URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

Analysis of an Optically Transparent Antenna Designed from Silver-Carbon Nanotube Hybrid Conductive Coating

Rakib Hasan(1), R. Baktur*(1), M.Ricci(2), C.E.Treacy(2), and R.Sivarajan(2)
(1) Department of Electrical and Computer Engineering, Utah State University, Logan UT 84321, USA
(2) Nano-C, Inc., 33 Southwest Park, Westwood, MA 02090, USA

Abstract

This paper studies an optically transparent antenna fabricated from a thin silver-carbon nanotube hybrid conductor. The transparency of the antenna is 89.3% and operates at 2.9 GHz. A method to estimate the antenna's efficiency, simulations, and measured gain are presented.

1 Introduction

Optically transparent antennas have been gaining steady interest due to their advantage and capability of integration with panels, window glass, and screens. Potential applications include security, cars, smart homes, and communication diversity.

Main approaches for optically transparent antennas have been using transparent conductors such as thin conductive film [1] or transparent Oxide [2]. More recently, silver nanowires have been reported to show great potential in being the next generation transparent conductors [3], but there is still room to investigate novel enhanced transparent conductors and to study the the limiting factors for the antenna design.

Single walled carbon nanotube films have been investigated for their microwave properties at high frequencies [4], and the hybrid between silver nanowire and carbon nanotube is expected to meet the stability, optical,mechanical, and microwave property requirements needed for emerging applications such as flexible and wearable antennas. This paper presents a study on transparent antennas designed from a hybrid silver nanowire-carbon nanotubes conductor.

2 Analysis

2.1 Geometry and Material Properties

A flat monopole antenna was chosen in this study because of the design simplicity and ease of fabrication. The antenna geometry is as shown in Figure 1, where a thin layer of silver-carbon nanotube (Silver-CNT) hybrid transparent conductor was coated on a piece of polycarbonate. The hybrid conductor coating was prepared at Nano-C, Inc. by using their Invisicon® 9503 single pot hybrid inks.

The dimension and material properties of the monopole is listed in Table 1. It should be noted that the thickness of the coating does not include the polycarbonate substrate, rather, it is the thickness of the conductor. The monopole is mounted on a finite sized ground made from a circuit board and fed by an SMA connector. In order to secure a good electrical connection, a piece of copper tape was applied. The copper tape was included in the simulation to account for its effect on the antenna's properties.

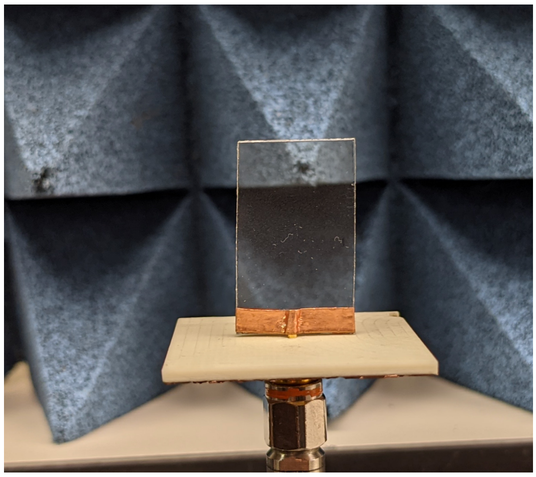

Figure 1. Fabricated Silver-CNT Hybrid Antenna.

Table 1. Geometry and Material Information.

Length (l)	24.87 mm
Width (w)	15.44 mm
Copper tape height (h)	3.0 mm
Thickness of the coating (t)	20 nm
Sheet resistance	13 Ω□
Optical transmission	89.3 %
Ground plane width	3.273 cm
Ground plane length	3.431 cm
Ground plane thickness	1.78 mm

2.2 Estimation of Antenna Efficiency

For a thin conductor as shown in Figure 2 with width w, thickness t, and length l, the resistance R is computed from

$$R = \rho \frac{l}{wt} \quad (\Omega), \tag{1}$$

where ρ is the resistivity of the conductor. It can be written as

$$R = \frac{\rho}{t} \cdot \frac{l}{w} \quad (\Omega). \tag{2}$$

The sheet resistance is then defined as

$$R_s = \frac{\rho}{t} \quad (\Omega\,\square). \tag{3}$$

As seen, it has the same unit as resistance. Therefore, to differentiate it, its unit is noted as Ω square. One should be careful not to mix the sheet resistance with resistivity.

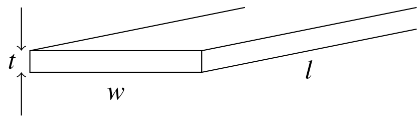

Figure 2. Thin Conductor Geometry

Since the thickness of the hybrid conductor is very thin in order to maintain a high optical transparency, an important measure is to compare the conductor thickness with the microwave skindepth δ, which is computed from

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}, \tag{4}$$

where f is the frequency and σ is the conductivity (i.e. $\frac{1}{\rho}$).

Using the material information in Table 1 and (4), the microwave skindepth of the coating is calculated to be 4.7 μm at 2.9 GHz, which means the thickness of the conductive coating is about 0.004 times as thin compared to the microwave skindepth. This leads to a high loss on the conductor and accordingly reduced antenna efficiency. From geometry and material information in Table 1 and (1), (3), the loss resistance of the monopole is calculated to be around 20 Ω, which is significant because a perfect quarter wavelength monopole antenna on an infinite ground has a radiation resistance of 37 Ω.

