Reduction of Mutual Coupling in Closely Spaced Strip Dipole Antennas with Elliptical Metasurfaces

Hossein M. Bernety and Alexander B. Yakovlev

Department of Electrical Engineering
Center for Applied Electromagnetic Systems Research (CAESR)
University of Mississippi

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Outline

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  - Dielectric Elliptical Cylinders at Microwave and Terahertz Frequencies
  - PEC Elliptical Cylinders at Microwave and Terahertz Frequencies
  - Strip as a Degenerated Ellipse

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  - Reduction of the Mutual Coupling Between Two Strip Dipole Antennas

- Conclusions
Cloaking with a Metasurface

- **Mantle Cloaking**
  - Based on scattering cancellation
  - An ultrathin metasurface
  - Anti-phase surface currents
  - Suppression of the dominant mode

**Electric field distributions**

1-D and 2-D Periodic Structures

- Vertical Strips
- Mesh Grids
- Capacitive Rings
- Patch Arrays

Graphene Nanopatches

- Graphene monolayer provides inductive surface impedance
- A conducting object needs capacitive surface impedance to be cloaked
- To resolve this issue, a patterned graphene metasurface is proposed, which owns dual capacitive/inductive inductance and can be used to cloak both dielectric and conducting objects

![Graphene Nanopatches Diagram]

\[ Z_S = R_s - jX_s \]
\[ = \frac{D}{\sigma_s(D-g)} + j\frac{\pi}{2\omega\varepsilon_0(\varepsilon_r+1)}D \ln[csc\left(\frac{\pi g}{2D}\right)] \]

- \( R_s \): surface resistance per unit cell
- \( X_s \): surface reactance per unit cell
- \( D \): periodicity size
- \( g \): gap size
- \( \varepsilon_r \): relative permittivity of the dielectric cylinder or the spacer

Cloaking using Graphene Nanopatches

**Dielectric Cylinder**

**PEC Cylinder**

Elliptical Cloak Designs at Microwaves
Elliptical Cloak Designs at THz Frequencies

- SiO₂ graphene monolayer

- graphene nanopatches

- SiO₂

- PEC

Parameters:
- \( a_0 \)
- \( a_1 \)
- \( b_0 \)
- \( b_1 \)
- \( D \)
Domain-Product Technique Solution for the Problem of Electromagnetic Scattering From Multiangular Composite Cylinders

Vitaliy P. Chumachenko, Member, IEEE

Abstract—This paper presents a domain-product technique solution for the problem of electromagnetic scattering from a two-dimensional structure composed of multiple perfect conductors and lossless dielectrics with arbitrarily polyhedral boundaries. The configuration is assumed to be excited by a plane wave polarized transverse magnetic or transverse electric to the axis of the cylinders. For both the interior and exterior subregions, efficient field representations are attained in the forms of Mathieu function expansions. A system of infinite matrix equations with respect to the expansion coefficients results from the boundary conditions. Solution to the system is found using a truncation procedure. Numerical examples are presented that demonstrate the validity, flexibility, and capability of the technique. In the middle frequency range, the approach proposed enables accurate numerical analysis of fairly complicated structures with low computational cost.

Index Terms—Cylinders, domain-product technique, electromagnetic theory.
Mathieu Equation

- Two-dimensional Helmholtz Equation:
  \[(\nabla^2 + K^2)E = 0\]

- where:
  \[\nabla^2 = \frac{1}{h^2} \left( \frac{\partial^2}{\partial u^2} + \frac{\partial^2}{\partial v^2} \right)\]

- Using the method of separation of variables we have:
  \[E(u, v) = R(u) S(v)\]

\[q = \frac{K^2F^2}{4}\]

- The radial Mathieu equation has four kinds of solution as:
  \[R'' - R(A - 2q \cosh(2u)) = 0\]
  \[S'' + S(A - 2q \cos(2u)) = 0\]

