Metasurface Beam-Steering Antenna at X-band Frequencies with Cloaking Applications

Erik Jermaine Kosh

Florida Institute of Technology, ekosh2019@my.fit.edu

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Metasurface Beam-Steering Antenna at X-band Frequencies with Cloaking Applications

by

Erik Jermaine Kosh

A thesis submitted to the College of Engineering & Science of Florida Institute of Technology in partial fulfillment of the requirements for the degree of

Master of Science in Electrical Engineering

Melbourne, Florida December 2023
We the undersigned committee hereby approve the attached thesis, “Metasurface Beam-Steering Antenna at X-band Frequencies with Cloaking Applications” by Erik Jermaine Kosh.

Brian Lail, Ph.D.
Professor and Department Head
Electrical Engineering and Computer Science
Major Advisor

Ming Zhang, Ph.D.
Professor
Aerospace, Physics and Space Sciences

Ivica Kostanic, Ph.D.
Associate Professor
Electrical Engineering and Computer Science
Abstract

Title: Metasurface Beam-Steering Antenna at X-band Frequencies with Cloaking Applications

Author: Erik Jermaine Kosh

Advisor: Brian Lail, Ph.D.

I intend to use metasurface materials to adjust antenna field properties while applying a cloaking application to the antenna. Cloaking applications have been used to shield the neighboring antenna waveforms so that they do not affect its antenna patterns and reduce the mutual coupling between the two antennas [15], [16]. In this application, I propose a metasurface beam-steering antenna at X-band frequencies using mantle-cloaking techniques to adjust and direct the beam-steering while ignoring other adjacent antenna patterns.

The first part of this application provides a method for cloaking antennas that are close to each other in distance (less than a few millimeters) to decouple them. This will prevent the adjacent antenna from being affected by other antenna patterns nearby. The last part of the design incorporates a metasurface multi-beam steering antenna that directs the beams independently of each other. By combining these two techniques, we can achieve a multi-beam steering antenna that does not distort each antenna’s beam pattern. Numerical finite element methods will be used to compute the designed result using Ansys HFSS [19].

The analysis will show that metasurface cloaking works for various applications to decouple near-field radiation patterns and incorporate a beam-steering component using the mantle cloaking technique. Further work can be contributed to this design approach to create more narrow beams instead of wide beams produced in this
study. The design approach used a passive element to direct the beam-steering. In future work, I believed that having an active element would achieve higher results.
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<th>Unit</th>
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<tr>
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<td>Wavelength</td>
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<td>$\lambda_0$</td>
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<tr>
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<td>F/m</td>
<td>Permittivity</td>
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<td>$\varepsilon_r$</td>
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<td>Relative Permittivity</td>
</tr>
<tr>
<td>$\mu$</td>
<td>H/m</td>
<td>Permeability</td>
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<tr>
<td>$\mu_r$</td>
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<td>Relative Permeability</td>
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<td>m/s$^2$</td>
<td>Speed of Light</td>
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<tr>
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<td>farad</td>
<td>Capacitance</td>
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<tr>
<td>$E$</td>
<td>V/m</td>
<td>Electric Field Intensity</td>
</tr>
<tr>
<td>$H$</td>
<td>A/m</td>
<td>Magnetic Field Intensity</td>
</tr>
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<td>$D$</td>
<td>C/m$^2$</td>
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<td>$B$</td>
<td>Wb/m$^2$</td>
<td>Magnetic Flux Density</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Np/m</td>
<td>Attenuation Constant</td>
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<tr>
<td>$\gamma$</td>
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<tr>
<td>$V$</td>
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Acknowledgment

I would like to give a special thank you to my wife, Danielle Kosh, for her continuous support and understanding during my time undertaking my research, developing my project, and composing my thesis. Without you this would not be possible.
Chapter 1  Introduction

1.1 Background

Invisibility has always been a topic of interest for academia and study. The idea of cloaking has military application prospects and other research aspects to include active RCS reduction methods. Current cloaking ideologies include transformation optics, transmission line network, microwave network cloaking, and scattering cancellation techniques (mantle cloaking). Transformation optics [3] is used for large cloaking but is limited to narrowband applications. Transmission line network is for large cloaking but only for 2-D cloaking structures [17]. Microwave network cloaking is also used for large cloaking applications and works with wideband frequencies as well as single layer cloaking structures [17]. Finally, mantle cloaking is for small antenna cloaking, which reduces scatting of the incident wave of the antenna and works for both passive and active sensor single [17].

