Electromagnetics Class Project (2 Credits)   Fall 2025

You will work on the class project of the Electromagnetics course, which accounts for 2 credits, during the last month of the 2025 fall semester. You should team up with one other student in the class for all the technical portion of the project. You can simply adopt the grouping of your previous lab sessions. One team only needs to turn in one project report and both team members get the same grade for this class project. **The final project report is due January 23, 2026.** Background knowledge of some topics can be found in the book chapter and slides provided to you. You may also need to dig out some useful information from other books or online resources by yourself.

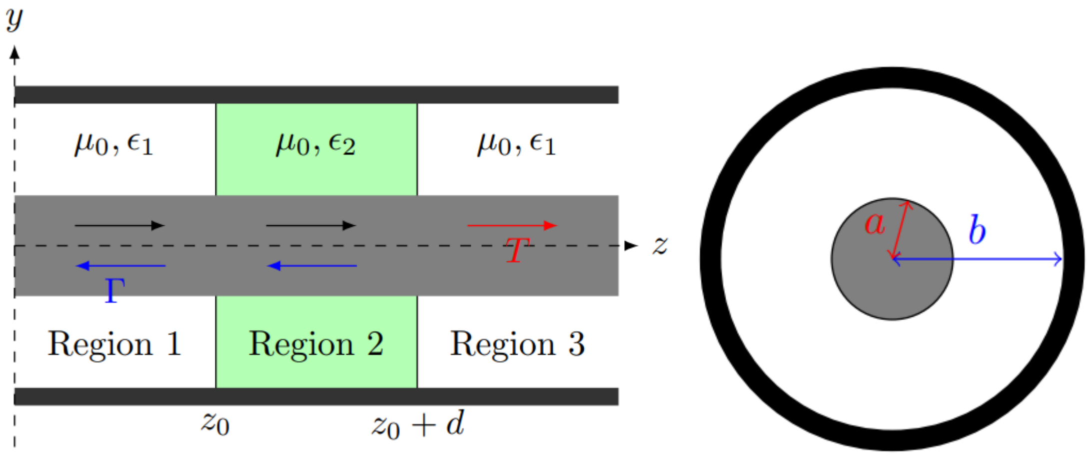
There are in total five different topics for you to choose. Topic 1 is mandatory for all groups. Each group also needs to choose another topic from Topic 2 to 5. **Please notify the TAs which topic you have selected (from Topics 2-5) by December 15, 2025.** Successful completion of the topics includes the simulation work, derivation, measurements and reports. Your TAs will check your simulation results as well.

Simulation software is needed for some topics. The software is installed on computers in the teaching lab 1D102, which will be open for you on request. Your TAs will provide necessary help on all the simulation, derivation and experiments. **You have to be very careful and follow the advice of your TAs when using the experimental devices.**

Detailed descriptions of the five topics are given below.

Topic 1

This topic pertains to the measurement of complex permittivity using a coaxial waveguide. Schematic configuration of the problem is shown below. The inner and outer radii are respectively a and b. The two conductors can be considered as PEC. A nonmagnetic material, with a thickness of d (known) and unknown **complex permittivity** $\boldsymbol{\varepsilon_2}$, is under test and resides in Region 2. Region 1 and Region 3 are filled with a nonmagnetic lossless material having permittivity ε_1. An incident wave propagating in $+z$ direction in Region 1 hits the material in Region 2. Then multiple reflections happen at the two interfaces at $z = z_0$ and $z = z_0 + d$. In reality, the material to be investigated is machined into a ring-shaped model having the same inner and outer radius as the coaxial waveguide and a thickness of d in the z direction, which can guarantee that the material can exactly fit inside the waveguide (no air gap between the material and the metal walls of the waveguide). We can use a vector network analyzer (VNA) to measure the reflection coefficient Γ (S_{11}) and transmission coefficient T (S_{21}), both are complex numbers with amplitude and phase. The major task you need to do is **determining the complex permittivity** $\boldsymbol{\varepsilon_2}$ **making use of** $\boldsymbol{\Gamma}$ **and** $\boldsymbol{T}$.



You need to follow these general steps.