- The angular Mathieu equation has the solution as:
  \[J_{pm}(q, u, n)\]
  \[Y_{pm}(q, u, n)\]
  \[H_{pm}^{(1)}(q, u, n)\]
  \[H_{pm}^{(2)}(q, u, n)\]

- \(p, m\) can be even or odd
Formulation of the Scattering Problem

\[ E_z^i = \sqrt{8\pi} \sum_n j^{-n} \frac{I_{pm}(q_0, u, n)}{N_{pm}(q_0, n)} S_{pm}(q_0, v, n) S_{pm}(q_0, \varphi, n); \ u > u_0 \]

\[ E_z^s = \sqrt{8\pi} \sum_n j^{-n} a_{pm} H_{pm}^{(1)}(q_0, u, n) S_{pm}(q_0, v, n) S_{pm}(q_0, \varphi, n); \ u > u_0 \]

\[ H_v = \frac{1}{j\omega\mu} \frac{1}{h} \left( -\frac{\partial}{\partial u} E_z \right) = \frac{1}{j\omega\mu h} \frac{\partial}{\partial u} E_z \]

\[ H_v^i = \frac{j}{\omega\mu h} \sqrt{8\pi} \sum_n j^{-n} \frac{f_{pm}(q_0, u, n)}{N_{pm}(q_0, n)} S_{pm}(q_0, v, n) S_{pm}(q_0, \varphi, n) \]

\[ H_v^s = \frac{j}{\omega\mu h} \sqrt{8\pi} \sum_n j^{-n} a_{pm} H_{pm}^{(1)'}(q_0, u, n) S_{pm}(q_0, v, n) S_{pm}(q_0, \varphi, n) \]

\[ E_z^t = \sqrt{8\pi} \sum_n j^{-n} [b_{pm} j_{pm}(q_1, u, n) + c_{pm} Y_{pm}(q_1, u, n)] S_{pm}(q_1, v, n) S_{pm}(q_0, \varphi, n); \ u_1 < u < u_0 \]

\[ H_v^t = \frac{j}{\omega\mu h} \sqrt{8\pi} \sum_n j^{-n} [b_{pm} j'_{pm}(q_1, u, n) + c_{pm} Y'_{pm}(q_1, u, n)] S_{pm}(q_1, v, n) S_{pm}(q_0, \varphi, n) \]
Boundary Conditions

- By applying boundary conditions:

\[(1)\quad E_{lu=u_1} = 0 \Rightarrow b_{pm}J_{pm}(q_1, u_1, n) + c_{pm}Y_{pm}(q_1, u_1, n) = 0\]

\[(2)\quad E^i + E^s_{lu=u_0} = E^t_{lu=u_0} \quad \Rightarrow \quad \text{Sheet Impedance Boundary Condition}\]

\[\begin{align*}
\sqrt{8\pi} \sum_n j^{-n} \left[ \frac{J_{pm}(q_0, u_0, n)}{N_{pm}(q_0, n)} + a_{pm}H_{pm}^{(1)}(q_0, u_0, n) \right] S_{pm}(q_0, v, n) S_{pm}(q_0, \varphi, n) \\
= \sqrt{8\pi} \sum_n j^{-n} \left[ b_{pm}J_{pm}(q_1, u_0, n) + c_{pm}Y_{pm}(q_1, u_0, n) \right] S_{pm}(q_1, v, n) S_{pm}(q_0, \varphi, n)
\end{align*}\]

\[(3)\quad Z_s \left[ H^i + H^s_{lu=u_0} - H^t_{lu=u_0} \right] = E^t_{lu=u_0} \quad \Rightarrow \quad \text{Sheet Impedance Boundary Condition}\]

