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Analysis of Optically Transparent Antennas Designed from Different Transparent Conductors

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ANALYSIS OF OPTICALLY TRANSPARENT ANTENNAS DESIGNED FROM DIFFERENT TRANSPARENT CONDUCTORS

by

Rakib Hasan

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ABSTRACT

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by

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Utah State University, 2022

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This master's thesis work presents an investigative study about the performance of transparent antennas. The antennas have been fabricated using two advanced transparent conductive films (TCF), namely Nano-C Hybrid and Silver-Nanowire (AgNW). Nano-C Hybrid is a new transparent conductive film which combines Carbon Nanotube and Silver Nanowire. The antennas are of monopole types and are mounted on a ground plane made out of a printed circuit board. Simulation works have been performed to find the optimum length-to-width ratio for the monopole. It has been found that the length has to be slightly higher than the width for a flat monopole in order to reduce the loss resistance and resonate at the designed frequency. The tested antennas made from these transparent materials have shown promising results which prove that the transparent materials can be considered as viable antenna design materials for various applications such as wireless communication technology. Gain of the transparent antennas is enhanced by widening and stacking the TCFs. Among the two transparent conductive materials tested during this research, the comparatively new material, Nano-C Hybrid, proves to be a potential competitor against commercially used Indium Tin Oxide (ITO) and AgNW in terms of transparency, conductivity, power handling capability, and usability.

(58 pages)

PUBLIC ABSTRACT

Analysis of Optically Transparent Antennas Designed from Different Transparent Conductors

Rakib Hasan

This master's thesis work presents an investigative study about the performance of transparent antennas. The antennas have been fabricated using two advanced transparent conductive films (TCF) namely Nano-C Hybrid and Silver-Nanowire (AgNW). Nano-C Hybrid is a new transparent conductive film which combines thin conductors like Carbon Nanotube and Silver Nanowire. The antennas made from Nano-C Hybrid and AgNW are of monopole types and are mounted on a ground plane made out of a printed circuit board and the antennas are excited using an SMA connector through that printed circuit board. Simulation works have been performed to find out the optimum length-to-width ratio for the monopoles so that they can be used to design an antenna that radiates at the desired frequency. It has been found that the length needs to be 1.25 times higher than the width of the monopole in order to reduce the loss resistance of the designed antenna. The antennas can operate in a wide range of frequencies, but performance varies marginally based on the material that has been used to fabricate them. The tested transparent antennas have shown promising results which prove that these transparent films can be considered as viable antenna design materials for various applications such as wireless communication technology. Simulation and experimental measurements indicate the gain of the transparent antennas is enhanced by widening and stacking the TCFs. There is a trade-off between the efficiency of the antenna and the transparency as stacking the TCFs reduces the transparency. Among the two transparent conductive materials tested during this research, the comparatively new material, Nano-C Hybrid, proves to be a potential competitor against commercially

used Indium Tin Oxide (ITO) and AgNW in terms of transparency, conductivity, power handling capability, and usability.

To my parents, my lovely wife, and my little brother...

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I am sincerely thankful to be able to work with Dr. Reyhan Baktur. She is not just my major professor; she has been a true inspiration and guidance to me. She has helped me become a better researcher by teaching me to explore the actual meaning and theory of the research topic. I thank her for her time, patience, and guidance throughout my time here at Utah State University. I would also like to thank Dr. Winstead and Dr. Dennison for agreeing to be in my thesis committee. My sincere thanks also go to Logan Voigt, Kelby Davis, and Heidi Harper for all their help and support.

Last but not the least, I express my earnest gratitude to my parents, my wife, my brother, and all those who were beside me when I needed them the most.

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

ACRONYMS

TCF	transparent conductive film
ITO	indium tin oxide
CNT	carbon nanotube
AgNW	silver nanowire
TCO	transparent conductive oxide
SWCNT	single wall carbon nanotube
MWCNT	multi wall carbon nanotube
RF	radio frequency
DC	direct current
AC	alternating current
SMA	subMiniature version A
VNA	vector network analyzer

CHAPTER 1

INTRODUCTION

Optically transparent antennas have gained steady interest in the field of wireless communication due to their optical and electrical advantages and capability of integration with panels, window glass, and screens. Potential applications include security, cars, smart homes, and communication. Transparent conductive films (TCFs), such as Indium Tin Oxide (ITO), Carbon Nanotube (CNT), Silver Nanowire (AgNW) are being considered as potential materials to construct a transparent antenna because these conductors can produce transmission of electric currents while retaining transparent properties [1].

Fabrication of transparent antennas requires an optically transparent conductor and different fabrication methods have been studied for this purpose. Various materials like copper (Cu), ITO, AgNW have been explored and experimental results show good radiation characteristics that proves the potential of transparent antennas being used in wireless communications [2, 3]. This prospect of using transparent conductors to build antennas have greatly motivated the research work of this thesis. The main goal of the thesis is to investigate the usability of different transparent conducting materials in the field of antenna communication.

When speaking of transparent conductors, the first name that comes to mind is Indium Tin Oxide (ITO) [4] followed by Carbon Nanotubes (CNT) [5]. ITO and CNTs have been considered for antenna fabrication as viable alternatives to the usual conductors like copper, aluminium, and iron. With time, AgNW have also emerged as a feasible option for transparent antenna design [6, 7]. A new approach of combining the above mentioned materials with one another or creating ultra thin metal meshes to improve the conductivity has recently become a good area of antenna research [8,9] and has expanded the scope of this thesis to explore a new kind of transparent conductor that is a hybeid between of AgNW and CNT. This new transparent conductor is manufactured by the company Nano-C [10] and because of the hybrid configuration, the new material will be addressed as Nano-C Hybrid throughout this thesis. The research work of this thesis investigates the usability of Nano-C Hybrid in antenna design as well as looks into the power handling capabilities of the hybrid material in comparison to AgNW. The findings of the investigation will be key to determine if making a hybrid material from AgNW and CNT would be better than just using the standalone materials in antenna design and manufacturing.

This thesis intends to explore the feasibility of transparent conductors as antenna design materials in various frequency range and determine which material is better in terms of power handling capabilities, high frequency radiation, and gain. Software simulations and measurements have been performed to compare AgNW and Nano-C Hybrid to get a better understanding of the key differences between these two conductive materials. This thesis work also looks into adequate methods of improving the gain of the antennas made from Nano-C Hybrid and AgNW.

CHAPTER 2
LITERATURE REVIEW

2.1 Transparent Conductors

Transparent conductors have the unique combination of transparency and electronic conductivity. A brief overview of the studies about different types of transparent conductors are presented in this chapter.

2.2 Transparent Conducting Oxides (TCO)

2.2.1 Indium Tin Oxide (ITO)

Indium Tin Oxide (ITO) is a widely used transparent and colorless thin film because of its electrical conductivity and optical transparency [11]. In 1951, a US based company named Corning developed and patented indium tin oxide (ITO), the most studied TCO so far [12]. Table 2.1 lists some key properties of ITO like thickness, sheet resistance, and transparency as reported in literature. The reported transparency values are different in terms of how the authors defined visible range. For example, in [13], the visible range is $400 - 700$ nm whereas in [14] and [15], the range is taken as $300 - 900$ nm and, $400 - 800$ nm, respectively. The transparency is measured at 550 nm by the authors of [16]. Although the reported transparencies are measured in slightly different values of the visible range, the data suggest that ITO can be considered a good transparent conducting oxide.

Table 2.1: Survey on Properties of ITO

Reference	Thickness (nm)	Sheet Resistance (Ω□)	Resistivity (Ω·cm)	Transparency (%)
[14]	500	8.50	4.25×10^{-6}	95
[17]	300	1.07	3.22×10^{-7}	77
[13]	150	27	4.05×10^{-6}	85
[18]	78	230.77	1.80×10^{-5}	Not Reported
[15]	447	12.60	5.63×10^{-6}	87
[16]	199	152	3.03×10^{-5}	89.1
[19]	700	4.29	3×10^{-6}	90
[20]	100	20	2×10^{-6}	85

■ Calculated from Reported Values ■ Data not Readily Verified

According to the reported literature, ITO is an advantageous transparent conducting oxide. But it has some drawbacks like high cost of materials, scarcity of indium, and brittleness. The brittleness often lead to problems like the film cracking and getting electrically isolated which is not ideal for space applications. To overcome all these problems and come up with a good alternative of ITO, researchers have explored some other TCOs like GZO and AZO.

2.2.2 Galium-doped Zinc Oxide (GZO)

Galium-doped Zinc Oxide (GZO) has become a topic of research as a potential alternative to ITO because GZO thin films are capable of showing 85 to 90% optical transparency in the visible range [21] and Galium is better than Indium in terms of cost and availability in the nature [22]. In Table 2.2, a brief summary has been presented on the recent research works conducted on GZO.

Table 2.2: Survey on Properties of GZO

Reference	Thickness (nm)	Sheet Resistance (Ω□)	Resistivity (Ω·cm)	Transparency (%)
[23]	150	19.80	2.97×10^{-6}	85
[24]	200	34.00	6.80×10^{-6}	90
[25]	350	142.86	5.00×10^{-5}	85
[26]	603	28.19	1.70×10^{-5}	87.3
[27]	449.89	18.76	8.44×10^{-6}	93.58
[27]	450.12	16.84	7.58×10^{-6}	92.88
[28]	100	120	1.20×10^{-5}	92

■ Calculated from Reported Values

Literature suggests transparency of GZO films for various film thickness is comparable to ITO film transparencies. GZO films have been deposited on glass [23], PET substrates [24] and their transparencies have been reported in different ranges of visible spectrum as researchers have recorded the transparency of GZO films in 400 – 800 nm [23], 600 – 900 nm [25], 535 nm [26], 550 nm [27], and 380 – 780 nm [28].