The calculation of the loss resistance in 1 assumes a uniform distribution of current across the area wt. The actual current on the dipole concentrates on the edges of the conductor, hence the loss resistance is higher than 20 Ω. On the other hand, due to the reduced conductivity of the silver-CNT hybrid, compared to a perfect electric conductor, the radiation resistance is going to smaller than 37 Ω. Through simulation study, the impedance of the silver-CNT monopole antenna is around 100 Ω, causing a low return loss of 6 dB when excited with a 50 Ω coax cable (Figure 1). Accordingly, the efficiency of the antenna is estimated to be

$$e = (1 - \Gamma^2) \cdot \frac{R_{radiation}}{R_{radiation} + R_{Loss}} < 27\%, \tag{5}$$

where the radiation resistance is taken as 37 Ω (i.e. perfect case). When the reduced radiation resistance is considered, as well as loss factors such contact with the connector are considered, the antenna may have less than 30% efficiency, even if an impedance matching circuit is placed between the antenna and the feed.

3 Simulation and Measured Results

The antenna in Figure 1 was simulated using HFSS. The antenna operates at around 2.9 GHz. As the thickness of the conductive coating is unrealistically thin for HFSS to yield a reasonably fast and converging result, the conductivity of the coating is reduced while keeping the thickness of the conductor as 1 microwave skindepth. This is evident from (1) that the resistance can be scaled using either conductivity or the thickness. A monopole antenna made of copper tape with the same dimension as the transparent antenna understudy was simulated and fabricated as a reference. The thickness of the copper tape is 0.11 mm, which is significantly thicker than the microwave skindepth. The simulated radiation pattern of the silver nanowire antenna and the reference is plotted in Figure 3.

Three identical antennas with geometry shown in Figure 1 with dimensions listed in Table 1 were fabricated from silver-CNT hybrid transparent conductor. The gain of the transparent antenna was measured to be about -6.5 dB less than the copper reference antenna. The measurement was carried out for three samples, and repetitive tests yielded the same - 6.5 dB gain reduction, which is consistent with the simulation (Figure 3).

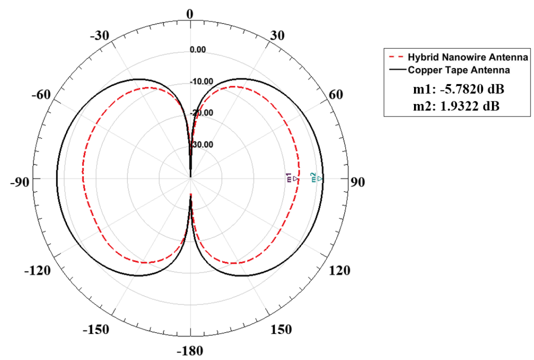

Figure 3. Radiation Patterns of the Transparent Antenna and the Reference Copper Antenna

It is intuitive to alter the antenna geometry in order to improve the gain and efficiency. From (1), it is seen that widening the antenna results in less loss resistance. While it is known that widening a monopole antenna may affect its other properties, it was found that doubling the width while keeping the rest of the parameter the same resulted in improved gain, as plotted in Figure 4.

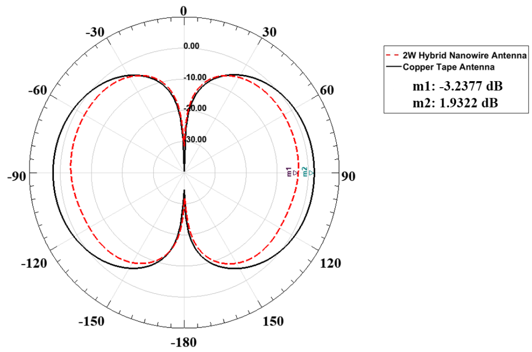

Figure 4. Radiation Patterns of the Widened Transparent Antenna and the Reference Copper Antenna

4 Discussions and Conclusions

The efficiency estimation in (5) means at least 5.5 dB gain reduction from a lossless monopole of the same dimension. The simulation and measured results show about 6.5 dB gain reduction, which can be regarded reasonably consistent with the estimation. When the frequency is increased, the microwave skindepth of the film reduces, making the thin conductor more effective, and therefore increasing the radiation resistance. In addition, it is seen that factors to improve the antenna efficiency include increasing the width and thickening the conductor, which means lowering the sheet resistance, while keeping the conductivity of the material unchanged. These results make it promising to apply the hybrid silver-CNT conductor in antenna design, as it is feasible to achieve an increased efficiency such as a 50%, while maintaining a high optical transparency.

References

[1] R.N. Simons and R.Q. Lee, “Feasibility study of optically transparent microstrip patch antenna,” *IEEE Antennas and Propagation Society International Symposium*, **4**, 1997.

[2] T. Yasin,R. Baktur,C. Furse, “A Study on the Efficiency of Transparent Patch Antennas Designed from Conductive Oxide Films,” *IEEE International Symposium on Antennas and Propagation (APSURSI)*, 2011.

[3] Y. Goliya, A. Rivadeneyra, J. F. Salmeron, A. Albrecht, J. Mock, M. Haider, J. Russer, B. Cruz, P. Eschlwech, E. Biebl, M. Becherer, and M. R. Bobinger, “Next Generation Antennas Based on Screen-Printed and Transparent Silver Nanowire Films,” *Advanced Optical Materials*, **7**, 2019, 1900995 (pp.1 of 9), doi: 10.1002/adom.201900995.

[4] Ryan C. Toonen, Julia B. Doggett, S. Gary Hirsch, Mathew P. Ivill, Eric H. Ngo, Clifford W. Hubbard, Henning Richter, and Ramesh Sivarajan, “Evaluation of Carbon Nanotube Thin Films for Optically Transparent Microwave Applications Using On-Wafer Probing of Corbino Disc Test Structures,” *Report: Army Research Laboratory*, 2013, ARL-TR-6362.