\[\begin{align*}
Z_s \left\{ \frac{j\sqrt{8\pi}}{\omega h_0} \sum_n j^{-n} \left[ J'_{pm}(q_0, u_0, n) \right] S_{pm}(q_0, v, n) S_{pm}(q_0, \varphi, n) - \right. \\
\frac{j\sqrt{8\pi}}{\omega h_0} \sum_n j^{-n} \left[ b_{pm}J'_{pm}(q_1, u_0, n) + c_{pm}Y'_{pm}(q_1, u_0, n) \right] S_{pm}(q_1, v, n) S_{pm}(q_0, \varphi, n) \right\} = \\
\sqrt{8\pi} \sum_n j^{-n} \left[ b_{pm}J_{pm}(q_1, u_0, n) + c_{pm}Y_{pm}(q_1, u_0, n) \right] S_{pm}(q_1, v, n) S_{pm}(q_0, \varphi, n)
\end{align*}\]
Bistatic Scattering Width

- The two-dimensional bistatic cross section is defined as:

$$\sigma_{2D} = \lim_{\rho \to \infty} 2\pi \rho \frac{|E^s|^2}{|E^i|^2}$$

- Finally, we have:

$$\frac{\sigma_{2D}}{\lambda} = \left[ \sum_{n} \sqrt{8\pi} j^{-2n} a_{nm} S_{pm}(q_0, \nu, n) S_{pm}(q_0, \varphi, n) \right]^2$$

$$\left[ \sum_{n} \sqrt{8\pi} j^{-2n} a_{ee}(q_0, \nu, n) S_{ee}(q_0, \varphi, n) + \sum_{n} \sqrt{8\pi} j^{-2n} a_{eo}(q_0, \nu, n) S_{eo}(q_0, \varphi, n) + \sum_{n} \sqrt{8\pi} j^{-2n} a_{oe}(q_0, \nu, n) S_{oe}(q_0, \varphi, n) + \sum_{n} \sqrt{8\pi} j^{-2n} a_{oo}(q_0, \nu, n) S_{oo}(q_0, \varphi, n) \right]^2$$
Quasi-static Closed-form Condition

❖ In the quasi-static limit ($q_0 = \frac{K_0^2 F^2}{4} \ll 1$, $q_1 = q_0 \varepsilon_r \ll 1$), the closed-form condition for a PEC elliptical cylinder under TM-polarized illumination can be derived as:

$$Z_{s-opt} = j \omega \mu F \cosh u_0 \frac{u_0 - u_1}{1 + \sinh 2u_0 \left(q_0(u_0 - u_1) + q_1 \left(u_1 + \frac{1}{2} \ln q_1\right)\right)}$$

❖ And also, the closed-form condition for a dielectric elliptical cylinder under TM-polarized illumination can be derived as:

$$Z_{s-opt} = j \omega \mu F \frac{1 - q_1 \sinh^2 u_0}{2 \sinh u_0 (q_0 - q_1)}$$
Surface Reactance Frequency Dispersion

- Frequency dispersion of the surface reactance for graphene monolayer and nanopatches with respect to the optimum required is found as:

\[ D = 5.064 \, \mu \text{m}, \, g = 0.524 \, \mu \text{m}, \, \mu_c = 0.2672 \, \text{eV} \]

\[ \mu_c = 0.5718 \, \text{eV} \]
Surface Conductivity of Graphene

Kubo Formula

\[ \sigma(\omega, \mu_c, \tau, T) = \frac{-je^2(\omega + j\tau^{-1})}{\pi\hbar^2} \times \left[ \frac{1}{(\omega + j\tau^{-1})^2} \int_0^\infty \left( \frac{\partial f d(\varepsilon)}{\partial \varepsilon} - \frac{\partial f d(-\varepsilon)}{\partial \varepsilon} \right) \varepsilon d\varepsilon - \int_0^\infty \frac{f d(-\varepsilon) - f d(\varepsilon)}{(\omega + j\tau^{-1})^2 - 4(\varepsilon/\hbar)^2} d\varepsilon \right] \]

Intraband Contributions

\[ \sigma_{\text{intra}} = j \frac{e^2 k_B T}{\pi\hbar^2(\omega + j\tau^{-1})} \left[ \frac{\mu_c}{k_B T} + 2\ln \left( e^{-\frac{\mu_c}{k_B T}} + 1 \right) \right] \]