1. Write out the electric and magnetic fields (or voltages and currents) in all the three regions using the method similar to the homework problem 8.9. Hint: using the voltages and currents, i.e., the transmission line method, may be simpler.
2. Use the boundary conditions at $z = z_0$ and $z = z_0 + d$ to establish four equations.
3. Solve for Γ and T, which will be expressed in terms of ε_2. Hint: you may use the "solve" function in MATLAB.
4. Finally, use the provided Γ and T (explained in the following note) to derive ε_2 from the two equations of Γ and T you got in step 3. For the cases that may have multiple solutions of ε_2, you need to provide all the possible solutions.
5. Use your obtained ε_2 and other known parameters to build a model in CST and simulate the Γ and T. This step can verify if your obtained ε_2 is correct.

Note: each group needs to do this problem for **different materials**. Each group will draw lots to determine the following parameters:

1. Coaxial waveguide dimensions a and b.
2. Thickness d of the material under test.
3. ε_1 in Region 1 and 3.
4. Frequency.
5. Γ and T.

Topic 2 (Limited to 9 groups)

This topic pertains to the design and measurement of a patch antenna. Read 14.1 and 14.2.1 of the book *Antenna Theory and Design* to gain basic knowledge of patch antenna.

Design one patch antenna working at the frequency and using the substrate given below.

Each team performs the design of the antenna at a unique frequency ranging from **2 to 3 GHz**

with a step of 0.05 GHz. You will draw lots to determine the specific frequency of each group. The substrate is lossless and has a relative permittivity of **4.2** and a height of 1 mm. The copper layer on top and bottom of the substrate is 35 μm.

Use the microstrip line feed method. The characteristic impedance of the air-filled coaxial probe is 50 Ω. Its inner conductor has a diameter of 2 mm and outer conductor has a diameter of 4.6 mm. You will need to figure out the location of the coaxial probe where the optimal matching condition at your design frequency can be achieved.

Use CST software to draw the models of the antenna. Set all the materials and simulation parameters. After the simulations are done, you need to check the simulation results to judge if some design considerations are fulfilled, which includes the following aspects.

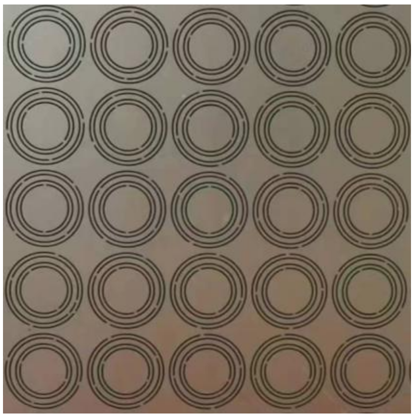
1) Check $|S_{11}|$ (return loss) to see if the antenna is working at your design frequency. This can be judged by observing if the dip of the $|S_{11}|$ curve is at your design frequency. If not, you can adjust the size of the patch or the location of the feed as well.
2) Check $|S_{11}|$ to see if acceptable matching condition is obtained. Acceptable matching condition means that $|S_{11}| < -10$ dB at the working frequency. If not, you can try to tune the location of the coaxial probe and/or the size of the patch. Tuning the location of the coaxial probe may in turn alter the working frequency of the antenna, so you need to readjust the size of the patch.
3) Try to make the relative bandwidth (frequency range in which $|S_{11}|$ is less than -10 dB) as wide as possible, which is defined as $(f_{high} - f_{low})/f_{design}$. Here f_{high} and f_{low} denote the higher and lower frequency of the band, respectively. Try to make its relative bandwidth greater than 2%.

The antenna will be fabricated by a company. You need to prepare a file of the antenna structure in proper format. Be sure to follow the advice of your TAs when making these files. After you obtain the fabricated antenna, solder a coaxial connector to it and use a vector network analyzer (VNA) to measure its reflection coefficient. Compare their measured and simulated results in your report. You will also have the opportunity to measure the 3D radiation pattern of your patch antenna using an anechoic chamber.

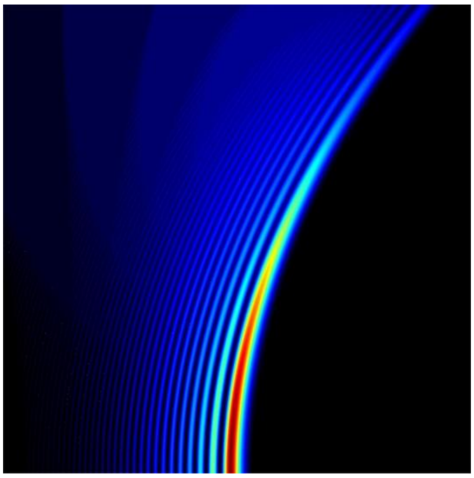
Please give the TA your detailed design parameters and proper layout file for the antenna by **January 10, 2026**. It takes about 10 days to fabricate it. **This is a firm deadline!!!**