Based on this application’s need for the design, mantle cloaking provides excellent scatting and the ability to cloak smaller antennas that work best for my antenna design. These two features make it the best cloaking technique for this proposed application’s design requirement.

The second incorporation into my design will allow for antenna beam-steering while using the cloaking application described above. To achieve the beam-steering a leaky wave metasurface antenna will be used to control the beam with a varactor diode incorporated to shape the beams [14]. Another way of achieving this is by holographic metasurface antennas that use precise wavefront control principles inspired by holography theory to achieve individual beam steering of antennas.
Both types of antennas represent innovative technology for controlling and optimizing electromagnetic wave radiation for beam steering.

1.2 Objective

The thesis aims to explore applications of metasurface beam steering with cloaking applications for wireless communication applications. This thesis will investigate the current applications of cloaking mechanisms and their benefits along with the holographic metasurface and its usage of beam-steering. Applying this new approach can provide excellent wireless coverage in a small space while not interfering with nearby antennas like in a small device like a cell phone. Demonstrating that applying the two concepts of cloaking applications and metasurfaces will further other new design concepts and approaches.

1.3 Organization

This thesis is organized into five sections. The introduction covered the background of different types of cloaking applications for antennas and their uses. In addition, background is provided on metasurface materials and how they are used for beam-steering, which is needed for my design. The literature review section covers previously published research related to metasurface beam-steering antenna at X-band frequencies with cloaking applications. In the design methodology, I review the theory implemented in my design approach. The results of our HFSS analysis are shared in the implementation and data results section. Finally, in the conclusion and future works section, the beam steering with the cloaking results and the future implications of this work are discussed.
Chapter 2  Literature Review

2.1 Slot Antennas Applications

Electromagnetic cloaking has emerged as a crucial technology for antenna applications, enabling the reduction of mutual coupling and the control of radiation patterns. Invisibility cloaking was first conceived by J.B. Pendry, where he devised a way of directing the electric displacement field $\mathbf{D}$, the magnetic field intensity $\mathbf{B}$, and the Poynting vector $\mathbf{S}$ [3] to provide a way of directing these fields to achieve cloaking. Previous research has addressed the issue of mutual coupling, redirection of electromagnetic fields, and directed radiation patterns. The ways to achieve cloaking have been well established [6], [21] - [29] and include transformation optics, plasmonic cloaking, transmission line networks, and scattering cancelation (mantle cloaking). In addition to the cloaking aspects of the design, I will further study previous methodologies of holographic theory used for independent control of beams and multibeam steering and how other researchers have addressed this issue.

2.2 Different Types of Cloaking Applications

One of the most common methodologies for cloaking utilizes transformation optics, which involves bending electromagnetic waves to conceal or cloak an object of interest. Transformation optics works by using coordinate transformations that will map the $\mathbf{X}$, $\mathbf{Y}$, and $\mathbf{Z}$ planes space of where the electromagnetic waves propagate to [1], [3].

Figure 1, taken from [3], shows the flow of electromagnetic waves around the objects to provide invisibility.
As detailed in Figure 1, transformation optics directing the electromagnetic waves are now capable of bending around the object of interest and guide the waves in unconventional ways. Thus, by bending the electromagnetic waves around the object, it can render the object invisible.

Some of the limitations involved with using transformation optics include the following [1]:

- It has a narrow bandwidth that only operates within a certain range.
- Complex inhomogeneity designs are usually required.
- Dielectric losses in the metamaterial occur.
- The bulky design of metamaterials required usually 4 - 6 larger than the object being.

Plasmonic cloaking is a cancellation technique that uses metamaterials with
an electric permittivity $\varepsilon$ and magnetic permeability $\mu$ that is less than 1 or a negative value to achieve invisibility [20]. Plasmonic cloaking is designed to use thin metamaterials [23] to suppress the scattering effects of the electromagnetic waves for select frequencies as detailed in the figure below [31].

![Image of Plasmonic Cloaking](image.png)

Figure 2.
Image of Plasmonic Cloaking

This cloaking technology has been shown to be effective across most of the visible light spectrum [30]. It even provides cloaking regardless of the impending angle of incident of the cloaked object.

Key challenges involved with using plasmonic cloaking include the following [1], [20], [22], [23]:

1. The cloaking material must be unique for the object being cloaked
2. Non-suitable for cloaking large objects
Transmission line cloaking is usually a series of connected metallic layers that will guide an electromagnetic wave around the object that is to be cloaked. Figure 3 [28] detailed how transmission line cloaking would be used around an object.