Interband Contributions

\[ \sigma_{\text{inter}} = \frac{je^2}{4\pi\hbar} \ln \left( \frac{2|\mu_c| - (\omega + j\tau^{-1})\hbar}{2|\mu_c| + (\omega + j\tau^{-1})\hbar} \right) \]

\[ Z_s = 1/\sigma \]

\(-e\) : charge of electron  \(T\) : temperature  
\(\omega\) : angular frequency  \(\varepsilon\) : energy
\(\mu_c\) : chemical potential  \(\hbar\) : reduced Planck’s constant
\(\tau\) : momentum relaxation time

Dielectric Elliptical Cylinder at THz Frequencies

- Geometry parameters are:
  \[ \varepsilon_r = 4 \text{ (silicon dioxide)} \]
  \[ a_0 = 12.5 \mu m \left( \lambda_0 / 8 \right) \]
  \[ b_0 = 10 \mu m \left( \lambda_0 / 10 \right) \]

- The required reactance is found to be: \[ X_s = 260 \ \Omega \]

- The design parameters are: \[ \mu_c = 0.6158 \text{ eV}, \ T = 300 \text{ K}, \ \tau = 1.5 \text{ ps} \]
Power Flow and Far-field Pattern

Uncloaked

Cloaked

\[ f = 3 \text{ THz} \]

\[ \varepsilon_r = 4 \text{ (silicon dioxide)} \]
\[ a_0 = 12.5 \mu m (\lambda_0/8) \]
\[ b_0 = 10 \mu m (\lambda_0/10) \]

SiO$_2$

graphene monolayer
Electric Field Distribution

Uncloaked

Cloaked

$\varepsilon_r = 4$ (silicon dioxide)

$a_0 = 12.5 \, \mu m \, (\lambda_0/8)$

$b_0 = 10 \, \mu m \, (\lambda_0/10)$

$f = 3 \, THz$
Closely Spaced and Overlapping Dielectric Elliptical Cylinders

Uncloaked

Cloaked

Uncloaked

Cloaked

\( l = 50 \mu m \)

\( f = 3 \text{ THz} \)

\( l = 48 \mu m \)
Cluster of Dielectric Elliptical Cylinders I

Uncloaked

Cloaked

$l = 50 \, \mu m = 0.5 \, \lambda$

$g = 3 \, \mu m$

$f = 3 \, THz$
Cluster of Dielectric Elliptical Cylinders II

Uncloaked

Cloaked

Uncloaked

Cloaked

$g = 3 \mu m$

$f = 3 \text{ THz}$
Overlapping of Dielectric Elliptical Cylinders

Uncloaked

Cloaked

$l = 140 \mu m = 1.4 \lambda$

$f = 3 \text{ THz}$
Dielectric Elliptical Cylinder at Microwave Frequencies

- Geometry parameters are:
  \[ \varepsilon_r = 10 \]
  \[ a_0 = 10 \text{ mm } (\lambda_0/10) \]
  \[ b_0 = 8.6655 \text{ mm } (\lambda_0/11.54) \]

- The required reactance is found to be: \[ X_s = 70.75 \text{ } \Omega \]

- The design parameters are:
  \[ D = 7.339 \text{ mm } (\lambda_0/13.62), w = 0.3626 \text{ mm } (\lambda_0/275.786) \]
Dielectric Elliptical Cylinder at Microwave Frequencies

- Geometry parameters are:
  \[ \varepsilon_r = 10 \]
  \[ a_0 = 10 \text{ mm (}\lambda_0/10) \]
  \[ b_0 = 8.6655 \text{ mm (}\lambda_0/11.54) \]

- The required reactance is found to be: \[ X_s = 70.75 \text{ } \Omega \]

