Two-dimensional Plasmonic Devices

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Outline

Preliminary Exam

- Plasmonics Overview
- Background
- Theory and Methods
  - Dispersion Relation
  - Computation of fields
- Results
- Proposed Work

Plasmonics Overview

- Utilizing the terahertz gap
- High electron mobility transistors (HEMTs)
- Two-dimensional materials
- Subwavelength Plasmonic waves
- Miniaturization of circuit and antenna devices
- Poor energy efficiencies
- Re-engineering of the transistor

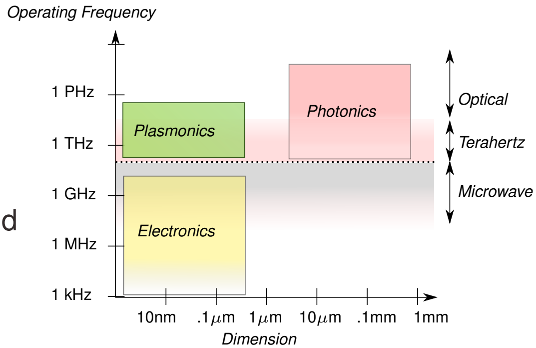


Figure: Typical GaAs/AlGaAs HEMT

Backrgound and Previous Work

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

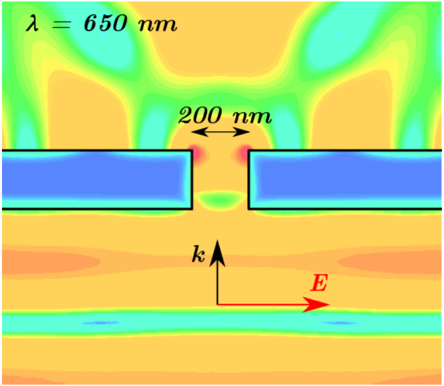


Figure: Subwavelength Transmission through a Silver slit

Optical Nanoantennas

Dispersion Relation

- 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

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

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

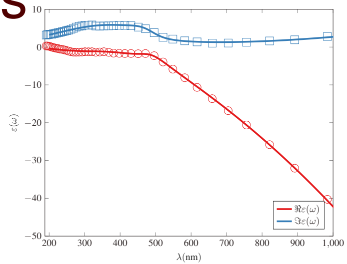
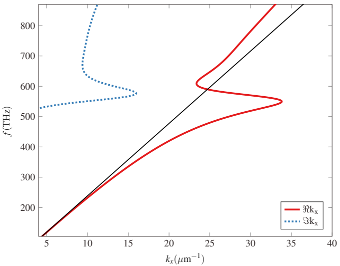


Figure: Dispesion curve for Gold-air SPPs



Backrgound and Previous Work

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

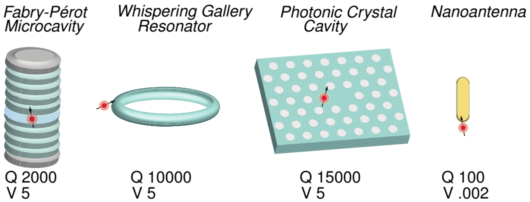
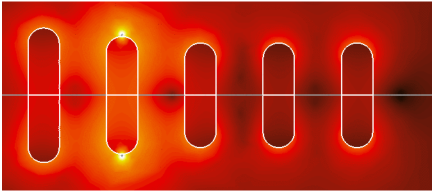


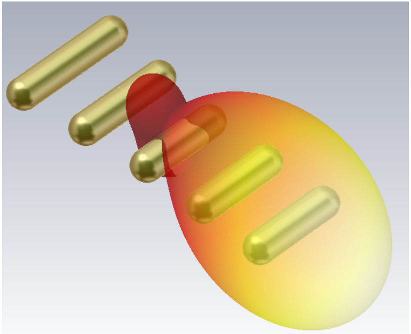
Figure: Optical resonant cavities for electric field enhancement

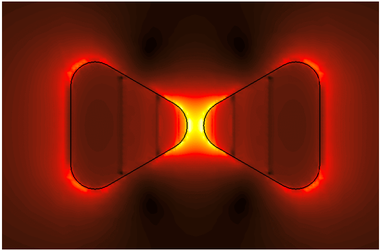
Backrgound and Previous Work

Optical Nanoantennas (contd.)

