Two-dimensional Plasmonic Devices

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Outline

Preliminary Exam

- Plasmonics Overview
- Background
- Theory and Methods
  - Dispersion Relation
  - Surface Integral equation
- Results
- Proposed Work

Plasmonics Overview

- Interaction of electromagnetic (EM) waves with surfaces
- Surface plasmon waves
- Two-dimensional materials
- Miniaturization of circuit and antenna devices
- Terahertz gap
- Poor energy efficiencies

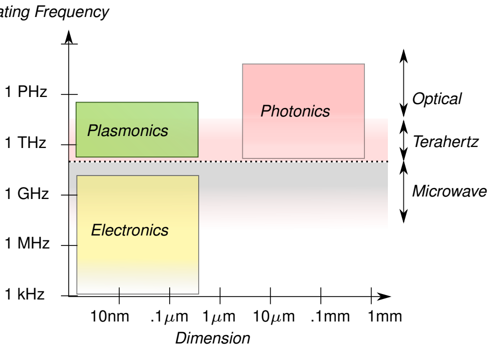


Figure: Communication Technologies at various frequencies

Background

Surface Plasmons

- Metal-dielectric interface

$$\mathrm{Re}\left[\varepsilon_{metal}\right](\omega) < 0$$

- Slow surface waves
- Subwavelength Control of electromagnetic waves
- Focusing beyond the diffraction limit

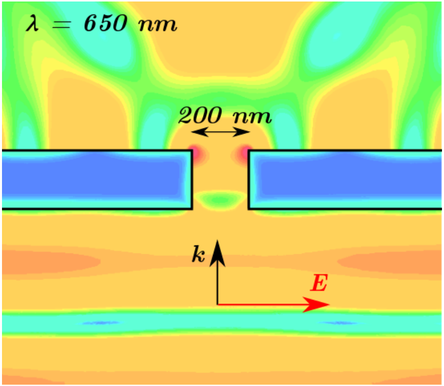


Figure: Subwavelength Transmission through a Silver slit

Background

Optical Nanoantennas

- Convert Localized near-field to efficient far-field radiation
- Low Q-factor
- Extremely small size
- High Purcell Factor

$$P = \frac{Q}{V}$$

- Directive radiation

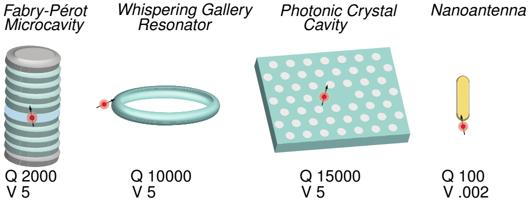
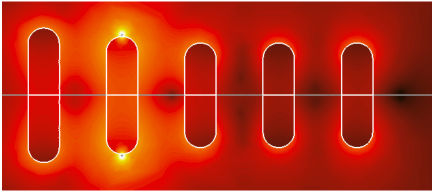


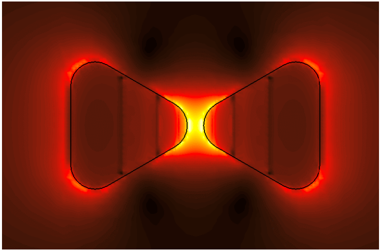
Figure: Optical resonant cavities for electric field enhancement

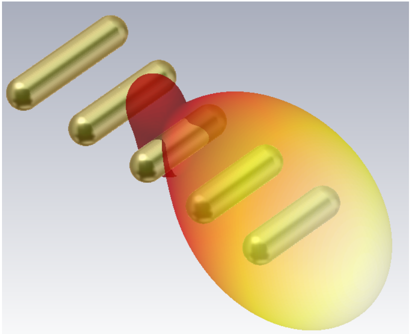
Background

Optical Nanoantennas (contd.)