- The design parameters are:
  \[ N=3 \]
  \[ D = 19.57 \text{ mm (}\lambda_0/5.109), w = 4.9 \text{ mm (}\lambda_0/20.408) \]
  \[ D = 7.339 \text{ mm (}\lambda_0/13.62), w = 0.3626 \text{ mm (}\lambda_0/275.786) \]
Electric Field Distribution

Uncloaked

$N = 8$

$f = 3$ GHz

Cloaked

$\varepsilon_r = 10$

$a_0 = 10$ mm ($\lambda_0 / 10$)

$b_0 = 8.6655$ mm ($\lambda_0 / 11.54$)
A strip can be modeled as a degenerated ellipse.

Geometry parameters are:

- \( a_0 = 10.04 \, \mu m \left( \frac{\lambda_0}{9.96} \right) \), \( b_0 = 6.67 \, \mu m \left( \frac{\lambda_0}{15} \right) \)
- \( a_1 = 7.5 \, \mu m = F \left( \frac{\lambda_0}{13.33} \right), \varepsilon_r = 4 \)

\[ X_s = -210 \, \Omega \quad D = 5.29 \, \mu m, \quad g = 0.6 \, \mu m, \quad \mu_c = 0.9 \, eV \]
Power Flow and Far-field Pattern

Uncloaked

Cloaked

$f = 3$ THz
Electric Field Distribution
Cloaking for Two Strips

Uncloaked

Cloaked

\( f = 3 \text{ THz} \)
Two Strips Horizontally Oriented

Uncloaked

Cloaked

$f = 3 \text{ THz}$
Two Strips with Overlapping Cloaks

Uncloaked

Cloaked

$f = 3 \, \text{THz}$

$g = 3.7 \, \mu m$
Two Connected Strips

Uncloaked

Cloaked

$f = 3 \text{ THz}$

Uncloaked

Cloaked

$l = \frac{\lambda}{3.33}$
Overcoming Mutual Blockage Between Neighboring Dipole Antennas Using a Low-Profile Patterned Metasurface

Alessio Monti, Student Member; IEEE, Jason Soric, Student Member; IEEE, Andrea Alù, Member; IEEE, Filiberto Bilotti, Senior Member; IEEE, Alessandro Toscano, Senior Member; IEEE, and Lucio Vegni, Life Member; IEEE

Abstract—In this letter, we investigate the possibility of using the mantle cloakng approach to reduce mutual blockage effects between two electrically close antennas. In particular, we consider the case of two dipoles resonating at different, close frequencies and separated by an electrically short distance ($\lambda_0 / 10$ at 3 GHz). We show that by covering the two antennas with properly patterned metasurfaces printed on realistic substrates, it is possible to make each antenna invisible to the other and preserve their individual operation as if they were isolated. This new cloaking application is confirmed by realistic full-wave numerical simulations.

Index Terms—Cloaking, dipole antennas, metasurfaces.

I. INTRODUCTION

In the last decade, there has been a worldwide effort in the design of electromagnetic covers that may strongly reduce the visibility, scattering signature, and electromagnetic in-
Strip Dipole Antennas

- Here, we present the applicability of elliptically shaped metasurfaces in order to reduce the mutual coupling between two closely spaced antennas.

- First, we consider two strip dipole antennas resonating at \( f = 1 \) GHz and \( f = 5 \) GHz, which are separated by a short distance of \( d = \lambda/10 \) (at \( f = 5 \) GHz). (Case I)

- Second, we consider two strip dipole antennas resonating at \( f = 3.02 \) GHz and \( f = 3.33 \) GHz, which are separated by a short distance of \( d = \lambda/10 \) (at \( f = 3 \) GHz). (Case II)

- To present how the mutual blockage is overcome, we consider three different scenarios of isolated, uncloaked, and cloaked for each case.
Case I

- We consider Antenna I (isolated) and Antenna II (isolated) which resonate at $f = 1$ GHz and $f = 5$ GHz, respectively, with omni-directional radiation patterns as shown below. Each antenna is matched to a 75-Ω feed.