Topic 3 (Limited to 6 groups)

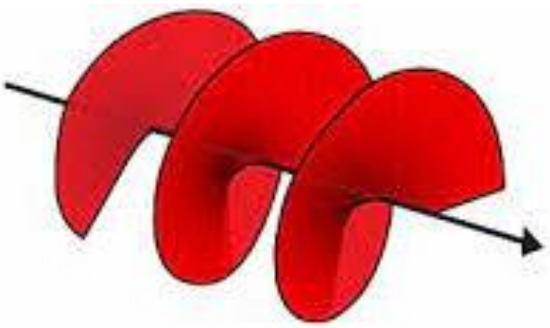
This topic pertains to the design of an Airy beam, an OAM beam, and negative reflection. Read the slides and papers regarding metasurface, Airy beams, and beams with orbital angular momentum (OAM) to gain basic concepts. The metasurface is a 2D structure composed of many small unit elements, with an example is shown in Fig. (a) below. Each element can be individually designed to lead to flexible amplitude and phase manipulation of an electromagnetic wave. The Airy beam has a curved propagation trajectory even if it is propagating in a homogeneous material as shown in Fig. (b) below, which is intuitively contradictory to the common sense. The OAM beam has a helical wavefront as shown in Fig. (c) below.



(a) Photo of a microwave metasurface



(b) Amplitude of an Airy beam



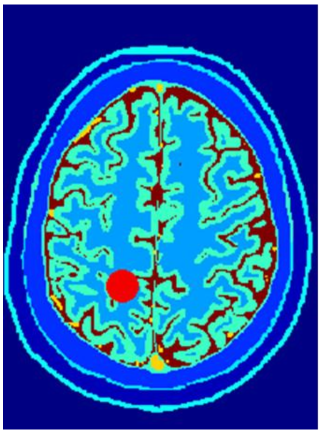
(c) Wavefront of an OAM beam

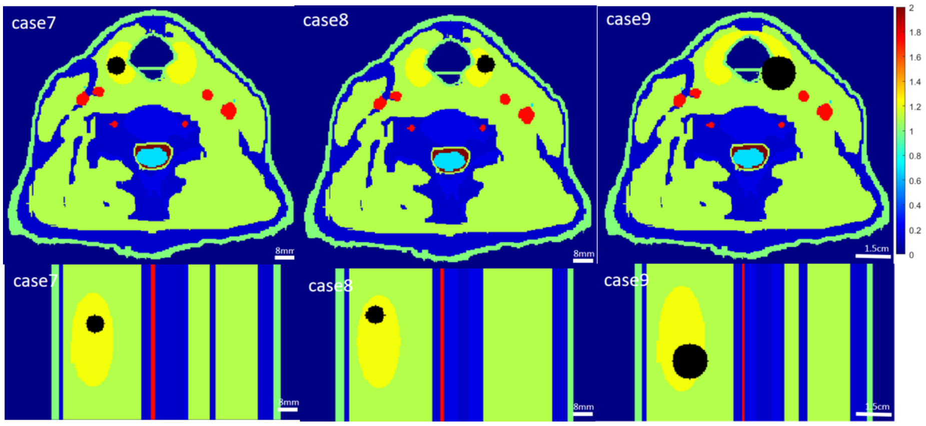
You need to design a metasurface to generate an Airy beam, an OAM beam, or negative reflection in the millimeter wave range from 30 to 50 GHz. You will draw lots to determine the specific frequency of each group. Different phase shift is achieved by tuning the unit element of the metasurface. The designed metasurface needs to offer a required phase distribution for an Airy beam, an OAM beam, or negative reflection. Example designs at lower frequencies are provided as a reference. Simply adjusting dimensions of the structure of the unit element can tune the operating frequency of the metasurface. TAs will guide you step by step for all the related details.

Use CST software to first draw the models of the unit element and tune its parameters. Then set up another model of the entire metasurface consists of at least 50 × 50 unit elements to simulate the generated beam. You need to check the simulated phase and amplitude of the generated beam to verify your design. You will also have the opportunity to measure the performance of a fabricated metasurface based on your design.