2.2.3 Aluminium-doped Zinc Oxide (AZO)

Aluminium-doped Zinc Oxide or AZO has emerged as a topic of research to be used in constructing TCFs as nature has abundant supply of Aluminium which eventually can cut down the cost of producing TCOs and help reduce the the use of the scarce materials like Indium or even Galium. Table 2.3 contains categorized overview of researches on AZO as a transparent conducting oxide which indicates AZO can be used as a viable option for preparing TCFs and its transparency is comparable to ITO and GZO in the visible region of 400 – 900 nm [29] and 400 – 800 nm [30, 31].

Table 2.3: Survey on Properties of AZO

Reference	Thickness (nm)	Sheet Resistance (Ω□)	Resistivity (Ω·cm)	Transparency (%)
[29]	100	37.50	3.8×10^{-6}	92
[29]	500	7.1	3.5×10^{-6}	90
[32]	341	9	3.07×10^{-6}	85.1
[30]	300	29.30	8.79×10^{-6}	90
[31]	600	3.75	2.25×10^{-6}	86

■ Calculated from Reported Values

So, even though ITO is the most studied transparent conducting oxide, GZO and AZO have emerged as potential competitors of ITO having comparable transparency in the visible region. Moreover, GZO and AZO can be used to overcome common drawbacks of ITO such as brittleness and low availability of material.

2.2.4 Carbon Nano-tube (CNT)

Carbon Nano-tube (CNT) is a carbon-based transparent conductor. CNTs have been studied due to their electrical conductivity, mechanical flexibility and stability, as well as their optical transparency [33]. CNTs can be considered as a rolled graphene sheet and are classified according to the number of rolls [34]:

- Single Wall Carbon Nanotube (SWCNT)
- Multi Wall Carbon Nanotube (MWCNT)

Table 2.4 displays a brief overview of the recent works which have been carried out on the electro-optical properties of CNT films. Usually transparent conducting films are characterized by the film thickness; but in case of CNT, researchers often report the diameter as a method of characterization. As it is shown in Table 2.4, diameter of the SWCNT under investigation has been reported instead of film thickness [35].

Table 2.4: Survey on Properties of CNT

Reference	Thickness (nm)	Sheet Resistance (Ω□)	Resistivity (Ω·cm)	Transparency (%)
[35]	1.9	220	Not Reported	84
[36]	130	169.76	2.21×10^{-5}	58.3
[37]	50	30	1.5×10^{-6}	70
[38]	100	69.93	6.99×10^{-6}	Not Reported

Calculated from Reported Values   Data Not Readily Verified   Diameter of CNT, Not Film Thickness

CNT films are reported to be capable of exhibiting optical transparency ranging from 83.4% to 90% and sheet resistance ranging from 24 to 208 Ω□. These values vary depending on how the CNT film has been deposited or prepared [39].

A very thin sheet of carbon is recognized as graphene and it also has the potential to be used as a transparent conducting film or TCF because of the thin nature and good electrical properties. A 100 m long graphene TCF is reported to have a sheet resistance of 150 Ω□ [40]. Another review on graphene reports that graphene transparent conducting films can show 80% and 90% of optical transparency with sheet resistance values of 280 and 350 Ω□, respectively [41].

2.2.5 Silver Nanowire (AgNW)

Silver Nanowire (AgNW) has some advantages like flexibility, surface flatness, and good enough opto-electrical properties which have made AgNW a good candidate for study in the transparent conductor area. Studies show AgNW networks with wire diameters of 45 – 110 nm have an average transparency up to 91% with sheet resistance as low as 6.5 Ω□ [42]. As-prepared AgNW has been observed to have sheet resistance of 37.6 Ω□ at 89.8% transparency. AgNW films have some drawbacks as well. These films tend to get oxidized very easily when exposed to air and water leading to a sharp increase of the sheet resistance and decrease in the transparency [43]. Metal networks like Copper-AgNW have been tested and it is seen that this reduces the sheet resistance to 18.6 $\Omega\,\square$ retaining 88.4% transparency [44]. Aluminum-doped Zinc Oxide (AZO)-AgNW-Aluminum-doped Zinc Oxide (AZO) structure has been reported to have a transparency of 79.9% with a lower sheet resistance of 6.2 $\Omega\,\square$ only [45].

2.3 Transparent Antenna

Antennas made from transparent conducting materials have been a topic of study since it has been realized that these type of antennas can be used in various applications without the need of much space and also because of the opto-electrical properties and flexible form factor. Study shows that a monopole antenna made from ITO can be used at a frequency of 3.9 GHz while maintaining a 88% transparency. The efficiency of the antenna increases from 58% to 66% if the material is a mesh between ITO and AgNW [46]. Highly transparent ITO material has been used to develop antennas which operate from 4 MHz to 13 GHz but yield very low amount of gain ranging from -6.9 dB to 2 dB [47–52]. Silver Nanowire (AgNW) is another promising material for transparent antenna fabrication. It has been seen that, the high conductivity of silver makes AgNWs suitable candidates for antennas that yield higher gain than most other transparent antennas [53, 54]. AgNW has been explored extensively in very high frequency range which is not seen in the case of ITO. AgNW antenna has been designed to work in $18 - 40$ GHz range with a 0.8 dB gain at 30 GHz whereas another study suggested an AgNW based antenna can be designed to work at 61 GHz with 3.7 dB gain [55, 56]. In the past ten years, a very few number of studies have been done on other transparent conductors like Galium-doped Zinc Oxide, Graphene, etc. and the studies show that these materials are much more lossy than ITO and AgNW and exhibit very low gain [57, 58].

Combination of more than one transparent conductor have been another area of the latest antenna research and has paved a new way of increasing the usability of transparent and conductive materials in antennas. Research conducted in [46, 50, 59, 60] provide experimental data that suggest, using one transparent conductor with another transparent conductor or using one transparent conductor with another highly conductive metal can increase the overall conductivity of the transparent film and enables the design of an efficient transparent antenna.

CHAPTER 3
STUDIES ON PROPERTIES OF TWO MOST ADVANCED TRANSPARENT CONDUCTIVE FILMS

3.1 Shelf Life

Silver Nano-wire (AgNW) and newly developed Nano-C Hybrid have been studied in terms of their shelf life. The study is carried out on two sets of AgNW and Nano-C Hybrid samples developed two years apart. Properties of the samples under investigation has been listed in Table 3.1 as reported by the manufacturer.

Table 3.1: Transparent Conductive Samples Under Investigation

Production Date	**Sample**	**Sheet Resistance (Ω □)**	**Transparency**
December 2020	AgNW	13	92.9%
	Nano-C Hybrid	13	89.3%
March 2022	AgNW	12.7	93.5%
	Nano-C Hybrid	10.6	87.6%

The samples are mostly exposed to air as they are kept in the lab in the plastic envelopes in which they were shipped. The envelopes are opened to get access to the samples in order to perform tests. But the unused portion of the samples have always been kept inside the plastic envelopes and away from any physical touch of human hands or dust.

3.1.1 Sheet Resistance and Conductivity

The investigation suggests that the resistance of the samples increases marginally with time. This increase in resistance is higher in case of AgNW. There are two probable causes of this phenomenon. First, the samples have aged over time and aging is prominent in AgNW than Nano-C Hybrid. Second cause would be the handling of the films as the conductive layer is very thin and is easily disturbed as it comes in contact with any other surface like human hands.

3.1.2 RF Frequency Response

The S_{11} response of the antennas made from the AgNW film suggests that the samples which are shipped at a later date have better response in high frequency (10 GHz) than the samples shipped before that. In case of the Nano-C Hybrid, the response of the new sample and the older sample are comparable. This observation indicates that the newly developed Nano-C Hybrid can retain its capabilities of performing in the RF frequency range for a substantial amount of time after its production. On the contrary, AgNW films looses some of its capabilities over time as can be seen in Figure 3.1.

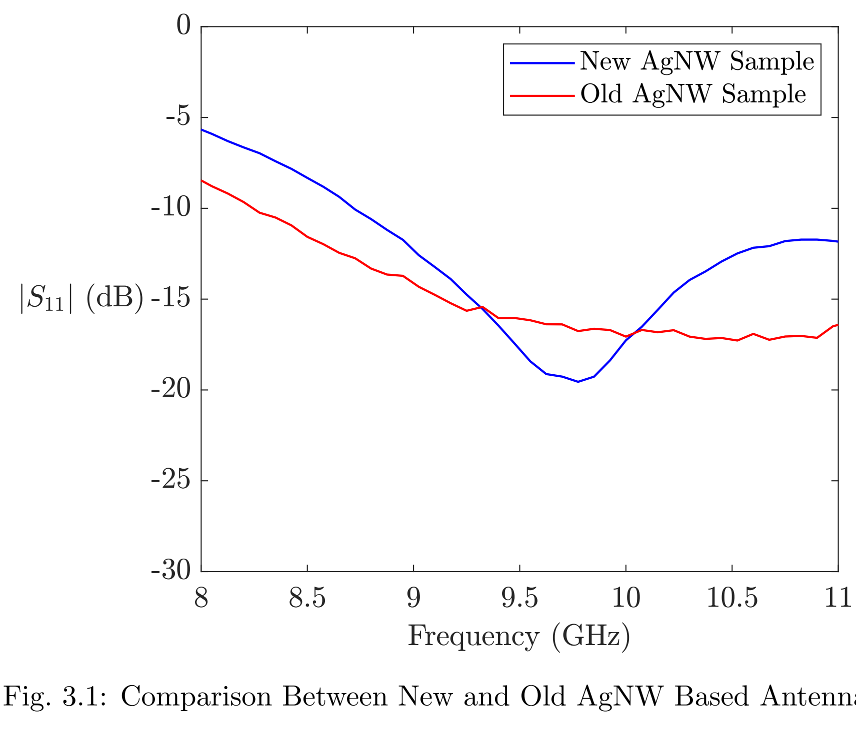


Fig. 3.1: Comparison Between New and Old AgNW Based Antenna

From the graph, it can be seen that, antenna made with the new AgNW sample has slightly better S_{11} response than the antenna made from the old AgNW sample in spite of having almost identical sheet resistance as listed in Table 3.1. On the other hand, the new Nano-C Hybrid has sightly lower sheet resistance than the old ones and their RF performance is also indicative of that even after being almost two and half years apart in terms of production. Figure 3.2 shows the response of new and old Nano-C Hybrid based antenna.