- Scaled-down microwave designs
  - Directivity: Yagi-Uda antenna
  - Broadband: Bowtie antenna







Background

Optical Nanoantennas

- Metal-dielectric Interface

$$k_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_1 \varepsilon_2(\omega)}{\varepsilon_1 + \varepsilon_2(\omega)}}$$

- Accurate material description using Drude-critical points

$$\varepsilon_2(\omega) = \varepsilon_\infty - \frac{\omega_d^2}{\omega^2 + j\gamma\omega} + \sum_{i=1}^{N} G_i(\omega)$$

$$G_i(\omega) = C_i \left[\frac{e^{j\phi_i}}{\omega_i - \omega - j\Gamma_i} + \frac{e^{-j\phi_i}}{\omega_i + \omega + j\Gamma_i} \right]$$

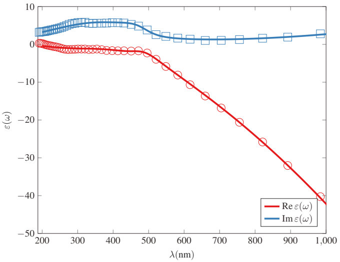
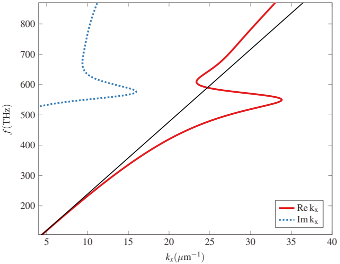


Figure: Dispesion curve for Gold-air SPPs



Background

Two-dimensional Electon Gas (2DEG)

- Semiconductor Heterostructure Interface
- High concentration of free electrons
- **Two-dimensional Surface waves**
- Formation of Quantum Well

  Two-dimensional confinement of electrons

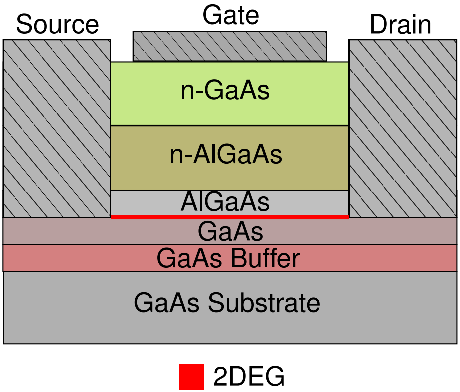
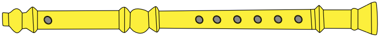


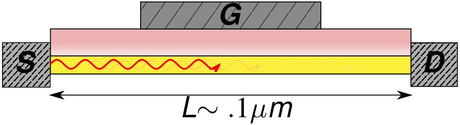
Figure: Typical GaAs/AlGaAs HEMT

Background

2DEG (contd.)

- Plasma waves in 2DEG
- Dyakonov-Shur instability
  - Voltage bias at source and drain terminals
  - Plasma resonance
  - Emission of terahertz radiation
  - External radiation detection
- *Electronic Flute*
- Tunable resonance with gate voltage
- Shallow water waves
  - Surface waves





$$\lambda = \frac{c}{f}$$

$$\implies 300\mu\text{m}$$

Theory

2DEG formation

- Interface of two slightly different semiconductors/insulators
- High electron concentration ($\sim 10^{12} - 10^{14} cm^{-2}$)
- Triangular quantum well
  - Entrapment of electrons in transverse direction
  - Free lateral movement

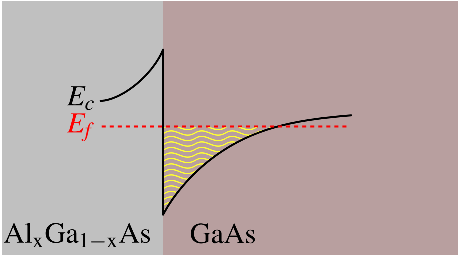


Figure: Band diagram of a GaAs/AlGaAs heterostructure

E_c - Conduction band edge

E_f - Fermi level

Theory

2DEG Dispersion Relation

- TE mode

$$k_{z1} + k_{z2} = \omega\sigma_s(\omega)$$

No real solutions for an isotropic environment

- TM mode

$$\boxed{\frac{\varepsilon_1(\omega)}{k_{z1}} + \frac{\varepsilon_2(\omega)}{k_{z2}} = -\frac{\sigma_s(\omega)}{\omega}}$$

