Microtechnique: 2025-2026 Master Semester 1
Fundamentals of integrated photonic components

Assignment #7

Metallic antenna structures

Problem 1: CST Simulation of a THz Bow-tie Antenna (50 Points)

Consider a bow-tie antenna consisting of a thin gold film deposited on a silicon substrate, as illustrated in Fig. 1. You are required to implement this structure in CST Microwave Studio.

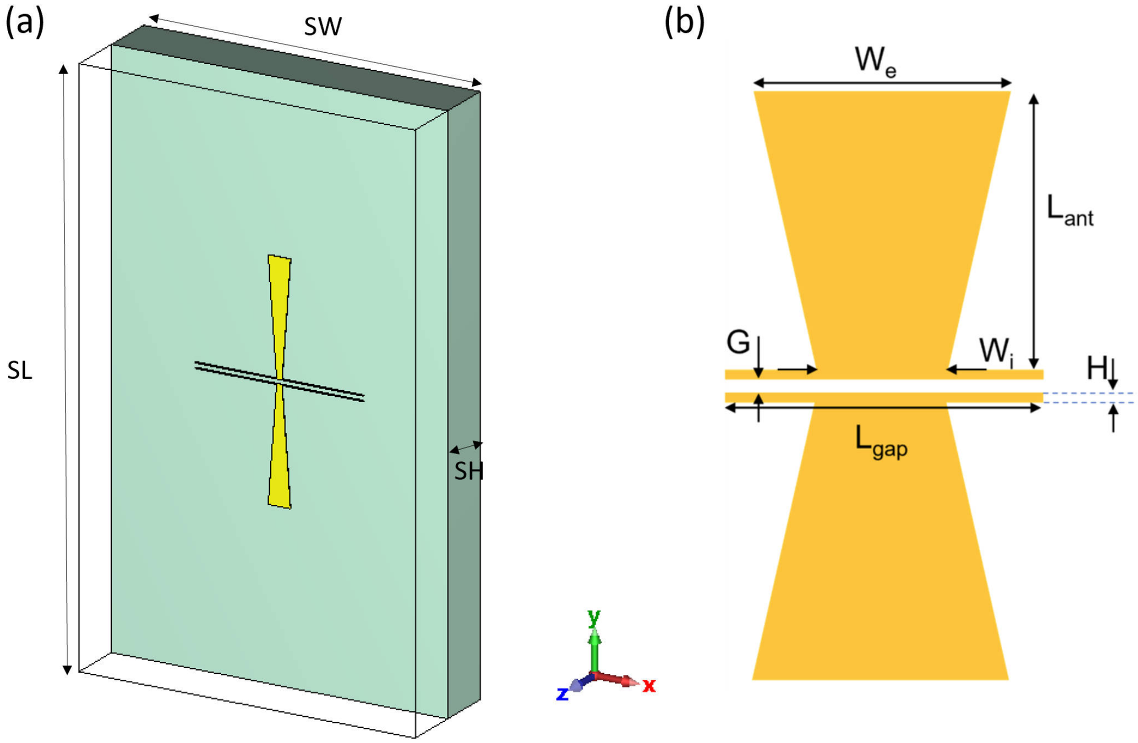


Figure 1: A schematic of a bow-tie antenna on CST

Modeling Instructions: To construct the 3D antenna geometry, refer to the CST manual on creating 3D structures by extruding 2D polygons. Please use the following initial geometric and simulation parameters:

- **Substrate (Silicon, loss free):** SH = 50 μm (Thickness), SL = 800 μm (Length), SW = 500 μm (Width).

- **Antenna (Gold):** $W_e = 50\ \mu m$ (External width), $W_i = 5\ \mu m$ (Internal width), $L_{ant} = 150\ \mu m$ (Single arm length), L_{gap} (Gap length, use the number in the question below accordingly), $G = 3.5\ \mu m$ (Feed line width/Internal gap width); $H = 2\ \mu m$.
- **Deposition:** $H_{pad} = 0.3\ \mu m$ (Gold film thickness).
- **Simulation Environment:** $H_{back} = 10\ \mu m$ (Vacuum background height), Frequency range: 0.01 − 2 THz.