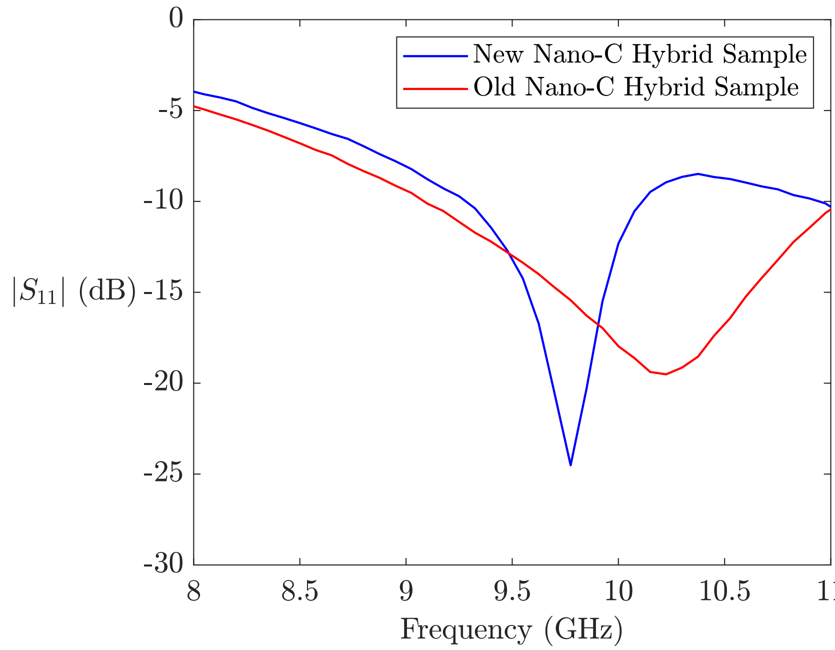


Fig. 3.2: Comparison Between New and Old Nano-C Hybrid Based Antenna

The investigative results described in Section 3.1.2 suggest, the antenna made from AgNW antenna shows tendency of reduced performance whereas the Nano-C Hybrid antenna does not. This indicates, Nano-C Hybrid films are more capable of retaining their properties for a longer period of time than AgNW films.

3.2 DC Power Handling

The new samples of AgNW and Nano-C Hybrid have been tested under DC conditions to find out how much DC power can pass through them before they start to burn out. It has been observed that Nano-C Hybrid can handle sightly more power than AgNW. The surface current density (J_S) is measured along the width of the tested samples and the measurement suggests that AgNW samples break down at a lower surface current density than the Nano-C Hybrid samples. The test has been conducted with different sizes of the samples by cutting the samples by half both in length and width in each iteration. This is done to measure the maximum power at the breakdown point for different sample sizes. The size chart is shown in Table 3.2. Figure 3.3 shows the schematic of the DC power test setup.

Table 3.2: Sample Size Index for DC Power Test

Size 1	Length	36.5 mm
	Width	28.5 mm
Size 2	Length	18.4 mm
	Width	14.5 mm
Size 3	Length	9.4 mm
	Width	7.5 mm

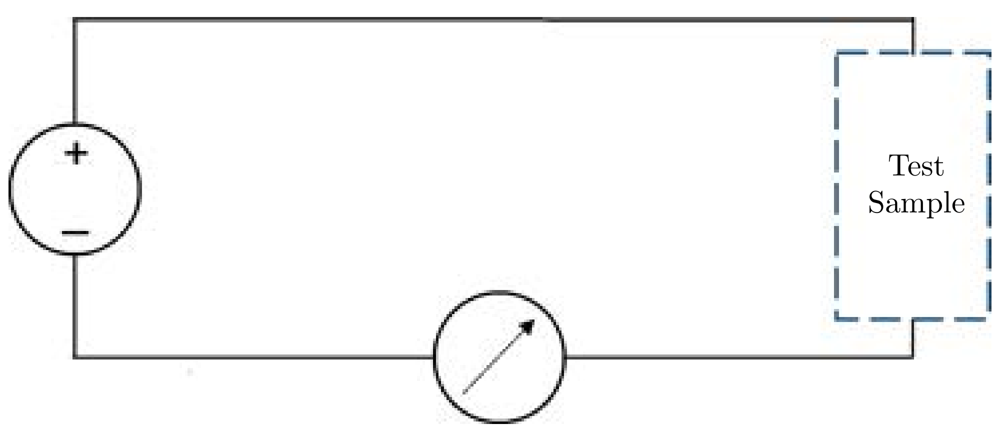


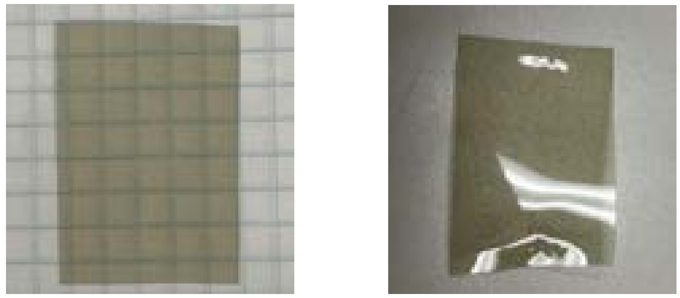
Fig. 3.3: DC Power Test Setup

Table 3.3 contains the results of the investigation conducted with samples of different sizes as listed in Table 3.2. It has been observed that reducing the size of the samples into quarter size of the previous sample does not affect the measured resistance but clearly indicates the decline in maximum power handling capacity for both Nano-C Hybrid and AgNW. The breakdown power for Nano-C Hybrid is higher than AgNW irrespective of the sample size. This proves Nano-C Hybrid can handle more power in DC than AgNW films, which is a clear indication that significant improvement can be made in terms of DC power conduction by combining carbon nanotubes and silver nanowire rather than using standalone AgNW transparent conductive films. The data suggest that Nano-C Hybrid breaks down at a higher amount of DC voltage than AgNW of the same size. The surface current density (J_S) for different sample size remains in close proximity with each other for both Nano-C Hybrid and AgNW.

Table 3.3: DC Power Handling

Size Index	Sample	Voltage, V (V)	Current, I (A)	Resistance, R (Ω)	Power, P (mW)	J_S (A/m)
1	Nano-C Hybrid	8	0.308	25.97	2464	11.49
	AgNW	5	0.161	31.06	895	5.77
2	Nano-C Hybrid	6	0.221	27.15	1326	15.03
	AgNW	4	0.122	32.79	488	8.55
3	Nano-C Hybrid	4	0.159	25.16	636	21.20
	AgNW	3	0.090	33.33	270	12.07

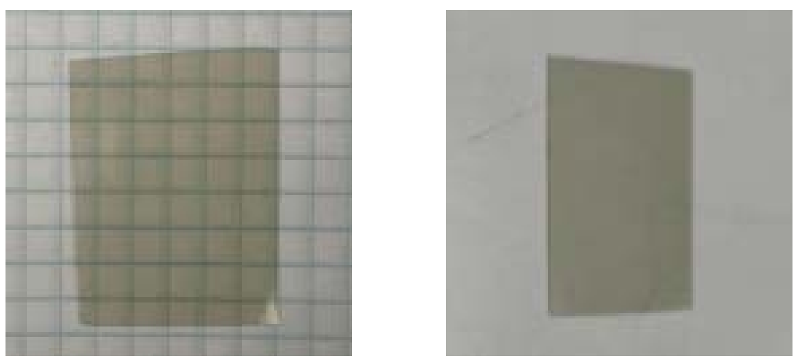
While conducting the DC power test, it has been observed that Nano-C Hybrid experiences slight deformation like bending when exposed to a high voltage. Figure 3.4 shows the deformation of the Nano-C Hybrid sample (Size Index 1) after the DC power handling test has been conducted.



(a) Before (b) After

Fig. 3.4: Effect of DC Power on Nano-C Hybrid

The AgNW sample of the same size does not exhibit any kind of deformation even after being exposed to the maximum voltage it can handle. Figure 3.5 shows that AgNW sample have no sort of deformity after begin exposed to high voltage.



(a) Before (b) After

Fig. 3.5: Effect of DC Power on AgNW

Although it is not completely clear why Nano-C Hybrid gets misshaped with high DC voltage or power; the assumption is that it has something to do with the production method of the film which determines the material and thermal properties of the films.

3.3 RF Power Handling

The Nano-C Hybrid and AgNW films have been tested to study the breakdown point of the respective films when RF power is used. The test has been conducted at 2 GHz and the samples have been prepared with a length of around 33 mm, which is approximately the length of a quarter-wavelength monopole antenna at 2 GHz. Figure 3.6 is the schematic of the test samples which have been used for RF power handling investigation.

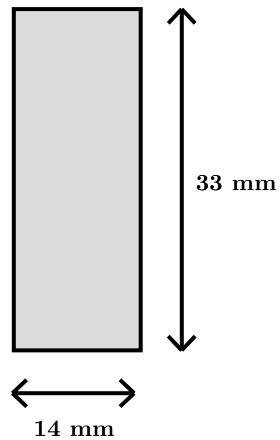


Fig. 3.6: Schematic of Sample for RF Power Test

For this particular test, the width of the antenna has been taken as approximately 14 mm, which makes the length-to-width ratio 2.5.

