Antennas Made of Transparent Conductive Films

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Abstract—The radiation characteristics of two kinds of antennas made of transparent conductive films are investigated: a planar inverted-F antenna (PIFA) and a monopole antenna. These antennas are designed to work at 2.4 GHz and their performances are compared with each other for several films with different sheet resistivities. Wire-grid models based on the moment method are applied for the numerical analysis. It is found that the film resistance influences the performance more strongly for the PIFA than for the monopole antenna due to the cavity-like behavior of the former.

1. INTRODUCTION

As mobile wireless communications have progressed drastically in recent years, mobile terminals are becoming smaller and smaller, and miniaturization of the antennas installed in mobile devices is required accordingly. The designing of antennas for small mobile devices is becoming much more difficult not only because the space is getting limited but also because other electrical parts influence the performance of the antennas. Transparent conductive films, such as indium tin oxide (ITO) and fluorine-doped tin oxide (FTO) films, allow the transmission of electric currents while retaining the optically transparency [1]. Applying transparent conductive films to construct antennas is a good alternative to meet the space requirement because the transparent antennas can be installed on the surface or the display window of the mobile devices without much visible design problem [2–7]. The interference from the other electric parts can also be suppressed thanks to the location of the antenna.

In this paper, two antennas widely used for small mobile devices are investigated: a planar inverted-F antenna (PIFA) which consists of a rectangular patch and a short-pin and a monopole antenna which consists of a trapezoidal radiator [7]. Wire-grid models based on the moment method are applied for the numerical analysis. The performances of the two antennas are compared with each other for several films with different sheet resistivities. It is found that the film resistance influences the performance more strongly for the PIFA than for the monopole antenna. The difference of the performance is explained by the difference of the operating mechanism between these two antennas.

2. CONFIGURATIONS

Figure 1 shows the configuration of the PIFA, where the patch is made of transparent conductive film and the short-pin and ground are made of copper. Fig. 2 shows the configuration of the
monopole antenna, where the trapezoidal radiator is made of transparent conductive film and the ground is made of copper.

The antennas are made of ITO and FTO, as well as copper as a reference. Fig. 3 shows a sample of the ITO antenna and Fig. 4 the transmittance at a wavelength of 550 nm for the ITO and FTO films. Both of the antennas are designed to work at 2.4 GHz. Fig. 5 shows the measurement of voltage standing wave ratio (VSWR) for the monopole antenna with several different films. The VSWR does not vary so much as the sheet resistivity is lower than 10 Ohm/sq. Fig. 6 shows the measurement of a radiation pattern at 2.4 GHz for the antenna. Again it is seen that the resistance does not influence the radiation seriously.

Figure 3: Sample of ITO antenna.

![Figure 3: Sample of ITO antenna.](image)

Figure 4: Transmittance of ITO and FTO films at a wavelength of 550 nm.

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Figure 5: Measurement of VSWR for a monopole antenna.

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Figure 6: Measurement of $E_\theta$ on $xz$-plane at 2.4 GHz for a monopole antenna.

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3. SIMULATION

Wire-grid models by using the software Numerical Electromagnetic Code version 4 [8] are applied for the numerical analysis. The grid size is set to 0.5 mm and the wire radius to 0.15 mm. The resistance of the transparent film is taken into account by directly loading a resistance on every discretized element. Because the typical thickness of the films is several hundred nanometers, much thinner than the skin depth at the operating frequencies, the loading resistance $R_l$ for an element is simply given by $R_l = \rho_s \Delta l / \Delta w$, where $\rho_s$, $\Delta l$ and $\Delta w$ are the sheet resistivity, length and width of the element, respectively. However, due to the restriction of the software, the dielectric substrate is not included in the simulation.
Figures 7 and 8 show the calculated VSWR for the PIFA and monopole antenna, respectively. Both of the VSWRs do not vary so much as the sheet resistivity is lower than 10 Ohm/sq. Fig. 8 differs a little from Fig. 5 due to the lack of dielectric substrate in the simulation.

Figures 9 and 10 show the calculated radiation patterns at 2.4 GHz for the PIFA and monopole antenna, respectively. It can be seen that the gain deterioration caused by the resistance is more serious in the PIFA than in the monopole antenna. Fig. 10 agrees with the measurement very well.
Figures 11 and 12 show the calculated radiation efficiency for the PIFA and monopole antenna, respectively. The efficiency increases at the higher frequency for both of the antennas because the ratio of the radiation resistance to the ohmic resistance tends to increase as the frequency increases [9]. It is seen that the efficiency of the PIFA is lower than that of the monopole antenna for the same resistivity.

4. COMPARISON BETWEEN PIFA AND MONOPOLE ANTENNA

Figure 13 compares the maximum gain at 2.4 GHz for the PIFA and monopole antenna, where the gain is normalized to the value of the corresponding copper antenna. The gain lowering rate is 0.47 and 0.20 dB/Ohm/sq for the PIFA and monopole antenna, respectively.

Figure 14 compares the efficiency at 2.4 GHz for the two antennas. While the efficiency lowering rate is 4.5%/Ohm/sq for the PIFA, it is 2.7%/Ohm/sq for the monopole antenna.

Figures 15 and 16 show the current distributions at 2.4 GHz for the PIFA and monopole antenna with perfect conductor, respectively. While the current mainly flows on the trapezoidal radiator in the monopole antenna, it flows on patch and ground in the PIFA. As a matter of fact, the PIFA behaves like a cavity and hence excites a large current on the whole patch. This is considered to be the reason why the film resistance influences the performance more strongly for the PIFA than for the monopole antenna.

Nevertheless, if an ITO film with a sufficiently small resistivity is used, radiation performance good enough for practical applications can be obtained by both antennas.
Figure 15: Current of a PIFA at 2.4 GHz.

Figure 16: Current of a monopole antenna at 2.4 GHz.

5. CONCLUSION
We have investigated a PIFA and a monopole antenna made of transparent conductive films. This study clarifies the fact that the influence of the film resistance on the radiation performance depends on the structure of the antennas and it provides quantitative data for the antenna design. It is expected that the transparent films can be used for both of the antennas in practical applications. It is hoped that the transparent antennas can provide a useful means for antennas integration when employed in mobile terminals in the near future.

REFERENCES