Surface wave supporting structures in the terahertz and optical frequency domains

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Outline

- Plasmonics Overview
- Background
- Theory and Methods
  - Sommerfeld Integral analysis
  - Dispersion relation
  - Surface Integral equation
- Results
- Conclusions

Plasmonics Overview

- Interaction of electromagnetic (EM) waves with free electrons
- Subwavelength localization of EM fields
- Plasma frequency
  - Metals - Optical frequency
  - Semiconductors - Terahertz
- Low efficiency

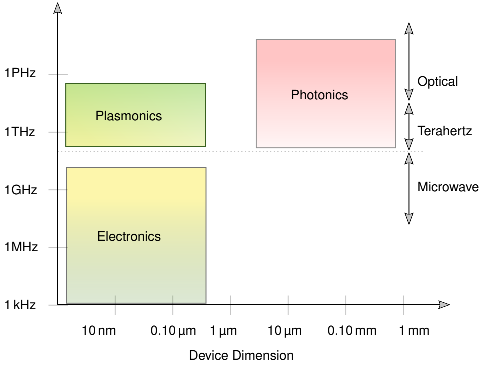


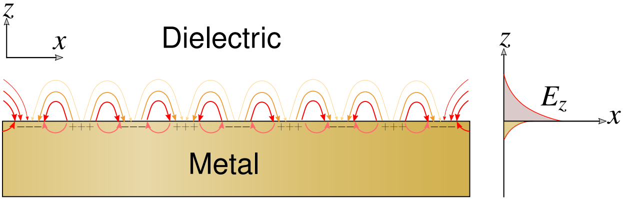
Figure: Communication Technologies at various frequencies

Plasmonics Overview

- Metal-dielectric interface
- Surface plasmon polaritons (SPPs)

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

- Plasma frequency
  - Metals - Optical frequency
  - Semiconductors - Terahertz
- Low efficiency



Background

Surface Plasmons

- Metal-dielectric interface
- Surface plasmon polaritons (SPPs)
- Slow surface waves
  - Wavelength
  - Semiconductors - Terahertz
- Low efficiency
- Metal-dielectric interface
- Slow surface waves
- Subwavelength Control of electromagnetic waves
- Focusing beyond the

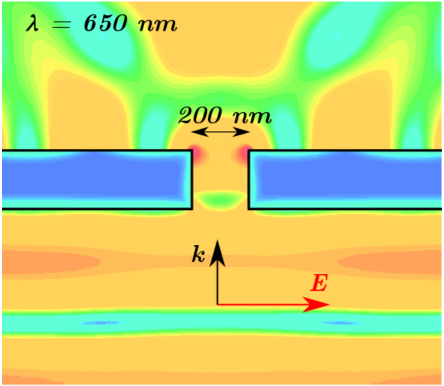


Figure: Subwavelength Transmission through a Silver slit

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

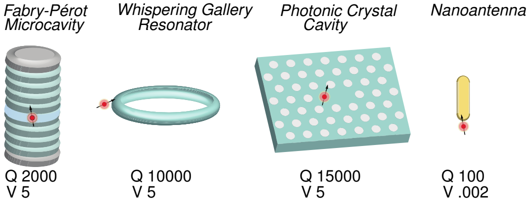
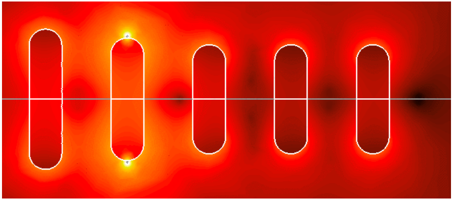


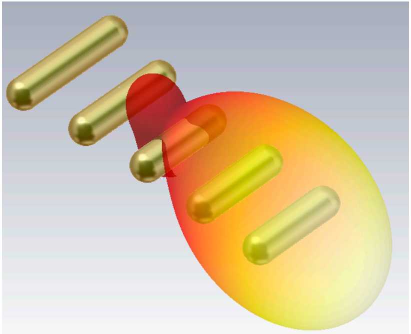
Figure: Optical resonant cavities for electric field enhancement

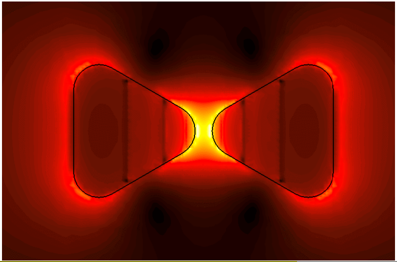
Background

Optical Nanoantennas (contd.)