3.3.1 Test Setup

In order to conduct the RF power handling test, the antennas made from the two transparent conductive films under investigation are needed to be fed by high input power. Typically the antennas can radiate with an input power of as low as −5 dBm and in order to find out the highest amount of RF power the antennas can handle, the input power needs to be amplified. That is why a very high power RF amplifier has been used to conduct this particular test. The equipment used for this test is listed below:

- E4433B ESG-D Series Digital RF Signal Generator
- N9000A CXA Signal Analyzer
- ZHL-30W-252-S+ High Power Amplifier

The transparent antenna is placed on the fixture. The fixture is connected to the power amplifier which is fed by the signal generator. This antenna is the transmitting antenna. Another antenna made from copper tape with the same dimension is placed on another fixture and is connected to the signal analyzer so that it works as the receiver. The complete test setup is shown in Figure 3.7.

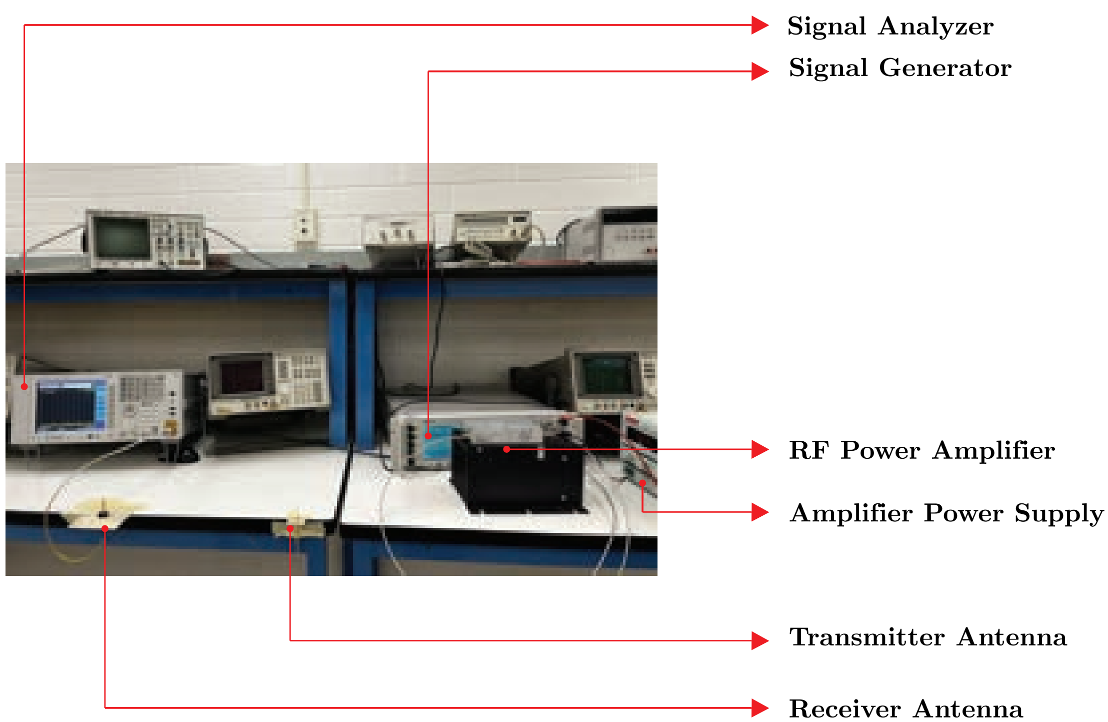


Fig. 3.7: RF Power Test Setup

The distance between the transmitter and the receiver is approximately 29 cm. The transmitting antenna is being fed by the amplified input power and the signal analyzer is being used to observe how much power is received by the receiver antenna. The RF amplifier has 50 dB of typical gain at 2 GHz so the starting input power from the signal generator is taken very low at −31 dBm and then it was increased gradually to see how much RF power the transmitting transparent antenna can handle.

3.3.2 Test Results

The RF power test shows the Nano-C Hybrid based monopole starts to radiate less power when the input power to the antenna is 42 dBm or approximately 16 W. On the other hand, the antenna made from AgNW breaks down at 39 dBm or approximately 8 W of input power. The test results are in line with the DC power test which suggested that Nano-C Hybrid can handle more power than AgNW. Also, just like with DC power, the Nano-C Hybrid based antenna experiences slight deformity with high RF power whereas AgNW based antenna does not. As shown in Figure 3.8, there is a clear crack in the middle of the Nano-C Hybrid sample after it was exposed to the maximum RF power it can handle. This phenomenon is very much similar to the one observed during the DC power tests (Figure 3.4). After getting deformed and burnt out by high RF power, the DC resistance of the Nano-C Hybrid sample became 2.13 kΩ which means it is not going to work as a good conductor anymore.

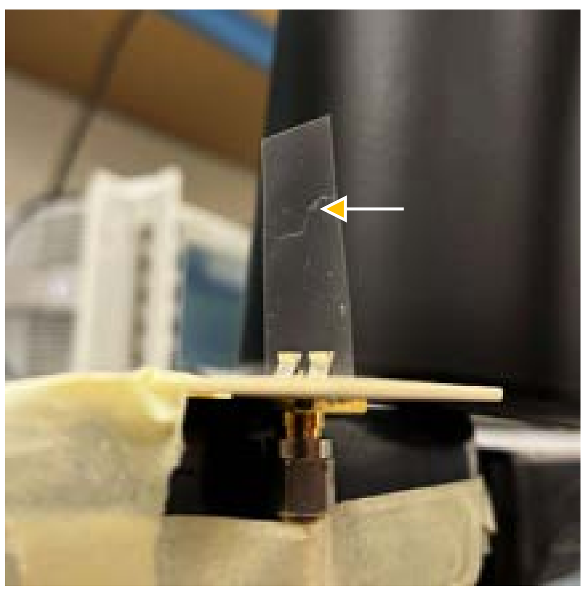


Fig. 3.8: Crack in Nano-C Hybrid Antenna after High RF Power

Figure 3.9 shows, the AgNW sample does not have any visible deformity or crack despite breaking down at less input power than Nano-C Hybrid antenna.

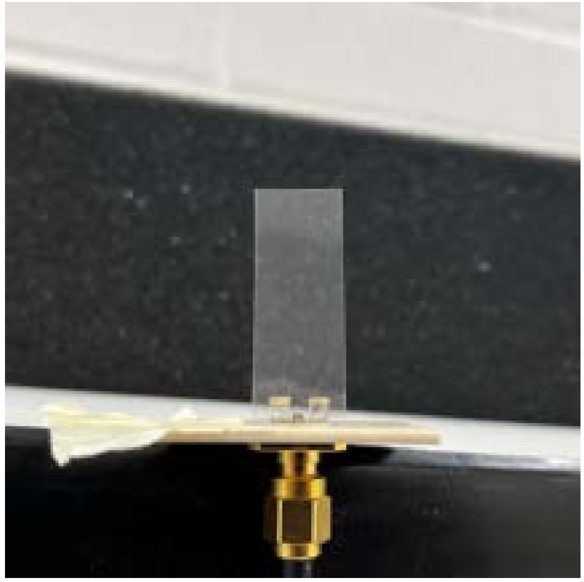


Fig. 3.9: No Crack in AgNW Antenna after High RF Power

This is also very similar to the DC power test conducted with AgNW sample, where any kind of deformity was not observed after exposing the samples to high DC power (Figure 3.5). The DC resistance of the AgNW sample became 10 MΩ, which is substantially higher than the typical DC resistance and also comparatively higher than the burnt Nano-C Hybrid films of the same size. This also proves that Nano-C Hybrid films can conduct and handle more DC and RF power than AgNW films.

3.4 AC Power Handling

The Nano-C Hybrid and AgNW films have been tested under AC power to determine if the impedance changes with respect to frequency and to see how they behave when fed with AC power. The test setup is as shown in Figure 3.10, where the samples are connected to the function generator and the multimeter. The input voltage and frequency in the function generator have been changed and the AC current has been noted from the multimeter at each step.

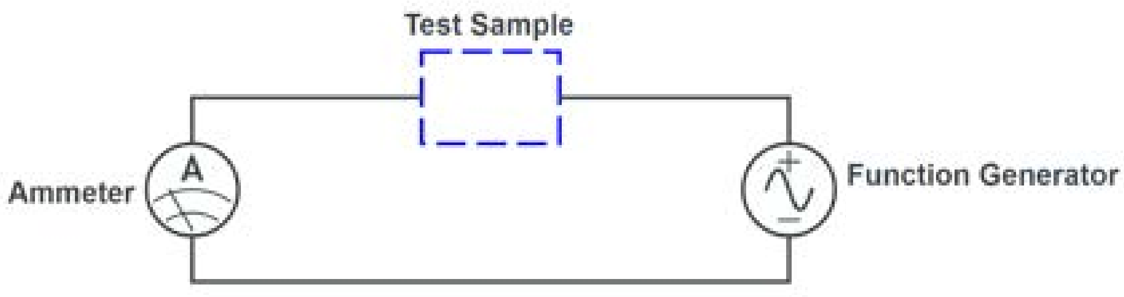


Fig. 3.10: AC Power Test Setup

The samples used for this investigation are 10 mm long and 7.5 mm wide. The first thing done after the samples are prepared is to measure the DC resistance before exposing them to AC power. The initial DC resistance of the samples have been listed in Table 3.4.

