Simulation based design of plasmonic waveguides, waveguide bends, and surface-wave splitters

Dr Jasmin Smajic¹, Prof. Christian Hafner², 06.07.2009

² Swiss Federal Institute of Technology (ETH)  
Laboratory for EM Fields and Microwave Electronics  
Gloriastrasse 35, CH-8092 Zürich, Switzerland  
Christian.hafner@ifh.ee.ethz.ch

¹ ABB Switzerland Ltd.  
Corporate Research Dättwil  
Segelhofstrasse 1K, CH-5405 Baden-Dättwil, Switzerland  
jasmin.smajic@ch.abb.com
Outline

- Introduction
  - Plasmon resonance
  - Surface plasmon polaritons
  - Numerical methods for analysis of the plasmonic structures
- Waveguide structures
  - Plasmonic slotline waveguide (PSWG)
  - Metallic heterowaveguide (MHWG)
  - 2D eigenvalue analysis
  - 3D analysis of the waveguide
- Waveguide bend
  - 3D analysis of the 90° waveguide bend
- Plasmonic surface wave splitter
  - 2D analysis of the surface wave splitter
- Outlook
Introduction
Plasmon Resonance

- Plasmon effect: the effect of collective vibrations of electrons in metal at infrared and optical frequencies
- Surface plasmon: the fluctuations of electron density at the metal-insulator interface
- Surface plasmon polariton: a surface plasmon coupled with photon
- The excited polariton propagates over the metal’s outer surface until it is either converted back into a photon or absorbed by the crystal lattice as a phonon
- Surface plasmon resonance (SPR): the excitation of the surface plasmons by external EM radiation
- Localized surface plasmon resonance (LSPR): metallic structure smaller than the wavelength
- Metal at optical and infrared frequencies: described as a homogenous domain with complex dielectric permittivity
Introduction
Surface Plasmon Polaritons

\[ \vec{E}_1(x, y) = (E_{0x1} \cdot \vec{e}_x + E_{0y1} \cdot \vec{e}_y) \cdot e^{j \beta x} \cdot e^{j \alpha_1 y} \]
\[ \vec{E}_2(x, y) = (E_{0x2} \cdot \vec{e}_x + E_{0y2} \cdot \vec{e}_y) \cdot e^{j \beta x} \cdot e^{j \alpha_2 y} \]

\[ \varepsilon_1 E_{0y1} = \varepsilon_2 E_{0y2}, \quad E_{0x1} = E_{0x2} = E_0 \]

\[ \beta = \frac{\omega}{c} \sqrt{\frac{\varepsilon_{r1} \varepsilon_{r2}}{(\varepsilon_{r1} + \varepsilon_{r2})}} \]

\[ \alpha_1 = \sqrt{(\frac{\omega}{c})^2 \varepsilon_{r1} - \beta^2} \]

\[ \alpha_2 = \sqrt{(\frac{\omega}{c})^2 \varepsilon_{r2} - \beta^2} \]
Introduction
Surface Plasmon Polaritons

\[ \vec{E}_1(x, y) = (E_{0x1} \hat{x} + E_{0y1} \hat{y}) \cdot e^{j\beta x} \cdot e^{j\alpha_1 y} \]
\[ \vec{E}_2(x, y) = (E_{0x2} \hat{x} + E_{0y2} \hat{y}) \cdot e^{j\beta x} \cdot e^{j\alpha_2 y} \]

\[ \varepsilon_1 E_{0y1} = \varepsilon_2 E_{0y2}, \quad E_{0x1} = E_{0x2} = E_0 \]

\[ \beta = \frac{\omega}{c} \sqrt{\frac{\varepsilon_r1 \varepsilon_r2}{\varepsilon_r1 + \varepsilon_r2}} \]

\[ \alpha_1 = \sqrt{\left(\frac{\omega}{c}\right)^2 \varepsilon_r1 - \beta^2} \]

\[ \alpha_2 = \sqrt{\left(\frac{\omega}{c}\right)^2 \varepsilon_r2 - \beta^2} \]
Introduction
Numerical Methods

Domain Methods
- Finite Element Method (FEM)
- Finite Difference Time Domain (FDTD)

Boundary Methods
- Multiple Multipole Program (MMP)
- Method of Auxiliary Sources (MAS)
- Meshless Boundary Integral Equation (BIE) Approach

A plasmonic slotline is an air slot in a thin silver film deposited on a silica substrate.