Coordinate System Setup: Use the $z = 0$ plane (X0Y) as the interface reference. Define the substrate within $z \in [-SH, 0]$ and the gold film within $z \in [0, H_{pad}]$. Configure the CST model as follows:

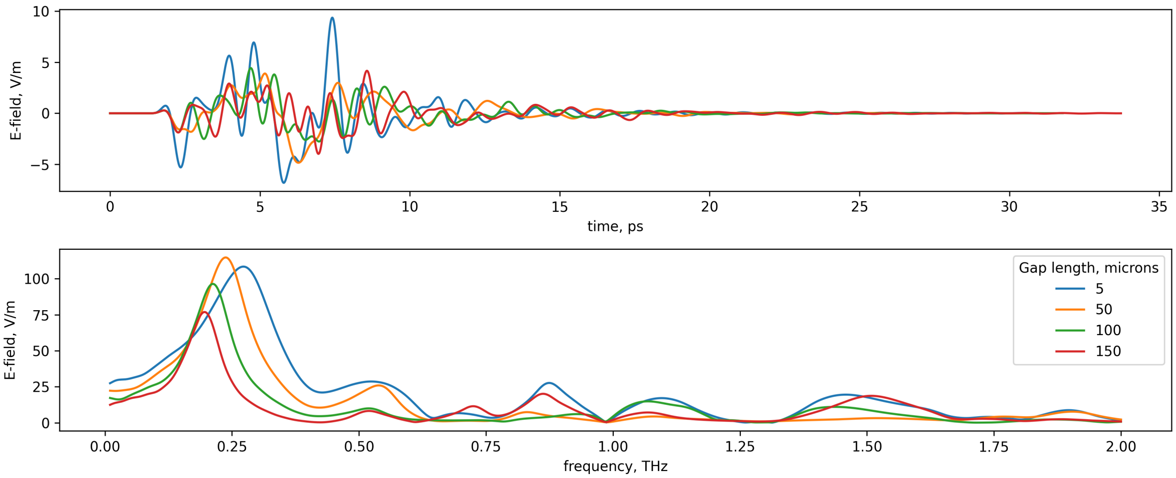
- **Boundary Conditions:** Set the boundaries along the z-axis to **Open (add space)** to provide sufficient distance for wave radiation and suppress non-physical reflections. For the x and y axes, configure the boundaries as **Open** to accurately simulate the transverse characteristics of the plane wave.
- **Background:** Set the "Upper Z distance" to H_{back}.
- **Excitation:** Define a "Plane Wave" source emitting a THz pulse propagating in the $-z$ direction (normal incidence). Set the electric field amplitude with Y-axis polarization.
- **Field Probe:** Place an E-field probe at the geometric center of the antenna gap at $z = H_{pad}/2$. Ensure it monitors all field components.
- **Field Monitors:** Set up E-field monitors from 0.1 THz to 2 THz with a step of 0.1 THz.
- **Mesh Settings:** Global Mesh Properties → Cells per wavelength: 10; Cells per max model box edge: 20.

Simulation Tasks (Accuracy: -60 dB):

1. **(15 point)** Perform a parameter sweep for L_{gap} values $\{5, 50, 100, 150\}\ \mu m$.
   - Plot the time-domain E_y signal and the corresponding frequency-domain spectra (linear scale) detected by the probe. **(10 pts)**
   - **Discussion:** Analyze the spectral trend as a function of L_{gap}. How does the peak frequency shift? Discuss the relationship between the resonance frequency and the antenna's geometric parameters. **(5 pts)**
2. **(10 Points)** Using $L_{gap} = 150\ \mu m$, generate 2D colormap plots of E_y on the XY plane at $z = 0.15\ \mu m$ for 0.2 THz and 1.5 THz (Use "Smart Scaling" for logarithmic visualization).
   - **Discussion:** Compare the field distribution within the gap for both frequencies. How many times does the field polarity flip within the gap? Explain the physical origin of this behavior. **(10 pts)**
3. **(15 Points)** Fix $L_{gap} = 5\ \mu m$ and sweep L_{ant} values $\{5, 50, 100, 150\}\ \mu m$.
   - Plot the time-domain E_y signal and the frequency spectra. **(10 pts)**
   - **Discussion:** How does the antenna length influence the spectral response? Characterize the resonance modes observed. **(5 pts)**