![Figure 3](image)

**Figure 3.**
Transmission line cloaking mesh with LC lumped elements

As described in [28] the transmission line mesh cloaking is using a lumped inductor \( L \) and capacitance \( C \), where the electromagnetic waves from the medium travel through the cloak inside the mesh configuration. Key challenges with transmission line cloaking include the following:

1. Bulky design required
2. Limited bandwidth
3. Complex design
Scattering cancellation (mantle cloaking) provides cloaking by having [7] medium that creates interference on scattering on the object needed to be cloaked. Mantle cloaking and plasmonic cloaking are very similar in achieving invisibility, but working with mantle cloaking provides more [31] bandwidth and a lower profile. Mantle cloaking can be used with elliptical and cylindrical configurations with a conformal metallic surface around an object, which prevents the adjacent antenna from propagating into the neighboring fields; this allows the two radiation patterns do not interfere with each other [1], [5].

Key challenges with scattering cancellation include the following:

1. Different metamaterial surfaces are required based on the object being cloaked
2. It is not ideal for large objects being cloaked

2.3 Metasurface Beam-Steering

Metasurface beam-steering is a field of research with various applications and future developments in progress. This type of beam-steering can be achieved by using a varactor element to direct the beam patterns. The varactor element is a passive device that can vary beam degrees from 0 – 180 degrees, while active elements can cover the full range from 0 – 360 degrees for beam-steering.

Previous studies have focused on synthesizing metasurface beam-steering that bridges the gap between computer modeling and practical implementation. One of the methods to implement metasurface beam-steering is the application of integral equations by method of moments [11]. It was shown to obtain a complex-valued initial design that meets the desired far-field beam steering specifications. Using the [11] optimization method to efficiently calculate the gradient of the cost function,
only two forward problem solutions are required, leading to pattern metallic cladding, ensuring accurate and efficient beam-steering.

Discrete dielectric Huygens’ metasurface is another way to achieve beam-steering of the electromagnetic waves in a controlled way. A typical design would consist of two adjacent objects, with a 180-degree phase difference, leading to effective beam splitting. The benefit of this method is cost-effectiveness compared to other methods, such as discretized metasurfaces [12]. It is particularly beneficial in the millimeter-wave frequency range where design and implementation challenges are more relevant.

Two other popular methods to achieve controlled metasurface beam-steering are transmissive and directly-fed leaky-wavy metasurface designs. To achieve beam-steering, transmissive metasurface uses spatially varying capacitive sheets separated by two dielectric [13] spacers; the sheet impedances are purely reactive that scatter the desired field. Constraints were applied to the sheet impedances to avoid the excitation of surface waves with high transverse wavenumbers. The directly-fed leaky wave metasurface [13] design involves control over the radiation pattern from the spatial variation. The spatial variation of the leakage and phase constants control the amplitude and phase profiles of the aperture.
Chapter 3  Design Methodology

3.1 Maxwell’s Equations

Before discussing the proposed design, we must first understand Maxwell’s equations. Below are Maxwell’s equations (1) – (4) in differential form.

\[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \]  (1) Faraday’s Law

\[ \nabla \times \vec{H} = \mu_0 (j + \varepsilon_0 \frac{\partial \vec{E}}{\partial t}) \]  (2) Ampère’s Law

\[ \nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0} \]  (3) Gauss’s Law Electric Field

\[ \nabla \cdot \vec{B} = 0 \]  (4) Gauss’s Law Magnetic Field

These equations form the foundation of electromagnetism, optics, and electric circuits, formed by James Clerk Maxwell in the 19th century [33]. Maxwell’s equations (1) – (4) describe the relationship between electricity and magnetism. Faraday’s Law describes the effects of electromagnetic induction; a circulating electric field can be produced by changing the magnetic field in an enclosed circuit. Equation (2), which is Ampère’s Law, allows you to calculate the strength of the magnetic field of current wires. Equation (3), Gauss’s Law for the Electric Field, is the divergence of the \( \vec{E} \) and how it is related to the charge density \( \vec{p} \), it also shows how the electric fields must behave. Equation (4), Gauss’s Law for Magnetic Field, tells us that the divergence of \( \vec{B} \) is always zero, meaning that there are no single monopoles. Maxwell’s equations are pivotal in understanding the electric and magnetic phenomena in the physical world.
3.2 Design Concept

As discussed in the literature review, there are numerous ways to create a metasurface beam-steering antenna at X-band frequencies with cloaking applications. My application uses a mantle-cloaking metasurface material to provide cloaking of neighboring fields and add the varactor diode component for the beam-steering. The methodology comes from combining previous work shown in [1], where the authors were able to decouple the slot antenna to recover their radiation patterns and provide isolation for each slot. Work in [2] showed that a metasurface antenna can steer beams by tuning the varactor diode cell. The idea is to have a metasurface beam-steering at X-Band frequencies with cloaking applications that can be used in either wireless communication or satellite applications where the need for space and interference are an issue that can affect other systems parameters.