The dimensions of the slot are much smaller than the wavelength.

The goal is to find a bound optical mode supported by the slotline.

Assumption: The bound mode is a hybrid mode.
Analysis: 2D vector elements are required.
Open boundary: PML absorbing boundary conditions are needed.

\[ \nabla \times \left( \frac{1}{n^2} \nabla \times \vec{H} \right) - k_i^2 \vec{H} = 0 \]

\[ \vec{H} = \vec{H}(x,y) \cdot e^{\gamma z}, \quad n^2 = \varepsilon, \]

Eigenvalue: \( \gamma = -\frac{1}{L_{\text{eff}}} - j\beta \)
Plasmonic Slotline
2D Eigenvalue Analysis

- Bound mode: $E_x$ and $H_y$ dominant (quasy-TEM, easy to excite by linearly polarized light).
- Significant propagation losses in silver

\[ \nabla \times \left( \frac{1}{n^2} \nabla \times \vec{H} \right) - k_0^2 \vec{H} = 0 \]

\[ \vec{H} = \vec{H}(x, y) \cdot e^{j \alpha}, \quad n^2 = \varepsilon, \]

Eigenvalue: \[ \gamma = -\frac{1}{L_{\text{eff}}} - j\beta \]

The z-component of time-average Poynting vector is shown at 750nm.
Dispersion relation of the fundamental mode of the slotline (red) is shown.
Propagation length of the fundamental mode of the slotline is shown.
Dispersion relation of the fundamental mode of the slotline (dark blue) is shown.
Propagation length of the fundamental mode of the slotline is shown.
Waveguide Structures
Metallic Heterowaveguide (MHWG)

- The dimensions of the structure are smaller than the wavelength.
- The goal is to find a bound optical mode supported by the MHWG.

Waveguide Structures
Metalic Heterowaveguide (MHWG)

- Bound mode: $E_x$ and Hy dominant (quasy-TEM, easy to excite by linearly polarized light).
- Significant propagation losses in metals

The z-component of time-average Poynting vector is shown at 750nm.
Waveguide Structures
Metalic Heterowaveguide (MHWG)

Results

Dispersion relation of the fundamental mode of the MHWG and PSWG is shown.
Waveguide Structures
Metalic Heterowaveguide (MHWG)

Results

Propagation length of the fundamental mode of the MHWG and PSWG is shown.
Waveguide Structures
3D Waveguide

Silver is modeled as a homogenous material with complex permittivity

Silica substrate, $n=1.44$
Waveguide Structures
3D Waveguide

Time-average Poynting vector of the fundamental mode of the slotline is shown.

Losses in silver (3D) = 34.43%
Losses in silver (2D) = 32.77%

61.3%
The electric field confinement of the fundamental mode of the slotline is presented.
Waveguide Bend
3D analysis of the 90° waveguide bend
Waveguide Bend
3D analysis of the 90° waveguide bend

Losses in silver (3D) = 42.98%
Losses in silver (2D) = 42.30%

Time-average Poynting vector of the fundamental mode of the slotline is shown.
Plasmonic Surface Wave Splitter
2D Analysis of the Surface Wave Splitter
Plasmonic Surface Wave Splitter
2D Analysis of the Surface Wave Splitter

630nm

1330nm
Outlook

- Modern 3D simulation models are very close to reality and therefore make virtual prototyping and design optimization possible
- High level of spatial discretization required for accurate analysis of the plasmonic structures can be achieved today even in the case of complicated 3D structures
- Presented waveguide solutions (PSWG) are within the current fabrication abilities
- Problem of losses in metal is an important drawback