Surface wave supporting structures in the terahertz and optical frequency domains

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Outline

- Overview
- Background
- Theory and Methods
  - Sommerfeld Integral analysis
  - Dispersion relation
  - Surface Integral equation
- Results
  - Super-resolution Imaging
- Conclusions

Overview

- Plasmonics: subwavelength localization of electromagnetic (EM) fields
- Plasma frequency
  - Metals - Optical frequency
  - 2D Electronic Systems (2DES) - Terahertz (THz)
- Bridging the THz gap

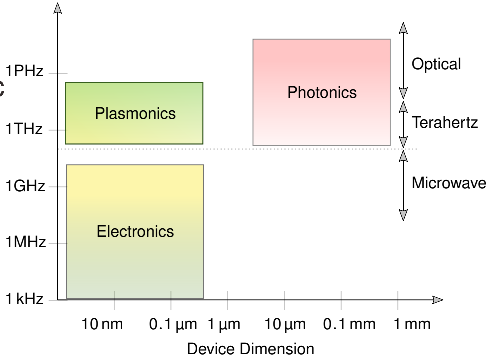


Figure: Communication Technologies at various frequencies

Overview

Terahertz 2DES

- Graphene
  - Grown separately, transfered to substrate
  - Currently not integrable to current electronics technology
  - Superior electronic properties
- Semiconductor heterostructures
  - Conventional epitaxial semiconductor device fabrication techniques
  - On-chip integration with silicon electronics

Background

Plasmonics Overview

- Interfacial wave phenomena
  - Metal-dielectric interface
  - Semiconductor heterostructure
- Surface plasmon polaritons (SPPs)
- Plasma frequency
  - Metals - Optical frequency
  - Semiconductors - Terahertz

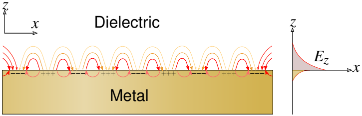


Figure: SPPs at optical frequencies

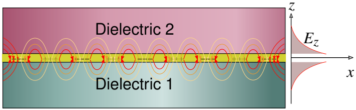


Figure: SPPs in the THz regime

Background

Surface Plasmon Polaritons

- Slow surface waves
- Reduced Wavelength
- Focusing beyond the diffraction limit

- Optical SPP

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

- THz SPP

$$\mathrm{Im}\left[\sigma_s(\omega)\right] < 0$$

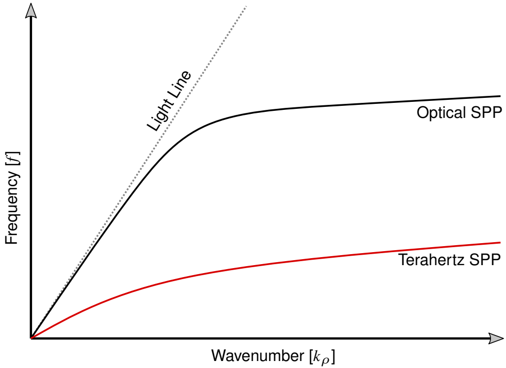


Figure: Dispersion Curve comparison

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

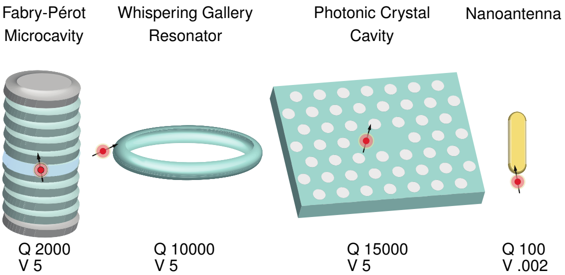
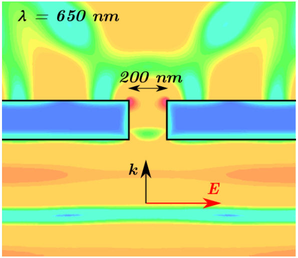


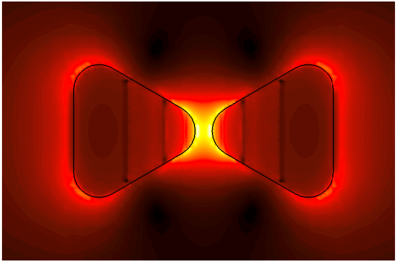
Figure: Optical resonant cavities for electric field enhancement

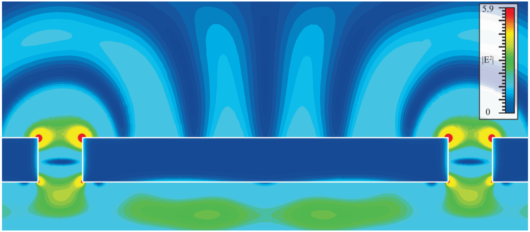
Background

Optical Nanoantennas (contd.)