Table 3.4: Initial DC Resistance of the Samples

Sample	Measured DC Resistance, R_{meas}, (Ω)
Nano-C Hybrid	10
AgNW	12

This particular test has been conducted with 0.5 V, 1.0 V, and 2.0 V of input peak voltage of the function generator and the frequency ranges from 50 Hz to 40 kHz. Figure 3.11 shows that the AC impedance remains very close to the DC measured impedance both for Nano-C Hybrid and AgNW at low frequency. This can be said in case of a lower frequency range, but it would have been better if it was possible to see the response in higher frequency range as well. The Tektronix CDM250 Digital Multimeter only works within this lower range of frequency and the function generator used for this test cannot go beyond $40kHz$. This leaves a scope of conducting research on this particular characteristics in the future, but for now, Figure 3.11 suggests the impedance of both Nano-C Hybrid and AgNW remain very close to the measured DC resistance as the frequency gradually rises. From this observation, it can be assumed that, the impedance will not dramatically increase and make the transparent conducting films unusable when the frequency is much higher.

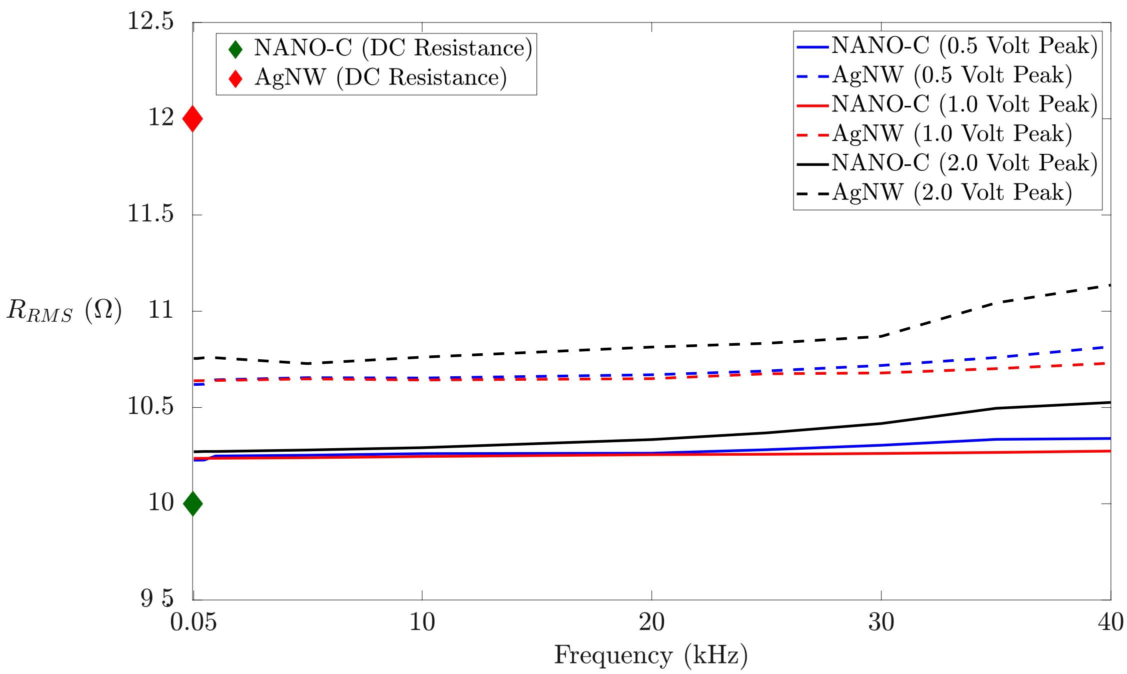


Fig. 3.11: AC Impedance Characteristics

Under the test conditions, it has been observed that both the Nano-C Hybrid and AgNW can withstand up to 10 V of peak voltage from the function generator and handle 4100 mW of power on average. This amount of voltage and power is significantly higher than the DC burn out voltage (4 V for Nano-C Hybrid and 3 V for AgNW) and power (636 mW for Nano-C Hybrid and 270 mW for AgNW) as shown in Table 3.3. This is an interesting observation that indicates, the samples might possess some material characteristics that allow them to withstand more power in AC than in DC.

CHAPTER 4
THEORY OF ANTENNA DESIGN FROM VERY THIN TRANSPARENT CONDUCTORS

The word antenna usually refers to some metallic device (as a rod or wire) which can be used for radiating or receiving radio waves [61]. Antennas can be made from different materials and substrates based on the characteristics that affect the performance of antenna [62]. Growing amounts of research have been going on to make antennas transparent due to the possible advantages and capabilities of integration with panels, window glass, and screens. Potential applications of transparent antennas include security, cars, smart homes, and communication diversity [63].

4.1 Transparency and Thickness

Transparent and electrically conductive materials include oxides of tin, indium, zinc, and cadmium, and metals such as silver. Usability of a transparent conductor can be determined from sheet resistance, and the thickness of the transparent conductive film (TCF). The sheet resistance, R_S, and thickness, t are related to each other as characterized by equation 4.1.

$$R_S = \frac{1}{\sigma t} \quad (\Omega\,\square) \tag{4.1}$$

where σ is the electrical conductivity and t is the film thickness.

4.2 Skin Depth

Since the thickness t of the transparent conductor is usually very thin in order to maintain a high optical transparency, an important measure is to compare the conductor thickness with the microwave skin depth δ, which is computed from equation 4.2,

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{4.2}$$

where f is the operational frequency and μ is the permeability. The optical transparency T can be characterized in terms of film thickness t as shown in Equation 4.3,

$$T = e^{-kt} \tag{4.3}$$

where k is a constant related to material properties such as electron mobility [64]. Lower film thickness would yield higher transparency but with higher sheet resistance which means the conductivity would be lower. This indicates a need of proper trade-off between the film thickness and the conductivity requirement to produce a good working TCF which can be implemented in antenna design.

4.3 Resistance Calculation

The sheet resistance, R_S and the film thickness t can be utilized to estimate the resistance of the TCF. Normally, resistance R is calculated using 4.4,

$$R = \frac{\rho L}{A} \quad (\Omega\,\square) \tag{4.4}$$

where ρ is resistivity of the sample, L is sample length and A is the cross sectional area of the sample which can be expressed as $A = Wt$ where W is the width of the sample. So, equation 4.4 can be re-written as,

$$R = \frac{\rho}{t}\frac{L}{W} \quad (\Omega) \tag{4.5}$$

Combining 4.1 and 4.5, the expression for calculating the resistance of the samples can be obtained as,

$$R = R_S \frac{L}{W} \quad (\Omega) \tag{4.6}$$

Equation 4.6 establishes a relationship between sheet resistance and the dimension of the sample. It is clear that the resistance of the TCF will vary based on its sheet resistance and also the length and width of the sample under investigation. From equation 4.6, the ratio of the length and width of the sample plays a vital role in determining the resistance and it has been observed with numerous iterations and simulations in this research that, the the optimum length-to-width ratio is 1.25.

4.4 Method for Gain Improvement

The thickness of the conductive layer in TCFs under investigation is very low in order to make the films transparent. Although, the actual conductive layer thickness in Nano-C Hybrid and AgNW has not been reported by the manufacturing company, for the purpose of this thesis, the thickness has been assumed to be 20 nm. Using this thickness and the sheet resistance of the films, the resistance and conductivity of a particular sample can be estimated. If the gain of the antennas made with Nano-C Hybrid and AgNW TCFs is initially lower, simulation and experimental results suggest there are at least two ways to improve the gain.

4.4.1 Widening

The length for each monopole antenna has been calculated to be equal to the quarter-wavelength of the respective resonant frequency and the width has been selected such that the length-to-width ratio is fixed at the optimum value of 1.25 as shown in Table 4.1.

Table 4.1: Standard Length and Width for Monopole Antenna Design

Frequency f (GHz)	Length L (mm)	Width W (mm)	Length-to-Width Ratio
2	37.5	30	1.25
3.75	20	16	1.25
5	15	12	1.25

From Table 4.1, a 2 GHz monopole antenna is 37.5 mm long and 30 mm wide. Simulation results have shown that, if the width is increased in such a way that it retains the optimum ratio with the length, the resonant frequency does not get affected significantly. This opens up a possibility to test the antenna gain by changing the width. Simulation results have proved that, the gain actually increases marginally if the width of the antenna is increased.

Table 4.2 shows the gain of a 2 GHz monopole antenna, both Nano-C Hybrid and AgNW based, exhibits approximately 0.3 dB increased gain if the width of the antenna is doubled.

Table 4.2: Simulated Gain for 2 GHz Monopole (Widening Test)

Antenna Material	Gain (dB)		Gain Increase (dB)
	Before Widening[1]	After Widening[2]	
Nano-C Hybrid	−1.21	−0.87	0.34
AgNW	−1.54	−1.23	0.31

1: L-to-W ratio is 2.5   2: L-to-W ratio is 1.25 (Optimum)

So, from simulation data, the gain of the antenna made from a transparent conductive film can be improved by increasing the width of the antenna keeping in mind that the width does not exceed the length in order to keep the resonant frequency intact. This means, it is necessary to maintain the optimum length-to-width ratio.

4.4.2 Stacking

Stacking two samples on top of another helps increase the gain of the fabricated antenna. Simulation results for a 2 GHz antenna have been listed in Table 4.3.

Table 4.3: Simulated Gain for 2 GHz Monopole (Stacking Test)

Antenna Material	Gain (dB)		Gain Increase (dB)
	Without Stacking[1]	With Stacking[1]	
Nano-C Hybrid	−0.88	0.06	0.82
AgNW	−1.26	−0.16	1.1

1: L-to-W ratio is 1.25 (Optimum)

The simulated radiation patterns depicted in Figures 4.1 and 4.2 confirm the fact that antenna gain can be increased by using more than one samples for both Nano-C Hybrid and AgNW.