Solution 1 (Problem 1):

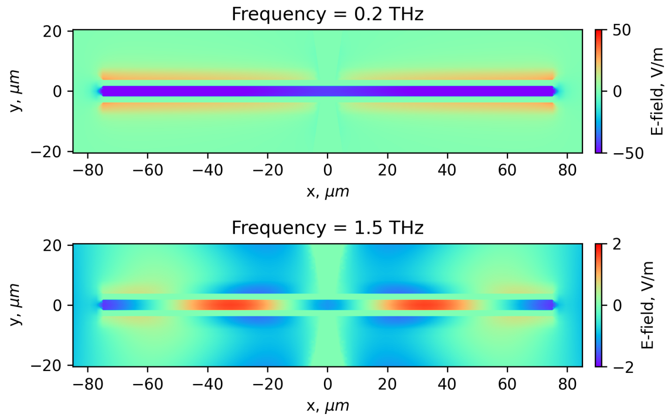
1.



As the gap length L_{gap} increases, the resonance frequency (peak frequency) shifts toward lower frequencies (redshift).

The resonance frequency is inversely proportional to the effective electrical length of the antenna. Increasing L_{gap} increases the overall spatial distribution of the structure, resulting in a longer resonant wavelength and thus a lower frequency. Additionally, a larger gap typically reduces the electric field coupling strength at the central feed point.

2.

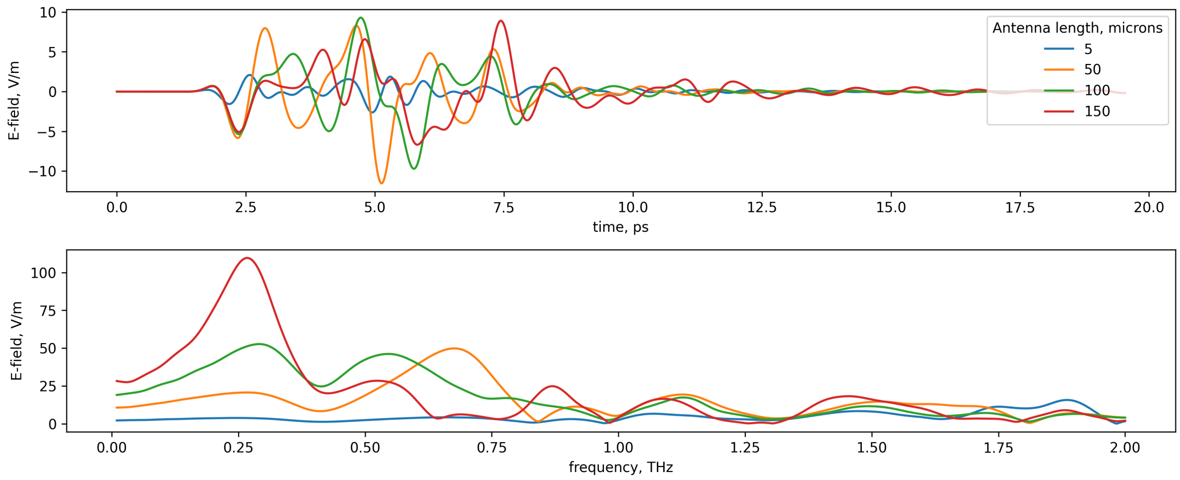


At 0.2 THz, the antenna operates in its fundamental mode, where the field distribution is relatively uniform along the arms without polarity inversion.

At 1.5 THz, because the operating wavelength becomes comparable to or smaller than the physical dimensions of the antenna, higher-order modes are excited. You will observe multiple polarity flips (phase inversions) of the electric field along the antenna arms.

This phenomenon is caused by the standing wave distribution. When the physical length is significantly larger than the wavelength, the antenna supports higher-order harmonic resonances rather than acting as a simple point source.

3.