- Scaled-down microwave antenna designs
  - Aperture antennas for subwavelength focusing
  - Broadband spectral response : Bowtie







Background

Two-dimensional Electron Gas (2DEG)

- Semiconductor Heterostructure in high electron mobility transistor (HEMT)
- High concentration of free electrons ($\sim 1 \times 10^{12} - 1 \times 10^{14}\,\mathrm{cm}^{-2}$)
- Very high Mobility ($\sim 1 \times 10^{4} - 1 \times 10^{6}\,\mathrm{cm}^{2}/\mathrm{V}/\mathrm{s}$)
- Formation of Quantum Well
    - Two-dimensional confinement of electrons

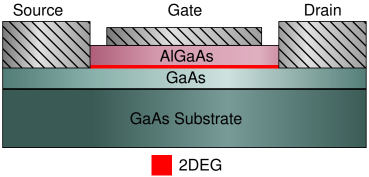


Figure: Typical GaAs/AlGaAs HEMT

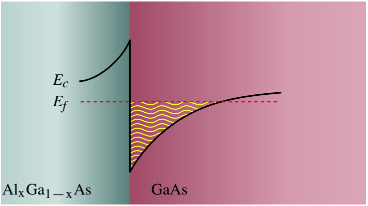
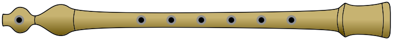


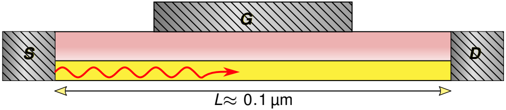
Figure: Band diagram of a GaAs/AlGaAs heterostructure

Background

2DEG (contd.)

- Plasma waves in 2DEG
- Dyakonov-Shur instability
  - Voltage bias at source and drain terminals
  - Plasma resonance
  - THz emission
- Electronic Flute
  - Tunable resonance with gate voltage
- Shallow water waves





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

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

Theory and Methods

2DEG Circuit model

- Drude-Lorentz Surface Conductivity

$$\sigma_s = \frac{N_s e^2}{m^*} \frac{\tau}{1 + j\tau\omega}$$

N_s - Surface charge density

τ - Scattering time

m^* - Effective electron mass

- Equivalent Circuit

$$\sigma_s = \frac{1}{Z} = \frac{1}{R + 1/j\omega C}$$

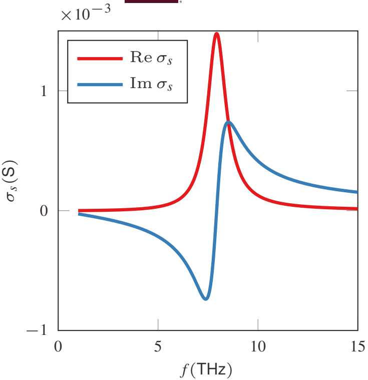
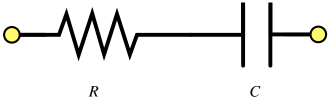


Figure: Room temperature GaN/AlGaN 2DEG surface conductivity

$$Z = R - \frac{j}{\omega C}$$



Theory and Methods

Dispersion Relation for a 2D Sheet

- Conductive Sheet in freespace
- TM mode surface wave

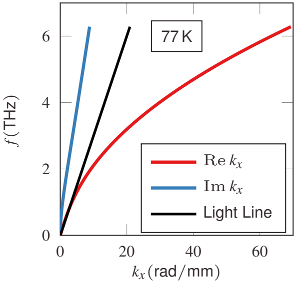
$$k_{\mathrm{P}}^{\mathrm{TM}} = \frac{\omega}{c}\sqrt{1 - \left(\frac{2}{\eta_0 \sigma_s}\right)^2}$$

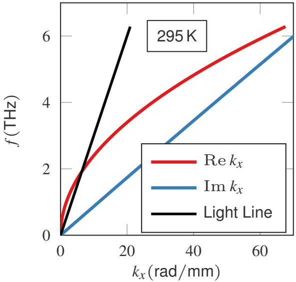
- Below plasma frequency

$$\operatorname{Im} \sigma_s < 0$$

- At low temperature

$$\operatorname{Im} |\sigma_s| \gg \operatorname{Re} |\sigma_s|$$





Theory and Methods

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Analyzing multilayer structure

- Equivalent transmission line (TL) network
- Dispersion relation
  - Transverse resonance condition

$$Y^{\uparrow}(z_0) + Y^{\downarrow}(z_0) + Y_{\sigma} = 0.$$

- Below plasma frequency