The design is of a rectangle waveguide slot metasurface antenna with beam-steering at X-Band with cloaking applied to each of the slots. The parameters of the rectangle waveguide are shown in Figure 4: $a_1 = 28.86 \text{ mm}$, $b = 10.16 \text{ mm}$, $t_1 = 0.25 \text{ mm}$, $x_1 = 100 \text{ mm}$, $W_1 = 2.45 \text{ mm}$, $W_2 = 2.55 \text{ mm}$, $S_L = 15 \text{ mm}$, $W_3 = 1.7 \text{ mm}$, $W_4 = 3.3 \text{ mm}$, $D_W = 0.425 \text{ mm}$, $D_H = 0.7 \text{ mm}$, $D_T = 0.9 \text{ mm}$, $L = 1.7 \text{ nH}$, $C_{ej} = 1.88 \text{ pF}$, $R = 2.5 \Omega$, $C_{ea} = 0.44 \text{ pF}$, $t_2 = 0.1 \text{ mm}$, $h = 0.23 \text{ mm}$, $d = 0.375 \text{ mm}$, $\epsilon = 2.1$, $x_2 = 24.25 \text{ mm}$, and $a_2 = 3.93 \text{ mm}$. The $R/C_{ea}$ combination shown in Figure 7 a is the R component and $C_{ea}$ in parallel.
The material of the waveguide is of PEC material and the interior volume is of air with $\varepsilon = 1$. Four different designs were created. Two models of the waveguide are without the cloaking elliptical cylinders and within those structures you have, the varactor [32] either is the ON or OFF state by using the configuration combination below to achieve this.
The final two models included the cloaking elliptical cylinders with the same varactor configuration shown in Figures 5 and 6. The current flow for each slot antennas can be seen in Figure 7. Note that Figure 7 only shows the varactor with the cloaking application, but the same varactor setup is used for the non-cloaking instance.
Figure 7.
Varactor Diode Current Flow (a) Current Flow going through the Varactor Diode in the +x direction in the ON State. (b) Current Flow going through the Varactor Diode in the +x direction in the OFF State.

The parameters used for the varactor diodes is from Skyworks (model SMV1231 series). The varactor was selected for the ability to tune the antenna pattern. The varactor of any passive element can be [32] modeled in HFSS by assigning the element as a “lumped RLC” boundary condition. In the lumped boundary state, you can create a combination of L, R, or C values in either a parallel or series equivalent circuit. In my model the varactor diode is as close as possible to the
specification sheet in terms of dimensions and size. I split the diode into four separate elements of the C, L, R, C or C, L, RC, C depending on the state being used.
Chapter 4  Implementation and Data Results

To implement the design, a leaky rectangular waveguide was created. Rectangle waveguides do not have transverse electromagnetic waves (TEM) and only produce either transverse electric (TE) mode or transverse magnetic (TM) mode.

Expressions [33] for the TE and TM waves are shown below. For my model analysis, the traveling wave is in the +x direction.

**TE Rectangular System**

\[ E_x = 0 \]  \hspace{1cm} (5)
\[ E_y = -\frac{1}{\varepsilon} \frac{\partial F_x}{\partial z} \]  \hspace{1cm} (6)
\[ E_z = -\frac{1}{\varepsilon} \frac{\partial F_x}{\partial y} \]  \hspace{1cm} (7)
\[ H_x = -j \frac{1}{\omega \varepsilon \mu} \left( \frac{\partial^2}{\partial x^2} + \beta^2 \right) F_x \]  \hspace{1cm} (8)
\[ H_y = -j \frac{1}{\omega \varepsilon \mu} \frac{\partial^2 F_x}{\partial x \partial y} \]  \hspace{1cm} (9)
\[ H_z = -j \frac{1}{\omega \varepsilon \mu} \frac{\partial^2 F_x}{\partial y^2} \]  \hspace{1cm} (10)