As the antenna length increases (from 5 μm to 150 μm), the primary resonance peak in the frequency spectrum shifts toward lower frequencies (redshift).

For short antennas (e.g., 5 μm): These will exhibit a resonance at a very high frequency. For long antennas (e.g., 150 μm): Observed multiple resonant peaks. The lowest frequency peak corresponds to the fundamental mode ($\lambda/2$).Higher frequency peaks correspond to higher-order harmonic modes (e.g., $3\lambda/2$). This occurs because the antenna is now electrically large enough to support multiple standing wave patterns within the simulated frequency range.

Problem 2: Dipole Antenna Propagation and Hertzian Dipole Theory (50 Points)

In this problem, we simplify the bow-tie structure into a standard **dipole antenna** to investigate wave propagation in dielectric media and compare simulation results with the **Hertzian Dipole** model. Modify the model from Problem 1 by setting $W_e = 5\ \mu m$ and $L_{gap} = 5\ \mu m$ as shown in Fig. 2.

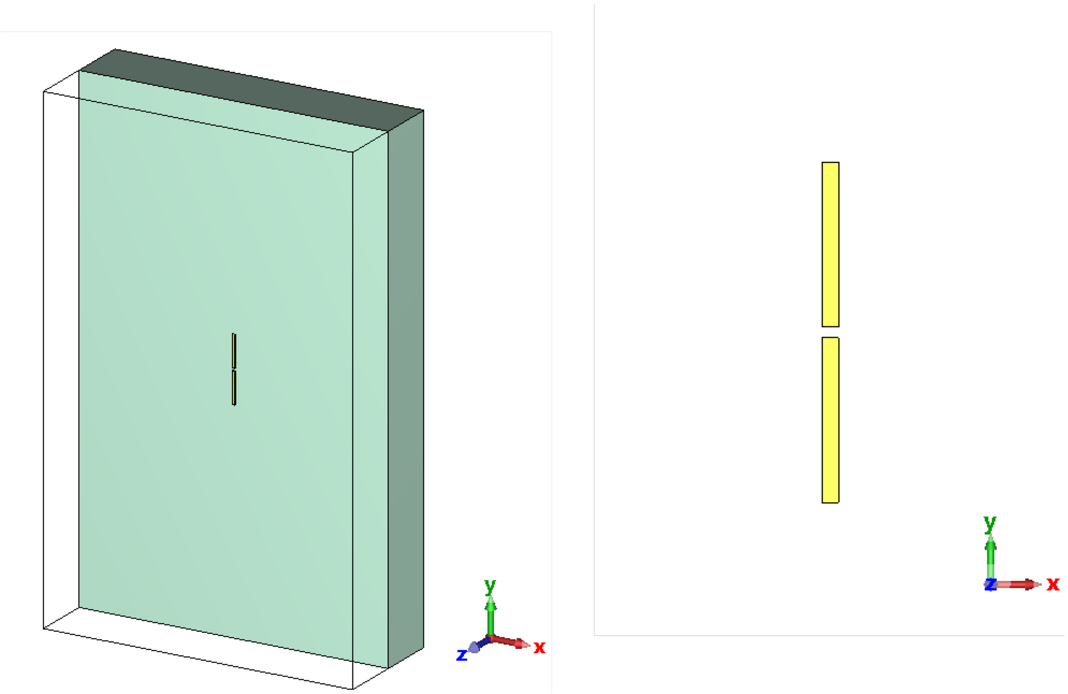


Figure 2: Schematic of the dipole antenna model for propagation and far-field analysis.

Model Adjustments: Instead of a Plane Wave, use a **Discrete Port** to excite the antenna locally.

- **Discrete Port Placement:** Position the port in the center of the antenna gap. According to the setup coordinates, the endpoints of the port should be set at $(0, 1.75, 0.3)$ and $(0, -1.75, 0.3)$ to bridge the internal gap of the antenna.
- **Substrate & Environment:**
  - SH = 100 μm (Silicon substrate thickness).
  - H_{back} = 100 μm (Vacuum height).
  - Boundaries should remain the same as Problem 1.
- **Far-field Monitor Placement:** To create the far-field pattern, click field monitor and choose the type **farfield/RCS**, input the frequency you need accordingly and click OK. After simulation, you can see the farfield results from the column **Farfields** below **2D/3D results**.