Real solution(s). Surface waves exist.

$$k_{zi} = \sqrt{\left(\frac{\omega}{c}\right)^2 \varepsilon_i(\omega) - k_x^2}$$

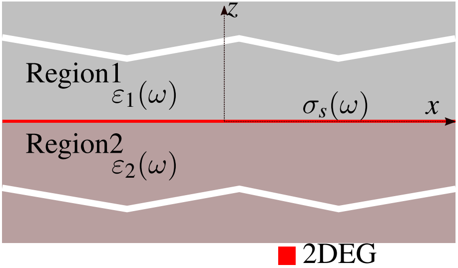


Figure: 2DEG at a semiconductor heterojunction

Theory

Material Description

- Complex valued
- Drude-Lorentz oscillator model

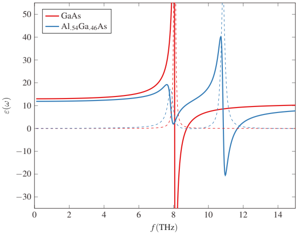
$$\varepsilon(\omega) = \varepsilon^{\infty} + \prod_{i} \frac{\omega_{li}^2 - \omega^2 - j\gamma_{li}\omega}{\omega_{ti}^2 - \omega^2 - j\gamma_{ti}\omega}$$

ε^{∞}- High-frequency limit

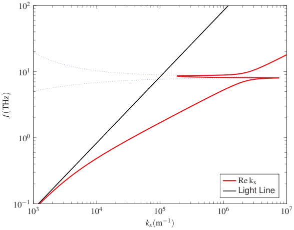
ω_{ti}- TO phonon frequencies

ω_{li}- LO phonon frequencies

γ - Damping constants



(a)



(b) Dispersion curve

Theory

Thin Sheet Simulation

- Volume Integral formulation

$$\mathbf{A} = \frac{\mu}{4\pi} \int_V \mathbf{J}_v(\mathbf{r}') \frac{e^{-jk_1|\mathbf{r}-\mathbf{r}'|}}{|\mathbf{r}-\mathbf{r}'|}\, \mathrm{d}v'$$

$$\mathbf{E}_1^{scat} = -\frac{j\omega}{k_1^2}\left(k_1^2 + \nabla\nabla\cdot\right)\mathbf{A}$$

$$\mathbf{J}_v = \frac{-jk_1}{Z_0}(\varepsilon_2 - 1)\mathbf{E}_2$$

- Surface current J_s approximated from J_v

- Impedance (Leontovich) Boundary Conditions

$$\mathbf{E}_{tan} = \eta Z_0 \hat{\mathbf{n}} \times \mathbf{H}$$

$$E^i = \eta Z_0 J_s(x') + \frac{\omega\mu}{4} \int_l J_s(x') H_0^{(2)}(k_2|x - x'|)\, \mathrm{d}x'$$

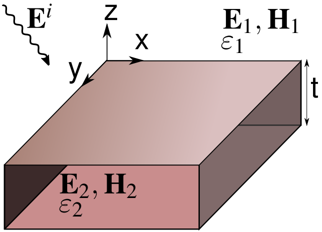


Figure: Dielectric Slab geometry

Proposed Scheme

Surface Integral Equation

- Surface Equivalence Theorem

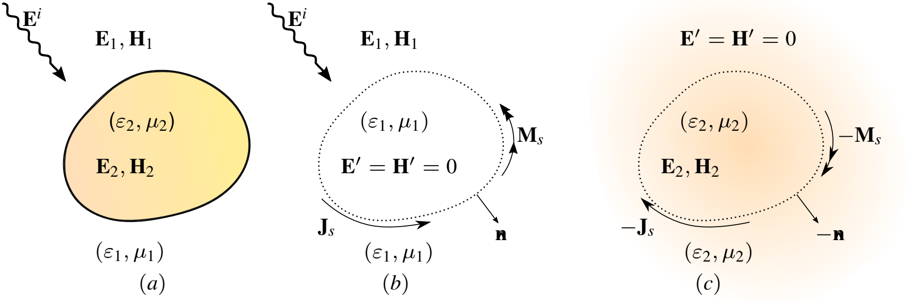


Figure: (a). Actual and its equivalent models for the (b) external and, (c) Internal region