![Diagram of Antenna I and Antenna II with specifications:]

- **Antenna I**:
  - $W = 4$ mm
  - $\Delta = 0.2$ mm
  - $L = 130.5.5$ mm

- **Antenna II**:
  - $W = 4$ mm
  - $\Delta = 0.2$ mm
  - $L = 27.5$ mm
Neighboring Uncloaked Dipole Antennas

- Now, the antennas are placed in close proximity to each other. The presence of Antenna II does not have much effect on Antenna I since its length is small compared to the wavelength of the resonance frequency of Antenna I, but Antenna I changes the matching characteristics and radiation pattern of Antenna II drastically.

\[ f = 1 \text{ GHz} \]

\[ d = 6 \text{ mm} \]
Cloaking 2-D Metallic Strip

- a 2-D Metallic Strip can be considered as a degenerated ellipse
- TM-polarized plane-wave excitation.

\[ Z_{TM,H\text{strips}}^{TM} = \frac{-j\eta_0 c \pi}{\omega (\varepsilon_r + 1) D} \frac{1}{\ln \csc \left( \frac{\pi g}{2D} \right)} \]

- \( f_0 = 3 \text{ GHz} \)
- \( a_0 = 8.457 \text{ mm} (\lambda_0/11.82) \)
- \( b_0 = 3.908 \text{ mm} (\lambda_0/25.58) \)
- \( \varepsilon_c = 10 \)
- \( Z_s = -j85.15 \Omega \)
- \( D = 8.93 \text{ mm} \)
- \( g = 0.6 \text{ mm} \)
Cloaking 2-D Metallic Strip

\[ f_0 = 3 \text{ GHz} \]
\[ a_0 = 8.457 \text{ mm (} \lambda_0 / 11.82 \text{)} \]
\[ b_0 = 3.908 \text{ mm (} \lambda_0 / 25.58 \text{)} \]
\[ \varepsilon_c = 10 \]
\[ Z_s = -j85.15 \Omega \]
\[ D = 8.93 \text{ mm} \]
\[ g = 0.6 \text{ mm} \]

\[ \phi = 90^\circ \]

Uncloaked (Analytical)
Uncloaked (CST)
Cloaked (Analytical)
Cloaked (CST)

\[ \varepsilon_e \]

Capacitive Rings
How to Cloak Antenna I?

- Since the length of Antenna I is 2.5 times the wavelength of Antenna II, therefore, we propose to use the analytical approach for infinite length as a good approximation to find the required metasurface for this case.

\[ L_1 \approx 2.5 \lambda_2 \]

- \( Z_s = -j40 \, \Omega \)
- \( a_0 = 2.2 \text{ mm } (\lambda_0/27.27) \)
- \( b_0 = 0.9165 \text{ mm } (\lambda_0/65.46) \)
- \( \varepsilon_r = 25 \)
- \( D = 6.515 \text{ mm} \)
- \( g = 1.29 \text{ mm} \)

![Graph showing RCS vs. Frequency with Uncloaked and Cloaked cases](image-url)
Neighboring Cloaked Dipole Antennas

- 3-D radiation patterns of Antenna I at 1 GHz (left) and Antenna II at 5 GHz (right) for the scenario, in which Antenna I is cloaked for the resonance frequency of Antenna II and the antennas are in close proximity.

![3-D radiation patterns of Antenna I and Antenna II](image-url)
2-D Gain Pattern

- Restoration of gain patterns at the first and second resonance frequency of Antenna I (1 GHz, 3 GHz) and resonance frequency of Antenna II.
Isolated Antenna I (Case II)

- First of all, we consider the antenna I (Isolated Case), which resonates at \( f = 3.02 \text{ GHz} \) with an omni-directional radiation pattern as shown below. The \( S_{11} \) of the antenna along with its dimensions are shown below. The antenna is matched to a 75-\( \Omega \) feed.
Then, we consider the antenna II (Isolated Case), which resonates at $f = 3.33$ GHz with an omni-directional radiation pattern as illustrated below. The $S_{11}$ of the antenna along with its dimensions are shown below. The antenna is matched to a 75-$\Omega$ feed.

