility is about $50\mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1}$, and therefore Fig. 3 indicates that a 90% transparent antenna has an efficiency of less than 15% at 2.4 GHz.

B. Effect of Frequency

For a given electron mobility and transparency, the surface resistance and the thickness of the film are fixed. But since the skin depth of the ITO film depends on antenna frequency as in

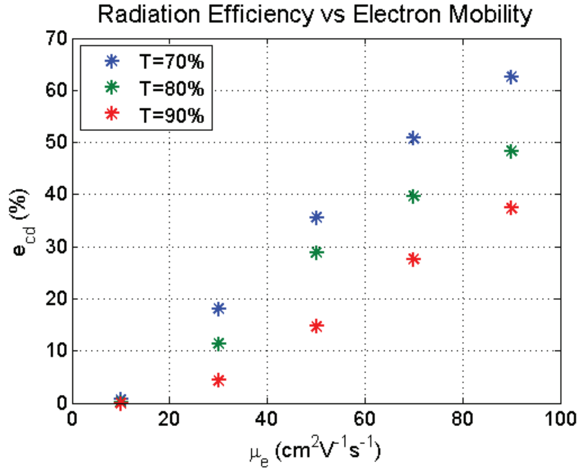

Figure 3. Effect of Electron Mobility on Antenna's Radiation Efficiency

(4), it is expected that a higher frequency predicts a more efficient antenna. We examined a group of 5 patch antennas designed from the same ITO film but at 5 different resonance frequencies. The substrate is the same as the previous study and the transparency is set to be 80%. The computed efficiency is presented in Fig. 4. It is seen that at 5 GHz, an 80% transparent ITO patch antenna can have about 50% efficiency.

As explained in the introduction, for integration with solar cells, an antenna needs to have at least 90% transparency. Therefore we studied a 90% transparency ITO patch antenna at 5 GHz and its efficiency is found to be about 32% for the same substrates as in the previous two studies. Although this efficiency is still low, it indicates a feasible gain of 3 dB and possibility of an integrated solar panel array antenna design to achieve higher gain for practical satellite missions.

C. *Effect of Dielectric Constant of the Substrate*

It is known that a substrate with lower permittivity supports a patch antenna with higher gain. To see the maximum possible efficiency of an 80% ITO patch antenna at S band, we computed the antenna efficiency for varied substrate permittivity. The thickness of the substrate is kept as 2mm. The thickness of the substrate is kept as 2mm. The results are plotted in Fig. 5 and it is seen that the maximum efficiency of an 80% transparent antenna is less than 45% for frequency less than 2 GHz.

IV. CONCLUSION

This paper presents a study on the efficiency of an ITO patch antenna. The thickness of the transparent oxide is considered in the study. It is shown that the electron mobility, a parameter that is determined by the material development, is the primary limiting factor for the transparent antenna. However, even with today's material processing method, it is feasible to achieve a practical ITO patch antenna by selecting a substrate with lower permittivity and raising the operational frequency. For example, an efficiency of 30% can be achieved for an ITO patch with 90% transparency at 5 GHz. The effect of the thickness of the substrate on the antenna design is well known such that a thicker substrate supports a better antenna, which means it is possible to further improve the efficiency of a 90% transparent antenna by carefully selecting the substrate.

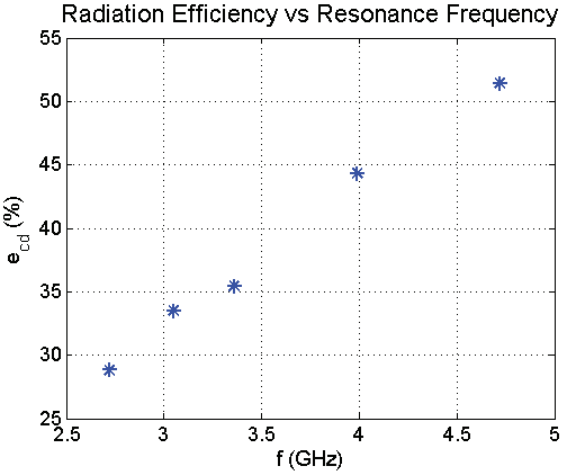

Figure 4. Frequency Effect on Antenna's Radiation Efficiency

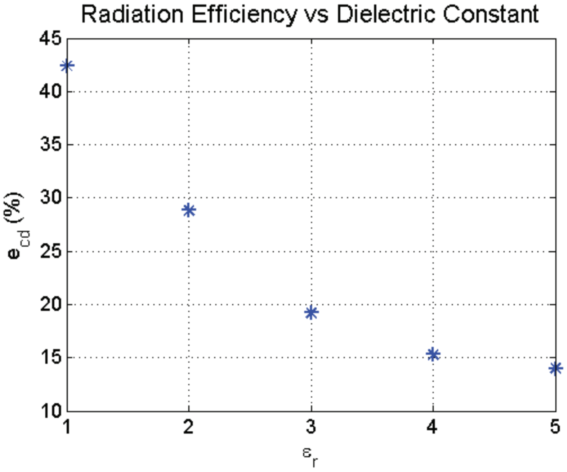

Figure 5. Dielectric Constant Effect on Antenna's Radiation Efficiency

Although it is desirable to improve this efficiency with progress in material science, the 30% efficient antenna can be employed in array design for higher gain requirement. This implies potential application of integrating highly transparent patch antennas with large surfaces such as solar panels and window glass for various applications.

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