Proposed Scheme

Surface Integral Equation

- Exterior Region

$$\begin{aligned}
\mathbf{E}_1 &= \mathbf{E}_i + \mathbf{E}_1^{scat} \\
&= -\frac{\omega}{4k_1^2}\left(k_1^2 + \nabla\nabla\cdot\right)\int_C \mathbf{J}_s(\mathbf{p}')H_0^{(2)}(k_1|\rho-\rho'|)\,\mathrm{d}l' \\
&\quad - \frac{1}{4\varepsilon j}\nabla\times\int_l \mathbf{M}_s(\rho')H_0^{(2)}(k_1|\rho-\rho'|)\,\mathrm{d}l' + \mathbf{E}_i
\end{aligned}$$

$$\begin{aligned}
\mathbf{H}_1 &= \mathbf{H}_i + \mathbf{H}_1^{scat} \\
&= \frac{1}{4j}\nabla\times\int_l \mathbf{J}_s(\rho')H_0^{(2)}(k_1|\rho-\rho'|)\,\mathrm{d}l' \\
&\quad - \frac{\omega}{4k_1^2}\left(k_1^2 + \nabla\nabla\cdot\right)\int_l \mathbf{M}_s(\rho')H_0^{(2)}(k_1|\rho-\rho'|)\,\mathrm{d}l' + \mathbf{H}_i
\end{aligned}$$

Proposed Scheme

Surface Integral Equation

- Interior Region

$$
\begin{aligned}
\mathbf{E}_2 &= \mathbf{E}_2^{scat} \\
&= -\frac{\omega}{4k_2^2}\left(k_2^2 + \nabla\nabla\cdot\right)\int_C \left(-\mathbf{J}_s(\mathbf{p}')\right) H_0^{(2)}(k_2|\rho-\rho'|)\,\mathrm{d}l' \\
&\quad - \frac{1}{4j}\nabla\times\int_l \left(-\mathbf{M}_s(\rho')\right) H_0^{(2)}(k_2|\rho-\rho'|)\,\mathrm{d}l' \\
\mathbf{H}_2 &= \mathbf{H}_1^{scat} \\
&= \frac{1}{4j}\nabla\times\int_l \left(-\mathbf{J}_s(\rho')\right) H_0^{(2)}(k_2|\rho-\rho'|)\,\mathrm{d}l' \\
&\quad - \frac{\omega}{4k_2^2}\left(k_2^2 + \nabla\nabla\cdot\right)\int_l \left(-\mathbf{M}_s(\rho')\right) H_0^{(2)}(k_2|\rho-\rho'|)\,\mathrm{d}l'
\end{aligned}
$$

Proposed Scheme

Thin Flat Sheet TM_z

$$\hat{\mathbf{n}} \times (\mathbf{E}_1 - \mathbf{E}_2) = \mathbf{0}$$

$$E_i = \frac{\omega}{4} \int_L J_z(x') \left[H_0^{(2)}(k_1|x - x'|) + H_0^{(2)}(k_2|x - x'|) \right] \mathrm{d}x'$$

$$\hat{\mathbf{n}} \times (\mathbf{H}_1 - \mathbf{H}_2) = \mathbf{0}$$

$$H_i^{tan} = \frac{-j\omega}{2} \int_L M_x(x') \left[\varepsilon_1 H_0^{(2)}(k_1|x - x'|) + \varepsilon_1 H_2^{(2)}(k_1|x - x'|) \right.$$

$$\left. + \varepsilon_2 H_0^{(2)}(k_2|x - x'|) + \varepsilon_2 H_2^{(2)}(k_2|x - x'|) \right] \mathrm{d}x'$$

Proposed Scheme

Method of moments

- Integral equations to system of linear equations

$$\begin{bmatrix} Z_{mn} & 0 \\ 0 & Y_{mn} \end{bmatrix} \begin{bmatrix} J_n \\ M_n \end{bmatrix} = \begin{bmatrix} E_m^i \\ H_m^i \end{bmatrix}$$