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







Backrgound and Previous Work

Two-dimensional Electon Gas (2DEG)

- Semiconductor Heterostructure Interface
- High electron Mobility
- High concentration of electric charge
- **Two-dimensional Surface waves**
- Formation of Quantum Well

  Two-dimensional confinement of electrons

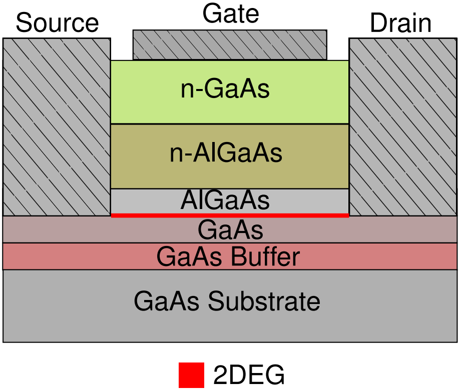
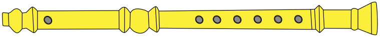


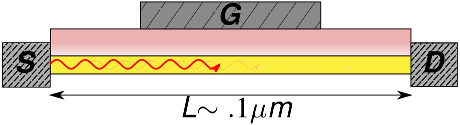
Figure: Typical GaAs/AlGaAs HEMT

Backrgound and Previous Work

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

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

  Two-dimensional confinement of electrons

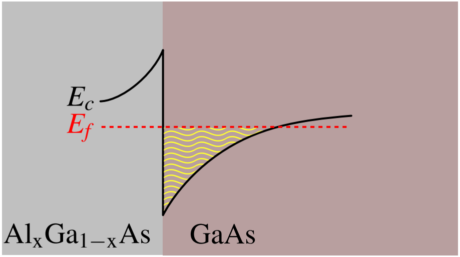


Figure: Band diagram of a GaAs/AlGaAs heterostructure

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.

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

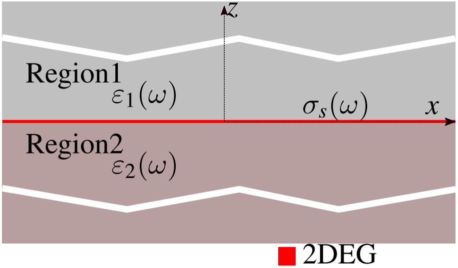


Figure: 2DEG at a semiconductor heterojunction

Theory

Material Description

- Complex valued
- Drude-Lorentz oscillator model

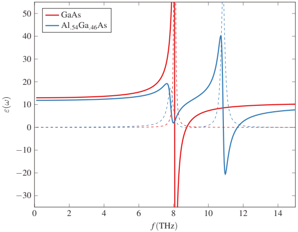
$$\varepsilon(\omega) = \varepsilon^{\infty} + \prod_i \frac{\omega_{li}^2 - \omega^2 - j\gamma_{li}\omega}{\omega_{ti}^2 - \omega^2 - j\gamma_{ti}\omega}$$

ε^{∞}- High-frequency limit

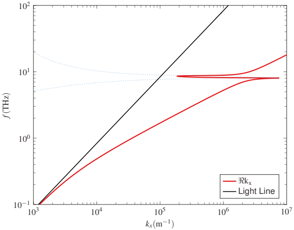
ω_{ti}- TO phonon frequencies

ω_{li}- LO phonon frequencies

γ - Damping constants



(a)



(b) Dispersion curve

Theory

Thin Sheet Simulation

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

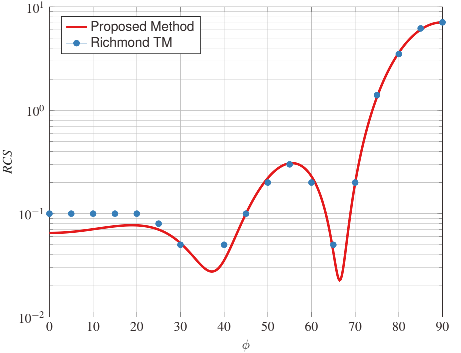
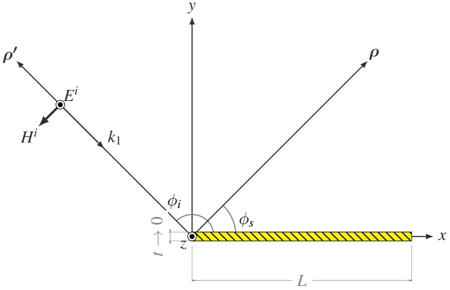


Figure: Radar Cross-section



Theory

Thin Sheet Simulation

- TE_z polarization
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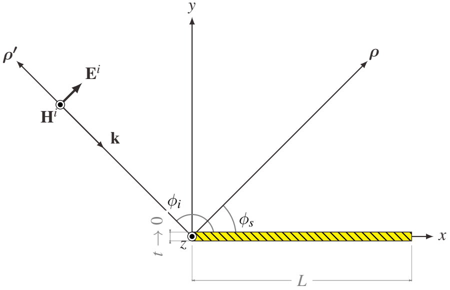

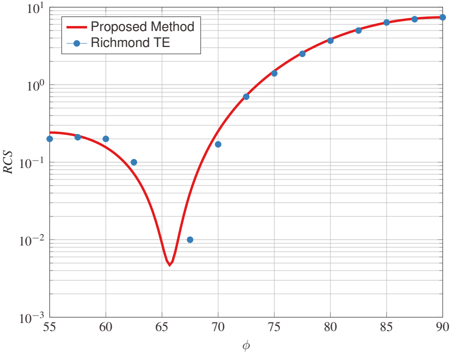

Figure: Radar Cross-section