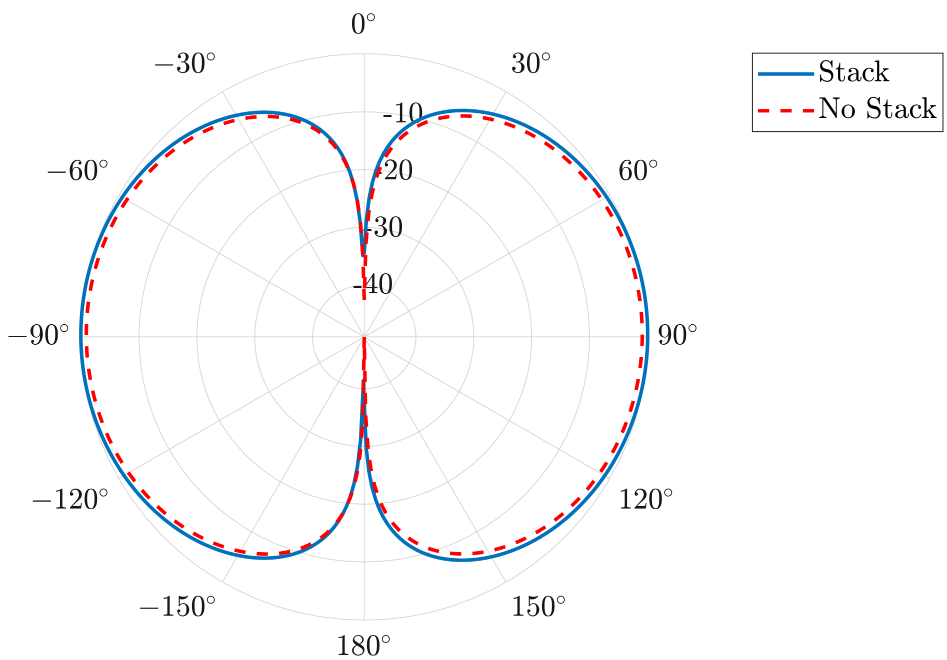


Fig. 4.1: Simulated Gain of 2 GHz Nano-C Hybrid Antenna

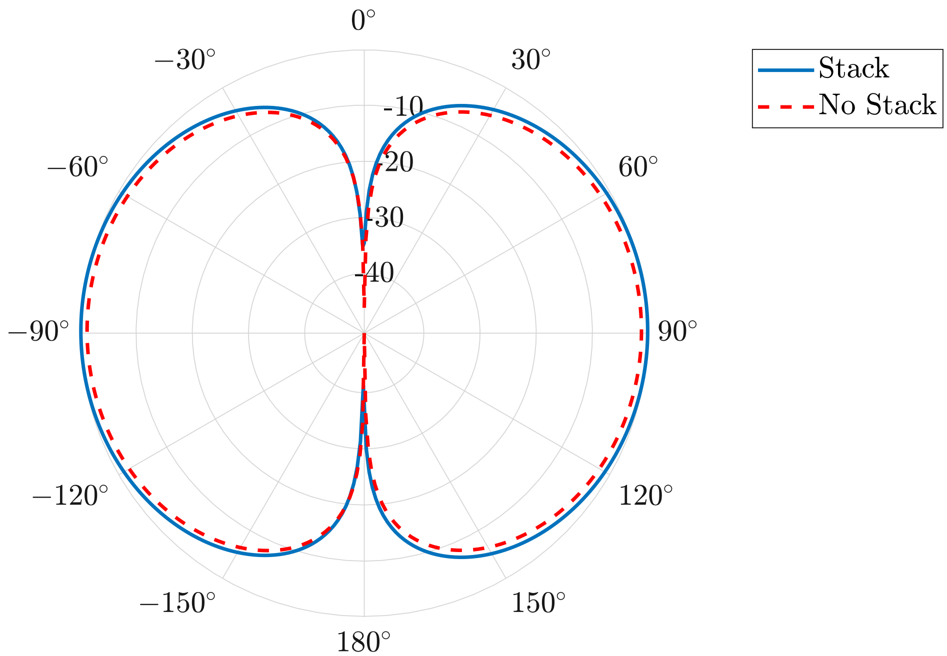


Fig. 4.2: Simulated Gain of 2 GHz AgNW Antenna

In the above figures, it is seen that, for both Nano-C Hybrid and AgNW based antennas, the gain increases at least 0.8 dB if two samples have been stacked together. In these simulations, the length-to-width ratio is the optimum value of 1.25.

CHAPTER 5
EXPERIMENTAL RESULTS ON ANTENNA DESIGN

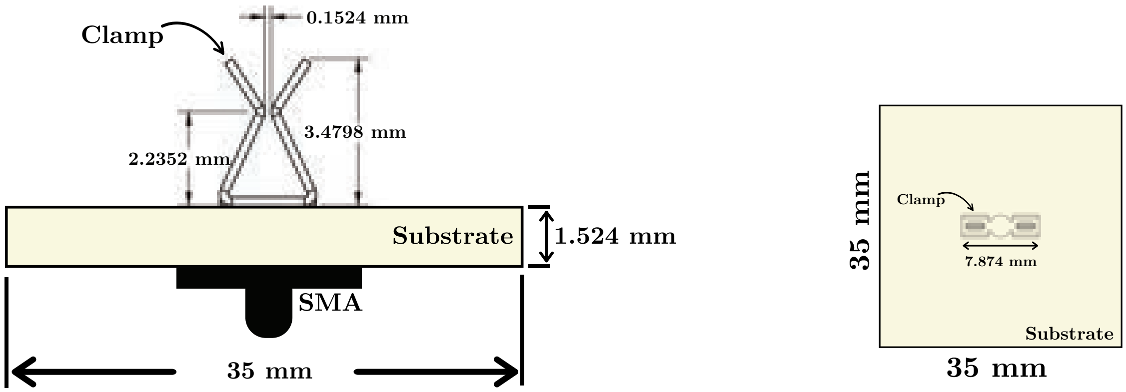
5.1 Description of the Test Fixture and Setup

The transparent conductive films used to design antennas are rectangular and hence the fabricated transparent monopole antennas are are also rectangular. The length of the monopoles are quarter-wavelength and the width is decided using the optimum length-to-width ratio of 1.25. In order to feed the antennas, a test fixture has been designed using the Rogers RO4003 substrate. The substrate has copper cladding on the top and the bottom side. The top copper cladding has been rubbed off using an LPKF S103 Milling Machine while keeping the copper cladding of the other side of the substrate intact. The board works as a ground plane for the antennas. The attributes of the test fixture are listed in Table 5.1.

Table 5.1: Properties of Test Fixture

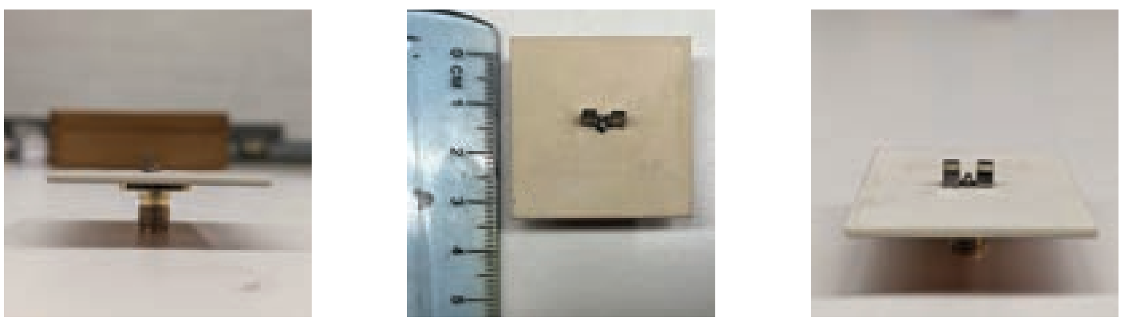
Material	Rogers RO4003
ϵ_r	3.55
Dimension	Length: 35 mm
	Width: 35 mm
	Height: 1.524 mm

A clamp made from 0.2 mm thick Pre-Tin Plated Phosphorus Bronze is placed on one side of the fixture to secure the test samples firmly on the fixtures and to properly feed the antennas. Figure 5.1 shows the schematic of the test fixture which has been used throughout the experiments conducted in this thesis work. Figure 5.2 includes some real life photos of the test fixture.



(a) Side View (b) Top View

Fig. 5.1: Schematic of Test Fixture



(a) Side View (b) Top View (c) Front View

Fig. 5.2: Test Fixture

The SMA connector is used to connect the fixture to the vector netwrok analyzer to observe and record the reflection co-efficient (S_{11}) of the antenna at different frequencies. Figure 5.3 shows how the samples are placed inside the clamps to securely place the samples on the fixture and perform measurements.

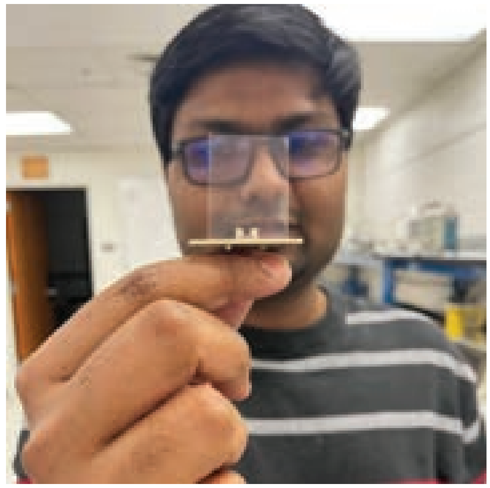


Fig. 5.3: Antenna Sample on the Test Fixture

The N5225A PNA Microwave Network Analyzer has been used in the test setup for S_{11} measurements. In case of gain measurements, following equipment have been used to set up the test environment:

- E4433B ESG-D Series Digital RF Signal Generator
- N9000A CXA Signal Analyzer

5.2 Frequency Response

First set of experiments have been performed to observe the response of the antennas made from Nano-C Hybrid and AgNW at different frequencies. Investigation results clearly suggests that both TCFs can be used to design antennas which can operate in a wide range of frequencies.

The S_{11} vs frequency plot shown in Figure 5.4 suggests Nano-C Hybrid and AgNW can be used to design 2 GHz antennas.