**Isolated Antenna II (Case II)**

- **W** = 4 mm
- **L** = 41.5 mm
- **$\Delta$** = 0.2 mm
- $f = 3.33$ GHz

The antenna is matched to a 75-$\Omega$ feed.
Now, the antennas are placed in close proximity to each other. As expected, the presence of each of the antennas affects the radiation pattern of the other one drastically because the near-field distribution is changed, and therefore, the input reactance is changed remarkably.

\( f = 3.02 \text{ GHz} \)

\( f = 3.33 \text{ GHz} \)
Separated Cloaked Dipole Antennas

- To reduce the mutual coupling, we cover each dipole antenna with an elliptically shaped mantle cloak structure consisting of inductive vertical strips and a spacer between the strip and the metasurface. The presence of the spacer, and then, the cloak structure, changes the resonance frequency of the antenna. Therefore, we reduce the length of the antenna in order to provide good matching at the desired working frequency. On the other hand, the parameters of the cloak structure should be chosen in a way that each antenna is invisible at the resonance frequency of the other one.

- We have performed an appropriate optimization to minimize the 3-D total RCS of each dipole antenna under Transverse Magnetic (TM) plane-wave excitation.
In this slide, the antenna I covered with the spacer and the metasurface is presented. To achieve a good matching at the desired resonance frequency of 3.02 GHz, we reduced the length of the antenna from \( L = 45.8 \) mm to \( L = 41.4 \) mm. The \( S_{11} \) parameter, permittivity of the spacer, and also, the dimensions of the cloak structure are shown below.

\[
D = 3.4034 \text{ mm} \\
w = 0.35 \text{ mm} \\
a = 2.2 \text{ mm} \\
b = 0.9165 \text{ mm} \\
\varepsilon_r = 6.15
\]

\( L = 41.4 \text{ mm} \)

Rogers RO3006 (Lossy)
In this slide, the antenna II covered with the spacer and the cloak design is presented. To achieve a good matching at the desired resonance frequency of 3.02 GHz, again, we reduced the length of the antenna from $L = 41.5$ mm to $L = 38.8$ mm. The $S_{11}$ parameter, permittivity of the spacer, and also, the dimensions of the cloak structure are shown below.

$$D = 3.4034 \text{ mm}$$
$$w = 0.3 \text{ mm}$$
$$a = 2.2 \text{ mm}$$
$$b = 0.9165 \text{ mm}$$
$$\varepsilon_r = 9.8$$

$L = 38.8$ mm

Rogers TMM 10i (Lossy)
Neighboring Cloaked Dipole Antennas

- The reflection coefficients at the input port of the Antenna I and the Antenna II in the cloaked case (the antennas are in close proximity to each other) are shown here. As can be seen, the impedance matching of the antennas are good near the resonant frequency of each isolated strip dipole antenna.

- Radiation patterns are:
Neighboring Cloaked Dipole Antennas

\[ f = 2.9441 \text{ GHz} \]

\[ f = 3.3515 \text{ GHz} \]

**E-Plane**

\[ f = 2.9441 \text{ GHz} \]

\[ f = 3.3515 \text{ GHz} \]

**H-Plane**

\[ f = 2.9441 \text{ GHz} \]

\[ f = 3.3515 \text{ GHz} \]
Conclusions

- An analytical approach has been proposed to cloak elliptical cylinders, and also, strips at microwave and low-THz frequencies by using conformal mantle cloak designs.

- Although the electromagnetic wave scattering of an elliptical cylinder is pertinent to the angle of incidence, it is shown that the cloak design is robust for any incident angle.

- The idea of cloaking strips has been utilized to reduce the mutual coupling between two strip dipole antennas.