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





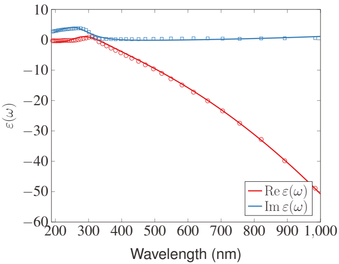


Background

Optical Nanoantennas

- Metal-dielectric Interface

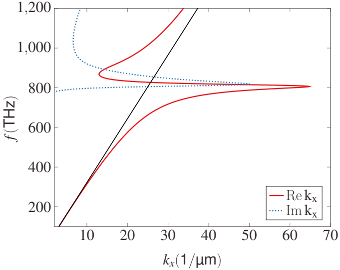
$$k_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_1\varepsilon_2(\omega)}{\varepsilon_1+\varepsilon_2(\omega)}}$$



- Accurate material description using Drude-critical points

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

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



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

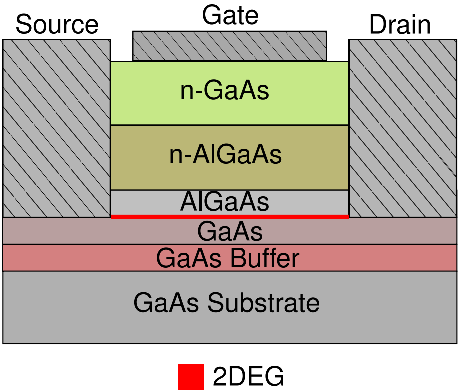
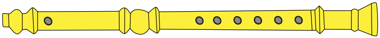


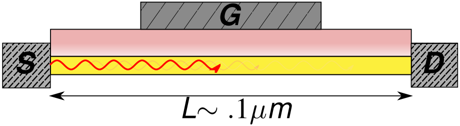
Figure: Typical GaAs/AlGaAs HEMT

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

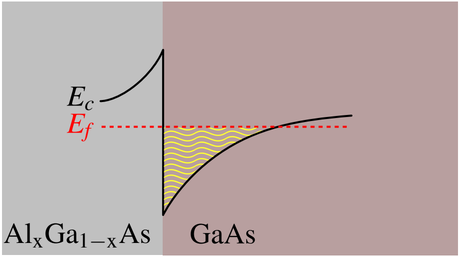


Figure: Band diagram of a GaAs/AlGaAs heterostructure

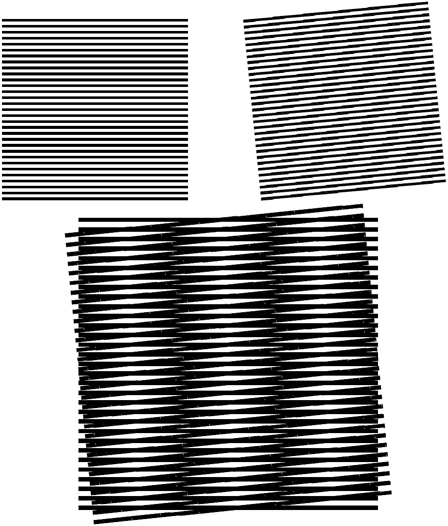
E_c - Conduction band edge

E_f - Fermi level

Nanoscale Imaging scheme

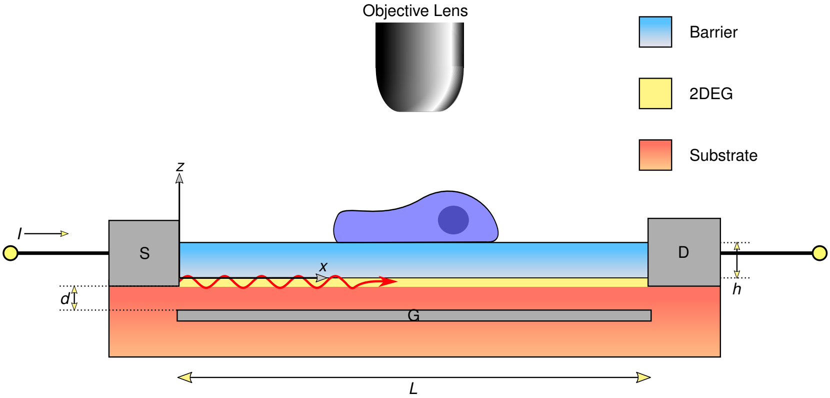
Basics

- Structured Illumination
  - Periodic sine pattern
- Moiré Fringes
  - Frequency modulation of two patterns
  - Resulting low-frequency signal
- Linear scheme
  - Low light intensity



Nanoscale Imaging scheme

Setup



Nanoscale Imaging scheme

Working Principle

- Illumination signal

$$I(\mathbf{r}) = 1 + \cos(\mathbf{k}_\rho \cdot \mathbf{r} + \phi)$$

- Observed Image (Spatial domain)