Simulation Tasks:

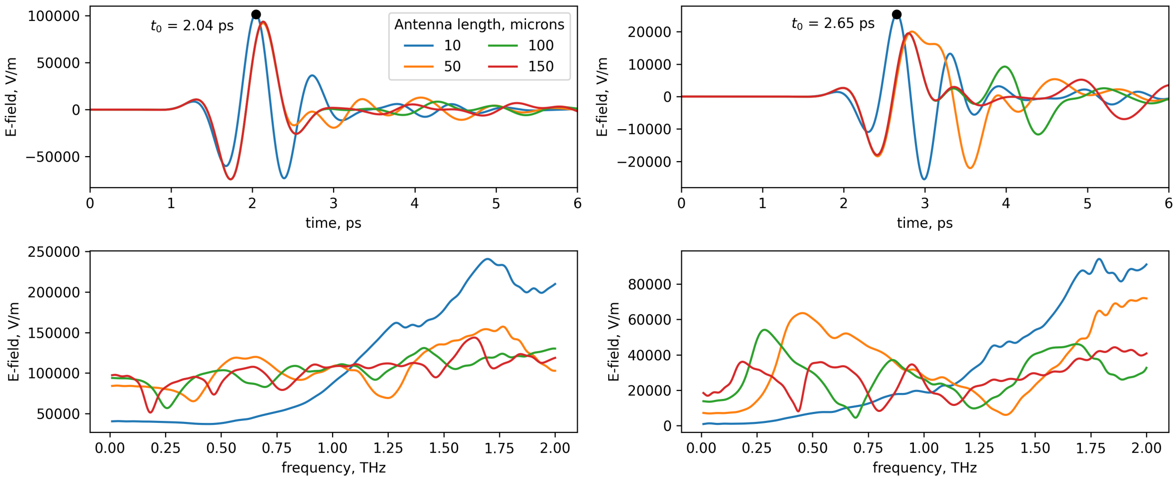
1. **(20 Points)** Sweep the antenna length $L_{ant} \in \{10, 50, 100, 150\}\ \mu m$.
   - Plot the E_y time-domain signals and frequency spectra for the four antenna length at Probe1 (0,0,-20) and Probe2 (0,0,-80). **(10 pts)**
   - **Discussion:** Calculate the time delay between the probes at $z = -20$ and $z = -80\ \mu m$. Use this to estimate the speed of light and refractive index in the silicon substrate. How does the amplitude decay correlate with the distance? **(10 pts)**
2. **(15 Points)** Focus on the case where $L_{ant} = 10\ \mu m$ (Total length $L = 27.5\ \mu m$).

- At 0.1 THz, the wavelength in free space is $\lambda_0 = 3000\ \mu m$. Does this antenna satisfy the condition for a **Hertzian Dipole** and why? **(5 pts)**
- Generate the 1D polar far-field plot (E-plane, $\phi = 90°$) at 0.1 THz. Describe the radiation pattern and explain how its shape relates to the theoretical model of an electrically small dipole. **(10 pts)**

3. **(15 Points)** Select the case $\mathrm{L_{ant}} = 300\ \mu m$ (Total length $L \approx 600\ \mu m$).
   - Plot the far-field patterns at 0.5 THz, 1.0 THz, 1.3 THz and 1.9 THz. **(10 pts)**
   - **Discussion:** As the frequency increases, describe the transition of the radiation pattern change. Explain this phenomenon in terms of the current phase reversal along the antenna arms when the physical length exceeds the operating wavelength. **(5 pts)**

Solution 2 (Problem 2):

1.