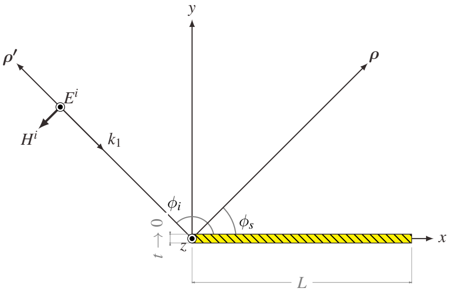
- Pulse basis functions and Point matching used
- Far-field

$$RCS(\phi) \simeq \int_0^L \left[J_z(x')\eta_1 + M_x(x') \sin(\phi_i) \right] e^{jk_1 x' \cos(\phi_i)} \mathrm{d}x'$$

Results

Thin Sheet Simulation (TM_z)

- TM_z polarization
- Dielectric Rod of length 2.5 λ
- $\varepsilon = 4$, $\mu = 1$



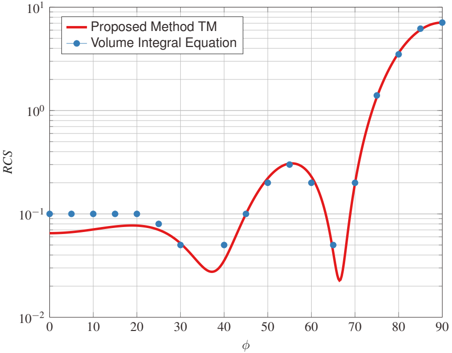


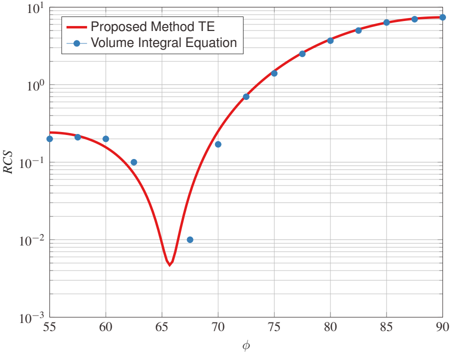
Figure: Radar Cross-section

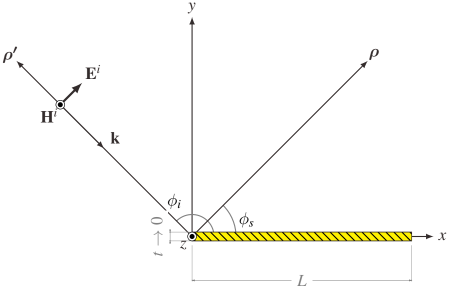
- Thickness of $.05\lambda$ assumed in Volume Integral equation model

Results

Thin Sheet Simulation (TE_z)

- TE_z polarization
- Dielectric Rod of length 2.5 λ
- $\varepsilon = 4$, $\mu = 1$



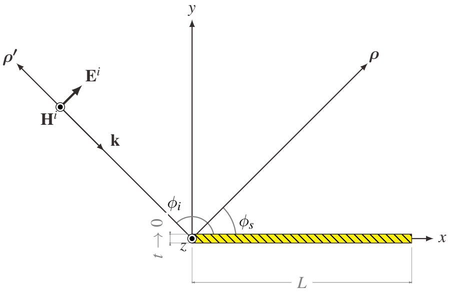


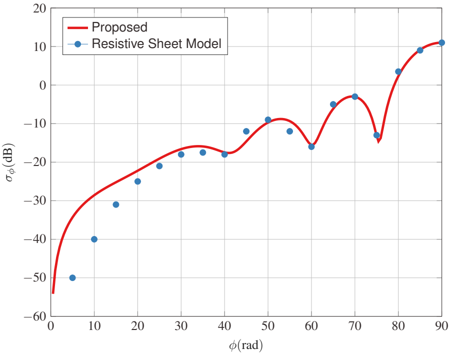
- Thickness of $.05\lambda$ assumed in Volume Integral equation model