**TM Rectangular System**

\[ E_x = -j \frac{1}{\omega \varepsilon \mu} \left( \frac{\partial^2}{\partial x^2} + \beta^2 \right) A_x \]  \hspace{1cm} (11)
\[ E_y = -j \frac{1}{\omega \varepsilon \mu} \frac{\partial^2 A_x}{\partial x \partial y} \]  \hspace{1cm} (12)
\[ E_z = -j \frac{1}{\omega \varepsilon \mu} \frac{\partial^2 A_x}{\partial y^2} \]  \hspace{1cm} (13)
\[ H_x = 0 \]  \hspace{1cm} (14)
\[ H_y = -\frac{1}{\mu} \frac{\partial A_x}{\partial y} \]  \hspace{1cm} (15)
\[ H_z = -\frac{1}{\mu} \frac{\partial A_x}{\partial y} \]  \hspace{1cm} (16)
The above equations will account for all the E-field and H-field components of the leaky rectangle waveguide. My analysis was meshed at 8 GHz frequency using Ansys HFSS, and I was only concerned about frequencies above that limit. The cut-off frequency for both the TE and TM modes can be solved using the following equation below:

\[ f_{cmn} = \frac{1}{2\pi\sqrt{\mu\varepsilon}} \sqrt{\left(\frac{mn}{a}\right)^2 + \left(\frac{np}{b}\right)^2} \]  

(17)

I will mainly focus on the TE_{10} dominate mode for my results. For a vacuum-filled waveguide the propagation constant and phase constant can be determined from the below equations where \( f > f_c \).

\[ f_c = \frac{1}{2\pi\sqrt{\mu_0\varepsilon_0} a} \]  

(18)

\[ \beta = \omega\sqrt{\mu_0\varepsilon_0} \sqrt{1 - \left(\frac{f}{f_c}\right)^2} \]  

(19)
Looking at the results from Figure 9, the TE\textsubscript{10} mode cutoff frequency is about 6.75 GHz, so any frequency before the 6.75 GHz, the system will not operate in that area.
Figure 10 shows the elliptical cloaking metasurface metal provides decent isolation between each of the 5 slots from the 0-degree phase to the 270-degree phase. With the highest E-Field of 24600 V/m, the E-Fields do not interfere with the neighboring slots. Figure 11 shows the difference in the design with the leaky waveguide having the cloaking material removed. The E-Field radiates within the neighboring slots, interfering with the radiation patterns.
Figure 10.
(a) E-Field @ 0-degree phase (No Cloaking with RLC OFF State) (b) E-Field @ 0-degree phase (No Cloaking with RLC ON State) (c) E-Field @ 90-degree phase (No Cloaking with RLC OFF State) (d) E-Field @ 90-degree phase (No Cloaking with RLC ON State)
Figure 11.
(a) No Cloaking with RLC OFF State Total 3D dB Gain Plot (b) No Cloaking with RLC ON State Total 3D dB Gain Plot (c) Cloaking with RLC OFF State Total 3D dB Gain Plot (d) Cloaking with RLC ON State Total 3D dB Gain Plot
Based on the ON State of the varactors shown in Figures 12a and 12d, the E-field passes through the waveguide and there is no beam-steering occurring. Meanwhile as the varactor in the OFF state seen in Figures 12b and 12c, the E-fields start beam-steering in the direction of propagation (+ x direction). The total dB gain values between the 4 different models are shown in Table 1 below.

<table>
<thead>
<tr>
<th>Waveguide Total Gain</th>
<th></th>
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<tbody>
<tr>
<td>No Cloak (Varactor ON State)</td>
<td>7.9 (dBi)</td>
</tr>
<tr>
<td>No Cloak (Varactor OFF State)</td>
<td>8.08 (dBi)</td>
</tr>
<tr>
<td>Cloak (Varactor ON State)</td>
<td>8.89 (dBi)</td>
</tr>
<tr>
<td>Cloak (Varactor OFF State)</td>
<td>9.24 (dBi)</td>
</tr>
</tbody>
</table>

Table 1

The total dB values were fairly close to each other with the cloaking, and the varactor is the OFF state, producing the highest yield of 9.24 dB gain.
Chapter 5  Conclusions and Future Work

A combined metasurface beam-steering at X-Band frequencies with cloaking applications operating at 8 GHz has been proposed. The waveguide antenna showed beam-steering capabilities and proved the concepts of mantle cloaking to separate radiation patterns between the 5 slots presented in this paper. For future work, a possible active element would be a viable option to achieve narrowed and more directed radiation beams.
References