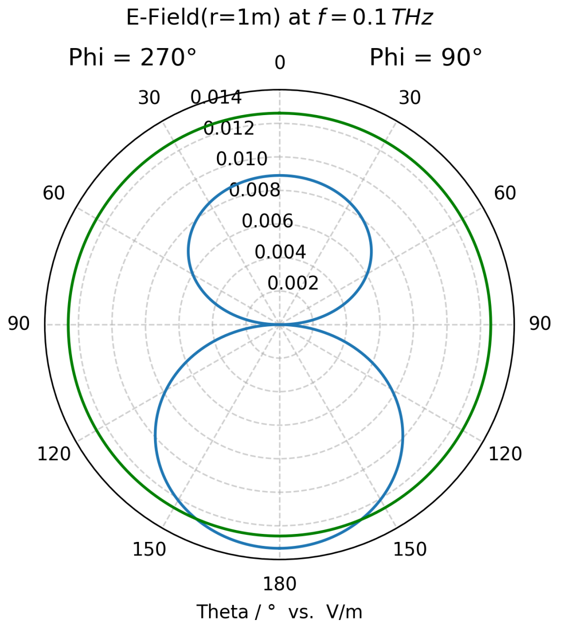
Based on the time-domain plots provided:The pulse peak at $z = -20\ \mu$m arrives at $t_1 = 2.04$ ps.The pulse peak at $z = -80\ \mu$m arrives at $t_2 = 2.65$ ps. The time delay is $\Delta t = 0.61$ ps over a distance of $\Delta z = 60\ \mu$m.

The estimated propagation speed is:

$$v = \frac{60\ \mu\text{m}}{0.61\ \text{ps}} \approx 9.84 \times 10^7\ \text{m/s}$$

As observed in the plots, the peak amplitude drops significantly (from $\sim 100\,$kV/m to $\sim 20\,$kV/m) as the wave propagates to $-80\ \mu$m. This confirms the wave is diverging (spherical spreading) and experiencing absorption losses within the substrate.

2.



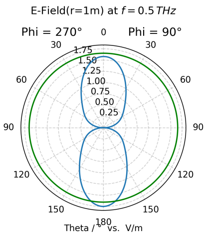
Calculating the electrical length ratio:

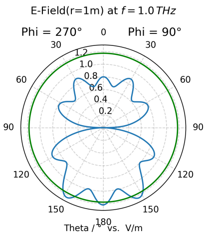
$$\frac{L}{\lambda_0} = \frac{27.5}{3000} \approx 0.0092$$

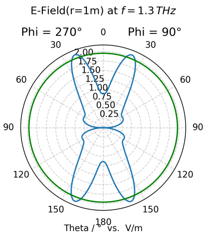
Since $0.0092 \ll 0.1$, the antenna satisfies the condition for a hertzian dipole.

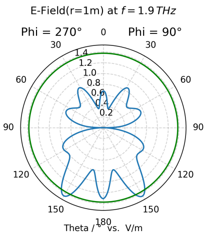
The generated 1D polar plot exhibits a classic ”figure-8” shape. This shape directly corresponds to the theoretical model of an electrically small dipole. The far-field radiation intensity is proportional to $\sin^2(\theta)$, which produces the characteristic two-lobed, symmetric pattern observed in the simulation. The asymmentry may caused by the substrate.

3.









At 0.5 THz, the antenna operates near its fundamental mode. The radiation pattern exhibits a classic dipole-like shape with two primary lobes directed along the Z-axis (0° and 180°).

At 1.0 THz, we observe the main lobes beginning to narrow (”pinching”), and small side lobes begin to emerge, indicating the onset of higher-order mode excitation.

At 1.3 THz, a distinct pattern splitting occurs. The single main lobe has completely split into multiple side lobes (forming a ”butterfly” or ”flower” shape).

At 1.9 THz, the pattern is dominated by four distinct lobes at oblique angles, with nulls or reduced radiation appearing where the main lobes previously existed.

This phenomenon occurs because the antenna has become electrically large. The physical length of the antenna significantly exceeds the operating wavelength λ at these higher frequencies. When $L > \lambda$, the current distribution along the antenna arms is no longer uniform in phase. Instead, the current forms a standing wave pattern that undergoes a phase reversal every half-wavelength along the wire. These alternating sections of current act like an array of point sources radiating with opposite phases. In the far field, the radiation from these sections interferes destructively in the broadside direction and constructively in oblique directions, causing the main beam to split into multiple lobes (harmonic modes).