Results

Thin Sheet Simulation (TE_z)

- TE_z polarization
- Dielectric Rod of length 2 λ
- $\varepsilon = 4$, $\mu = 1$





- Thickness of $.628/k_1$ assumed in resistive model

Field Computation

Integral Equations

- Difficulty in simulation of thin objects
- Dense mesh
- Computationally expensive
- No guarantee of correct solution

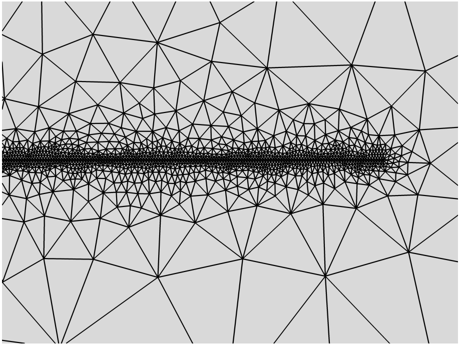
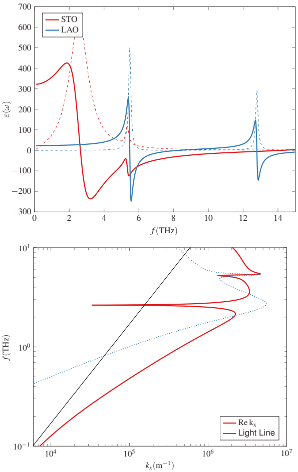


Figure: Typical mesh for a dielectric plate of thickness $.05\mu m$

Future Work

Use of oxide-based 2DEGs

- Perovskite oxides
- Higher electron concentration ($\sim 10^{14} cm^{-2}$)
- Higher wave confinement



(b) Dispersion curve

Future Work

Remove metal gate

- Metal gate with grating assists in radiation
- Simultaneously acts as reflector
- Re-engineering of the heterostructure

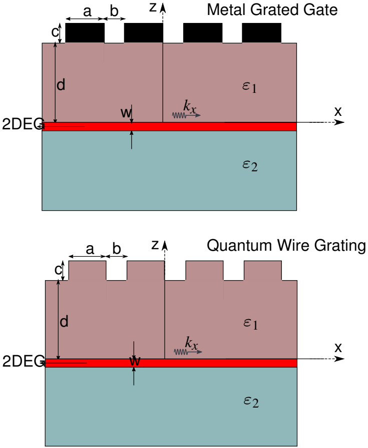
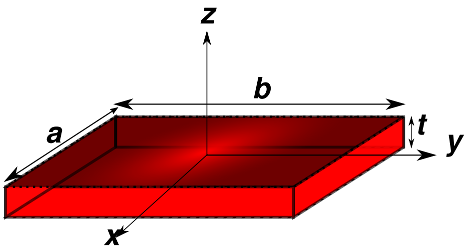


Figure: 2DEG System (a) Metal Gate (b) Quantum Wire

Future Work

3D Computation of fields

- Incorporate lateral effects
- Model 2DEG as a plate
- Investigate effects of finite thickness



Future Work

3D Computation of fields

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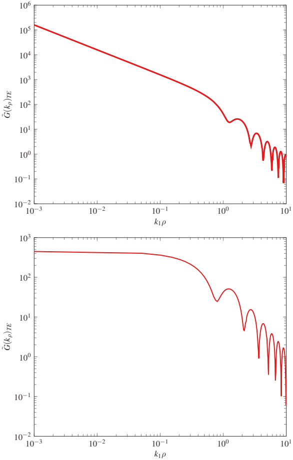

Figure: Sommerfeld integrals for Green function for a horizontal dipole. (a) Horizontal (TE) (b) Vertical Component (TM)

Summary

Two-dimensional plasmonic devices

- Plasmonic waves exist in the semiconductor heterostructures
- Instability leads to radiation in terahertz frequency regime
- 2D nature of waves permits subwavelength confinement
- Surface wave propagation
- Surface integral equation for thin sheets

Acknowledgements

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- The Fulbright Program

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Thank you!

Questions?