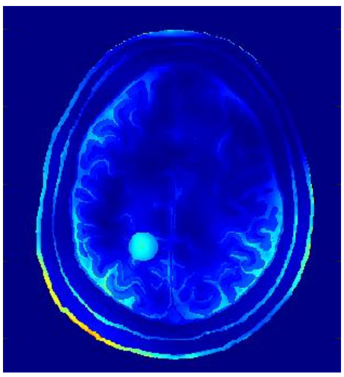
Topic 4 (Limited to 5 groups)

This topic pertains to the design of a phased antenna array for focused microwave brain tumor hyperthermia or thyroid tumor hyperthermia. Conductivity distributions of a realistic human brain with a tumor (the red spot) and a realistic neck with a tumor (the black spot) are shown below, which can be seen are highly electromagnetically inhomogeneous.

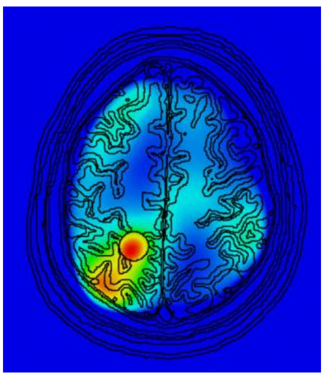




The microwave brain hyperthermia technique applies a phased antenna array on the head to radiate microwave power into the brain. By properly optimizing the radiation phase and amplitude of each antenna element, we can focus the microwave fields at the tumor to achieve elective heating of the tumor, as shown below.



Power distribution

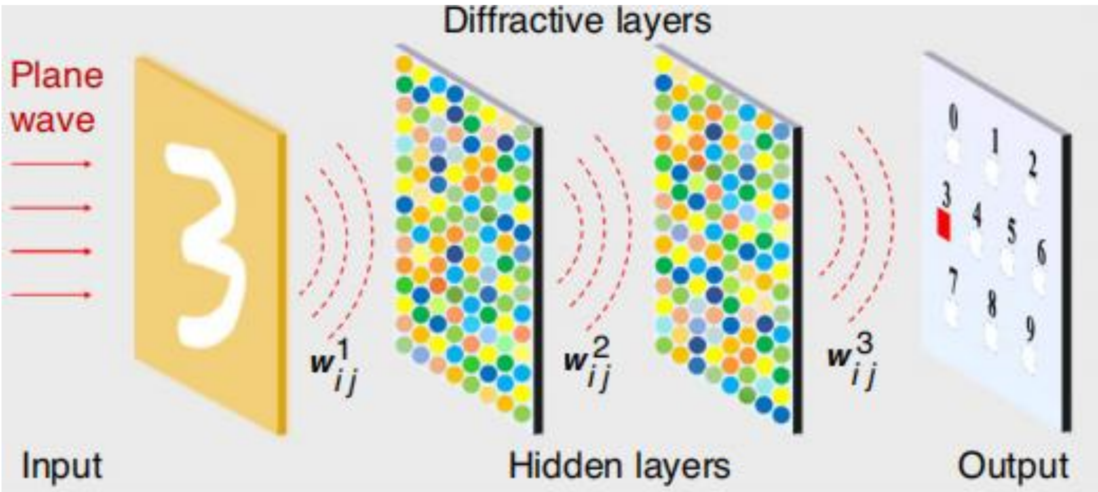


Temperature distribution

You need to design the configuration of the antenna array and do simulations to achieve good microwave focusing. Detailed antenna structure and materials are provided to you. The number of antennas is from 12 to 16. You will first need to build a model of the human head and antenna array in CST. After you get the simulated electric field distributions in the head, you will use a program in MATLAB to optimize the phase and amplitude of each antenna. Only simulation results are needed for this topic.

Topic 5 (Limited to 3 groups)

This topic pertains to the design of a metasurface-based diffractive neural network (DNN) for intelligent breast tumor detection or skin tumor detection. This topic also involves deep learning and related Python programming. The schematic of a DNN is shown below. It can perform computation based on the physical propagation of electromagnetic waves through several layers of metasurface. Many works have applied DNNs on number classification and fashion product classification. Phase of each meta-atom of the metasurfaces can be tuned from 0 to 2π.



You need to design the meta-atom distributions in each layer of metasurface to realize the detection of a breast tumor. Detailed meta-atom structure is provided to you. Three layers of metasurface are needed. Only simulation results are needed for this topic.