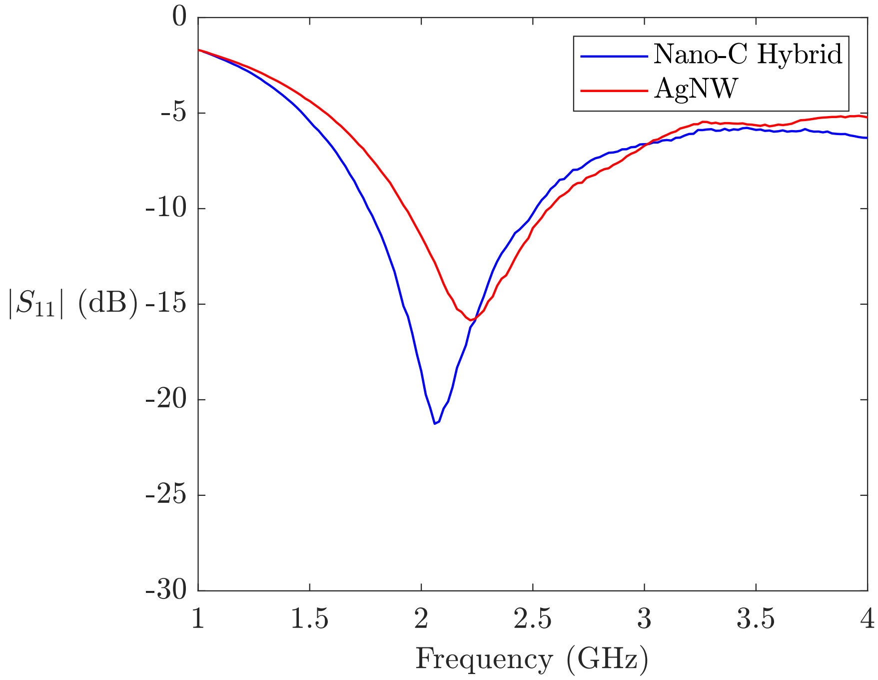


Fig. 5.4: Antenna Response at 2 GHz

Experiments conclude that the samples can actually be used to design antennas which are able to radiate at 2, 5, 8, and 10 GHz. Figures 5.5, 5.6, and 5.7 show Nano-C Hybrid and AgNW based monopole antennas work at 5 GHz, 8 GHz, and 10 GHz, respectively. The monopole antennas have been mounted on the fixtures using the clamps and it has been made sure that the antenna samples sit firmly onto the fixtures and there is no other radiating element nearby where these measurements have been performed. After considering all these facts, the measurement results for the 2 GHz, 5 GHz, 8 GHz, and 10 GHz antennas indicate that the transparent conductive films are capable of working as high frequency antenna materials.

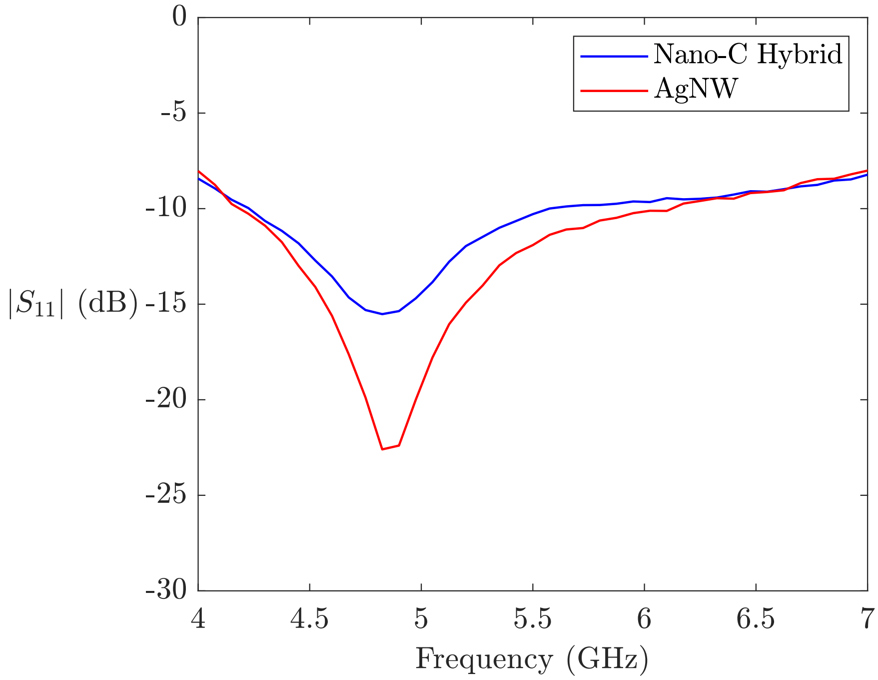


Fig. 5.5: Antenna Response at 5 GHz

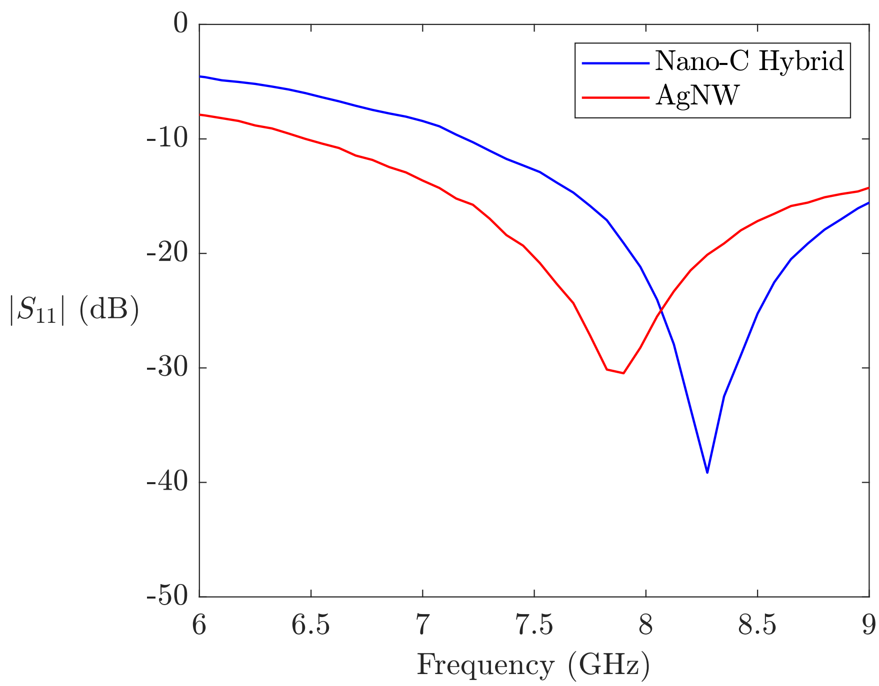


Fig. 5.6: Antenna Response at 8 GHz

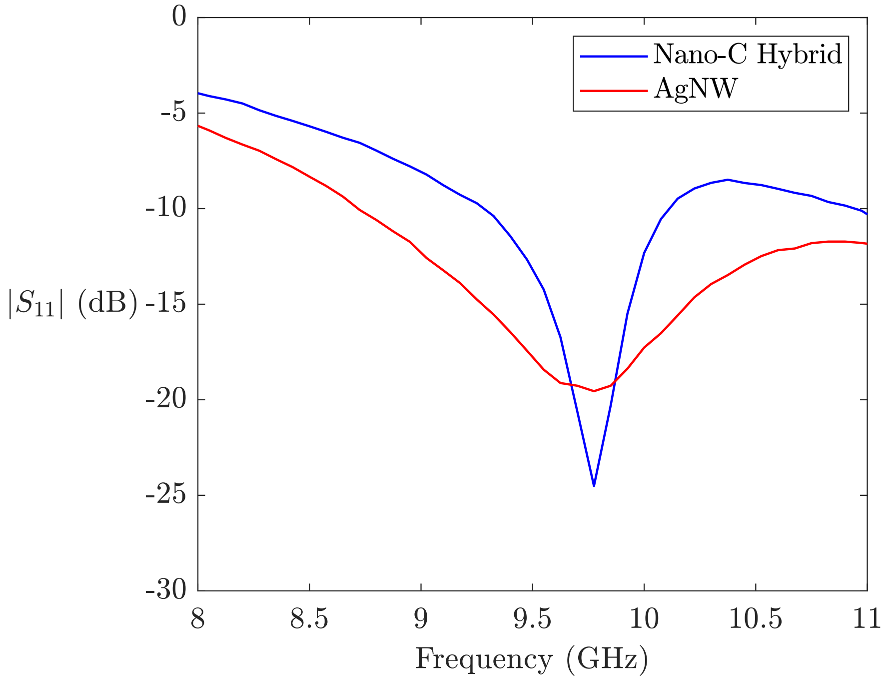


Fig. 5.7: Antenna Response at 10 GHz

Overall, the frequency response of the antennas made from transparent conducting films is a clear evidence of them being effective antenna design materials.

5.3 Gain Measurements

Relative gain measurements have been carried out for the antennas made from Nano-C Hybrid and AgNW. One of the antennas is fed with a power P_T by the E4433B ESG-D Series Digital RF Signal Generator and the other antenna is placed at a distance D, more than the far field distance of the transmitting antenna, and is connected to N9000A CXA Signal Analyzer to record how much power P_R is being received by the receiver antenna.