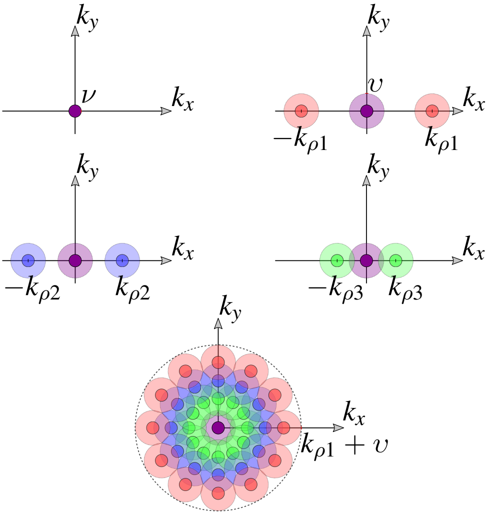
$$M(\mathbf{r}) = [F(\mathbf{r}) \cdot I(\mathbf{r})] \otimes H(\mathbf{r})$$

- Fourier transformed Image

$$\begin{aligned}\tilde{M}(\mathbf{k}) &= \left[\tilde{F}(\mathbf{k}) \otimes \tilde{I}(\mathbf{k})\right] \cdot \tilde{H}(\mathbf{k}) \\ &= \frac{1}{2}\left[2\tilde{F}(\mathbf{k}) + \tilde{F}(\mathbf{k} - \mathbf{k}_\rho)\mathrm{e}^{-\mathrm{j}\phi} + \tilde{F}(\mathbf{k} + \mathbf{k}_\rho)\mathrm{e}^{\mathrm{j}\phi}\right] \cdot \tilde{H}(\mathbf{k})\end{aligned}$$

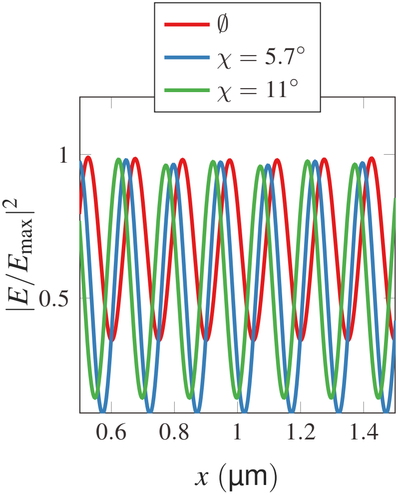
Nanoscale Imaging scheme

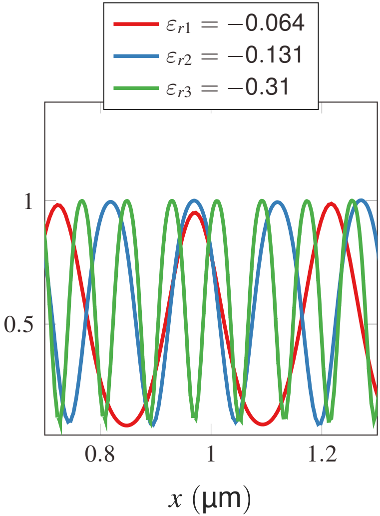
Image Reconstruction



Nanoscale Imaging scheme

Image Reconstruction





Nanoscale Imaging scheme

Results

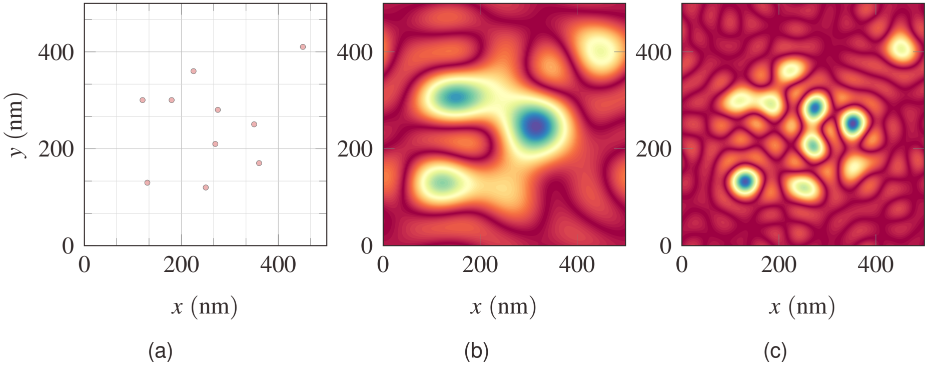


Figure: (a) Sample distribution. Simulation of the reconstructed sample image at: (b) $\mathrm{Re}\, k_\rho = 39.5$ (c) $\mathrm{Re}\, k_\rho = 80$

Summary

Two-dimensional plasmonic devices

- Subwavelength wave phenomena at optical and terahertz frequencies
- Realization of terahertz sources and sensors
- 2D nature of waves permits subwavelength confinement
- Plasmonic activity
- Nanoscale imaging using terahertz plasma waves

Acknowledgements

Sponsorship

- The Fulbright Program

Thank you!

Questions?