Friis transmission equation in log scale is utilized in this part of the experiments which is shown in Equation 5.1 [65],

$$P_R = P_T + G_R + G_T + 20log_{10}\left(\frac{\lambda}{4\pi D}\right) \quad \text{(dB)} \tag{5.1}$$

where the symbols are as follows,

P_R = Received Power

P_T = Transmitted Power

G_R = Receiver Antenna Gain

G_T = Transmitter Antenna Gain

λ = Wavelength

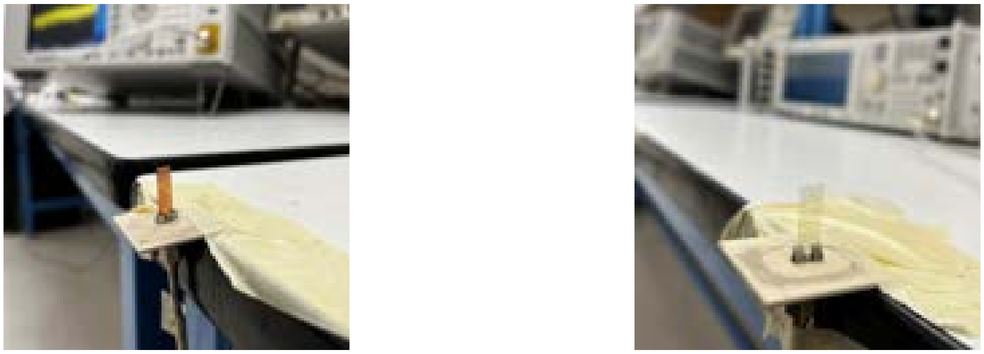
D = Distance between Transmitter and Receiver

For the copper tape based antennas, as they are identical, it has been assumed that, their gain is approximately the same which means $G_R = G_T$. Using this assumption, the gain of the copper tape antennas at different frequencies have been measured using Equation 5.1 and recorded in Table 5.2.

Table 5.2: Copper Tape Antenna Gain

Frequency (GHz)	Gain (dB)
2	1.66
3.75	1.64
5	1.61

Next, the copper tape antenna has been placed at the receiver end so that it can be used as a receiver antenna (Figure 5.8a) and the transparent antenna under test (Figure 5.8b) has been placed at the transmitting end. In this part of the experiment, for each frequency, the receiver antenna gain G_R is known from Table 5.2 which is then used in Equation 5.1 to calculate the transmitting transparent antenna gain. The complete test setup is shown in Figure 5.9.



(a) Copper Tape Receiver Antenna (b) Transparent Transmitter Antenna

Fig. 5.8: Receiver and Transmitter Antenna

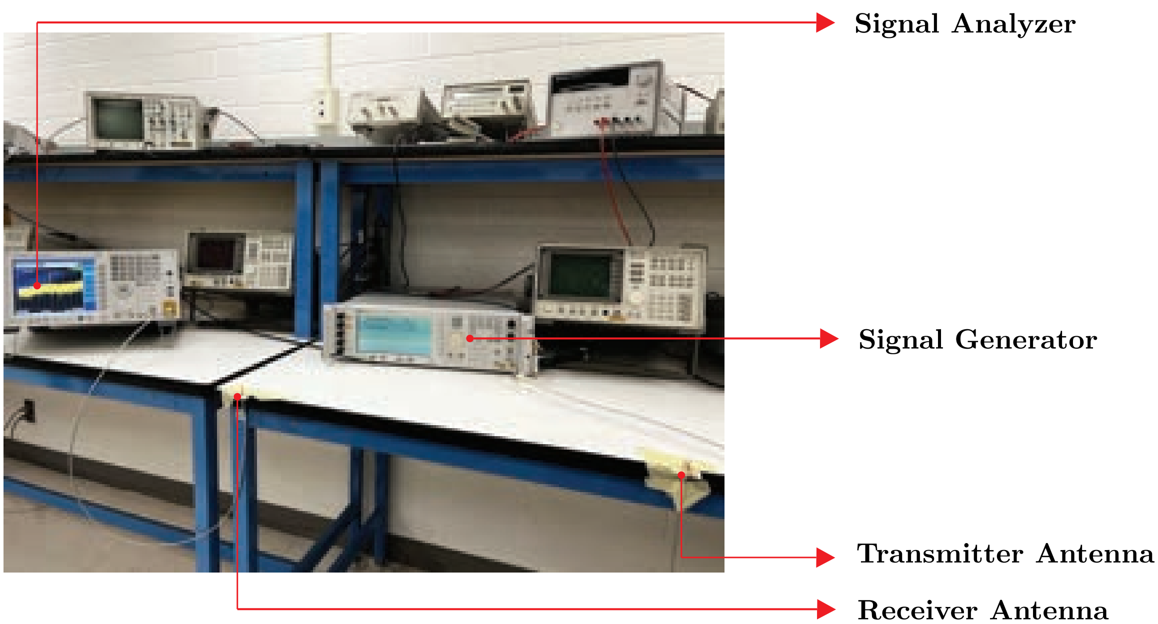


Fig. 5.9: Experimental Setup for Gain Measurement

The transmitter and the receiver antenna have been placed at a distance of $D = 48.7$ inches or 1.24 meters. Nano-C Hybrid based antennas of 2 GHz, 3.75 GHz, and 5 GHz have been used for gain measurement and the measurement results have been listed in Table 5.3.

Table 5.3: Average Measured Antenna Gain

Frequency (GHz)	Measured Average Gain (dB)	L/W Ratio
2	−2.79	1.25
3.75	−3.45	1.25
5	−3.02	1.25

The gain measurements have been performed three times and then the average gain value has been recorded. For the values shown in Table 5.3, the antenna dimension has been determined by using the optimum length-to-width ratio of 1.25.

5.4 Gain Improvement

As discussed in Section 4.4, the gain of the transparent antennas can be improved by widening the samples under test and by stacking more than one samples together on the test fixture. Experimental data proves that these two actions indeed improve the gain of the antenna.

Table 5.4 shows the gain values of Nano-C Hybrid sample based antenna before and after the width of the samples has been doubled.

Table 5.4: Average Measured Antenna Gain (Widening Test)

Frequency (GHz)	Measured Average Gain (dB)		Gain Improvement (dB)
	Before Widening[1]	After Widening[2]	
2	−3.39	−2.79	0.6
3.75	−4.19	−3.45	0.74
5	−3.82	−3.02	0.8

1: L-to-W ratio is 2.5 2: L-to-W ratio is 1.25 (Optimum)

Table 5.5 shows, the gain improves by at least 0.7 dB when two Nano-C Hybrid samples are stacked together on the test fixture. The length-to-width ratio for this stacking test has been kept at the optimum value of 1.25.

Table 5.5: Average Measured Antenna Gain (Stacking Test)

Frequency (GHz)	Measured Average Gain (dB)		Gain Improvement (dB)
	Before Stacking[1]	After Stacking[1]	
3.75	−3.45	−2.75	0.7
5	−3.02	−2.21	0.81

1: L-to-W ratio is 1.25 (Optimum)

In summary, these experimental data are evidence that when TCFs are used to construct a monopole antenna, the gain of that particular antenna can be tuned and improved by widening the antenna and by stacking more than one TCFs together. The length and width ratio must be kept in mind when making change of the dimension of the antennas. In case of stacking the films, it should also be considered that, the transparency will reduce as more films are stacked together. So, a trade-off is to be made between the transparency of the film and the antenna efficiency when designing antennas using a transparent conducting material.

CHAPTER 6
CONCLUSIONS AND FUTURE WORK

The purpose of this thesis research is to explore two advanced transparent conductive films, Nano-C Hybrid and AgNW, in the area of antenna design. These transparent films can conduct electrically while retaining the transparency characteristics. Studies show, TCFs can loose some of their core attributes over time. This kind of transformation is not swift, but definitely noticeable when put under test. Antennas made from new Nano-C Hybrid and AgNW samples work slightly better than those made from older samples. The transparency and performance of the antennas also depend on the sheet resistance R_S of the corresponding TCF. Higher sheet resistance yields higher transparency but lower antenna performance. So, there is a trade-off between sheet resistance, film thickness, transparency, and antenna efficiency when choosing the best antenna design element.

Power handling capability is different for Nano-C Hybrid and AgNW. Nano-C Hybrid can handle higher amount of DC, AC, and RF power than AgNW. The advantage AgNW has over Nano-C Hybrid is that they do not endure deformation when pushed to the highest limit. This can be an influential factor in deciding which material should be used for constructing antennas for specific applications. Apart from this phenomenon of deformity, Nano-C Hybrid outperforms AgNW in all the aspects of being a good conductive material. This means, combining CNT and AgNW helps create better transparent conductors.

The impedance of a TCF is a function of its sheet resistance, R_S and the respective length (L) and width (W). In order to create a rectangular monopole antenna using TCFs, the length should be slightly higher than the width. The good length-to-width ratio is found to be 1.25 and this should be kept in mind while designing a monopole antenna using a transparent conductive film. The resistance of the Nano-C Hybrid and AgNW films does not tend to rise dramatically with higher frequency which means these TCFs can be used to produce working S-band or X-band antennas.

Simulation results suggest, there are two effective ways to enhance the gain of a transparent antenna. If the width of the antenna is increased, the gain increases. Secondly, if two or more films are stacked together to make an antenna, the gain becomes higher than the gain of a single-sample antenna. It should be noted that, stacking the films will reduce the transparency; so, a trade-off between the transparency and the antenna efficiency has to be made. Experimental data corroborates this assumption as it is seen that, if the width of a Nano-C Hybrid or AgNW based monopole antenna is doubled, the gain is increased by at least 0.6 dB. On the other hand, the gain enhances by at least 0.7 dB when two samples having the optimum length-to-width ratio are stacked together instead of one. This is evidence that, widening and stacking can definitely be two practical methods of gain enhancement of a transparent antenna.

6.1 Future Work

Future works can be performed on this topic to find conclusive answers on the behavior of the transparent conductive films in higher frequencies in terms of AC impedance. More importantly, the material properties can be explored more deeply to determine why one type of TCF gets misshaped at higher power and the other type does not. Finally, the feasibility of the samples being used in antennas in the terahertz range can be another area of exploration.

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