Chapter 7 Plasmon Waveguides (I)

Introduction

7.1 Planar Elements for Surface Plasmon Polariton Propagation

7.2 Surface Plasmon Polariton Band Gap Structures

7.3 Surface Plasmon Polariton Propagation Along Metal Stripes
**Introduction (7.1-7.3)**

- Trade-off between **confinement** and **loss** in SPP Waveguides
- Example:
  - SPP on thin metal within a homogenous media in IR range
    - **Lateral confinement**: very weak (widely extended)
    - **Propagation length**: several cm (low loss)
  - SPP on nanowire or nano-particle waveguide
    - **Lateral confinement**: below diffraction limit
    - **Propagation length**: smaller than $\mu$m (large loss)

**Introduction (7.4)**

- Routing of SPPs on planar interfaces can be achieved by **locally modifying** their **dispersion** via **surface modulations**.
- The **lateral confinement** in **metal stripe and wire waveguides**, including focusing of SPPs in conical structures will be discussed.

**Introduction (7.5)**

- The inverse structure to metal stripes, **metal/insulator/metal heterostructures**, especially in **V-groove geometries**, also show high promise for waveguiding with
  - **Good confinement**
  - **Acceptable propagation length**.

**Introduction (7.6-7.7)**

- **Localized plasmon excitations in metal nanoparticles** can also be used as waveguiding modalities
  - Energy is transferred via **near-field coupling** between adjacent particles in linear chains.
- Emerging efforts to combat attenuation via **optical gain media as waveguide hosts** will be discussed.
7.1 Planar Elements for Surface Plasmon Polariton Propagation
(Control the Propagation Direction of SPPs)

Control the Propagation Direction of SPPs

• The propagation direction of SPPs at the interface of a metal film and a dielectric superstrate (air or dielectric) can be controlled via scattering of the propagating, two-dimensional waves at locally created defects in the otherwise planar film.
  – Scatterers can be introduced in the form of surface undulations
    • Nanoscale particle-like structures
    • Milling of holes into the film.

• Their controlled positioning enables the generation of functional elements such as
  – Bragg mirrors for reflecting SPPs [Ditlbacher et al., 2002b],
  – Focusing elements for increasing lateral confinement [Yin et al., 2005, Liu et al., 2005].

• This way, a planar two-dimensional photonic infrastructure for the guiding of SPPs can be created.

Control SPP propagation via Scattering

• A simple and compelling example of control over SPP propagation via scattering from height modulations was demonstrated [Ditlbacher et al., 2002b].

Routing of SPPs on a planar silver film using surface modulations. A laser beam focused on a nanowire or nanoparticle defect for phase-matching acts as a local source for SPPs. The micrograph shows a Bragg reflector consisting of lines of regularly spaced, particle-like undulations (Fig. 7.2). [Ditlbacher et al., 2002b].

Figure 7.2: (a) SEM image of a SPP Bragg reflector consisting of ordered particle arrays on a metal film substrate. (b) SPP propagation imaged via monitoring of the emission of a fluorescent superstrate. [Ditlbacher et al., 2002b].

Bragg Mirrors for SPPs

\[ d = \frac{\lambda_{SPP}}{2 \cos \alpha_{inc}} \]
Dielectric Optical Elements for SPPs

Calculation for the SPP dispersion relations for a glass/gold/superstrate three-layer system for both the $s$ mode (open symbols) and the $a$ mode [Hohenau et al., 2005b]

\[ 1 + r_{1,2}^P r_{2,3}^P \exp(2i k_{z,2}d) = 0 \]

\[ r_{i,j}^p = \left( \frac{k_{z,i}}{e_i} - \frac{k_{z,j}}{e_j} \right) / \left( \frac{k_{z,i}}{e_i} + \frac{k_{z,j}}{e_j} \right), \quad k_{z,j} = (e_j k_0^2 - k_x^2)^{1/2} \]

Increasing the dielectric constant $\varepsilon_3$ of the superstrate from $\varepsilon_3 = 1$ (circles) to $\varepsilon_3 = 2.25$ (triangles) leads to an increase in propagation constant and thus a decrease in phase velocity of the SPP. For $\varepsilon_3 = \varepsilon_5$, these two modes would evolve into the symmetric ($s$) or asymmetric ($a$) mode. [Hohenau et al., 2005b]

Figure 7.4. Focusing (top row) or reflection and refraction (bottom row) of SPPs via a cylindrical or triangular 40 nm thick dielectric structure deposited on top of a gold film. Images of the leakage radiation (a, b, d, e) and of the optical near field (c, f) clearly show the modification of SPP propagation for SPPs impinging on the dielectric structures (b, c, e, f). Reprinted with permission from [Hohenau et al., 2005b]. Copyright 2005, Optical Society of America.
Dielectric Optical Elements for SPPs

(Figure 7.5) Experimental setup of the excitation and near-field imaging for SPP focusing on a holey metal film (left). (a) SEM and (b) near-field optical image of the nanohole focusing array which couples the launched SPPs into a 250 nm wide silver stripe guide. [Yin et al., 2005]

Figure 7.5: Experimental setup of the excitation and near-field imaging for SPP focusing on a holey metal film (left). (a) SEM and (b) near-field optical image of the nanohole focusing array which couples the launched SPPs into a 250 nm wide silver stripe guide. [Yin et al., 2005]

(Figure 7.6) Generation and focusing of SPPs via illumination of circular or elliptic slits milled into a metallic film. The SPP intensity is monitored via near-field microscopy (a,c) or the exposure of a photoresist superstrate (b, d). [Liu et al., 2005]
7.2 Surface Plasmon Polariton Band Gap Structures

Band Gaps for SPP Propagation

- The concept of constructively reflecting SPPs on a metal film via Bragg reflectors created using periodically arranged metallic nanoparticles presented in Figs. 7.1 and 7.2 can be extended to the creation of band gaps for SPP propagation using regular metal nanoparticle lattices deposited on a metal film.

Band Gaps for SPP Propagation

- First Experiment demonstration by Bozhevolnyi in 2001
Figure 7.8. Topographical (a) and near-field optical (b) image of a channel defect waveguide in a triangular lattice of period 950 nm consisting of 438 nm wide and 80 nm high gold scatters on an gold film. A SPP excited at $\lambda_0 = 1515$ nm incident from the right propagates through the channel. [Marquart et al., 2005].

7.3 Surface Plasmon Polariton Propagation Along Metal Stripes
LRSSP and SRSPP Modes

Modes in Metallic Stripes Embedded in a Homogeneous Dielectric

Metallic Stripes Embedded in a Homogeneous Dielectric

- **Symmetric Mode** (as the **Odd** Mode in Ch2)
- **Asymmetric Mode** (as the **Even** Mode in Ch2)
  - Due to the different definitions between Ch7 & Ch2
For small thickness $t$

\[\Rightarrow \text{Gaussian/like lateral distribution}\]

**Confinement and Loss**

- **For $ss_b^0$ mode** in a Metallic Stripe Embedded in a Homogeneous Dielectric
  - is similar to the LRSPP mode in Ch 40
  - extends over many wavelengths into the dielectric host medium as its confinement decreases with thickness.
  - Confinement is defined by the fraction of the power flowing through the stripe itself to the total power in the mode
  - its loss decrease with thickness as well.

- **MIM** configuration has better confinement than IMI configuration. [Zia et al., 2005c]
Trade-off between Localization and Loss

General Principle

- Tight field localization to the metal interfaces
  - Significant amount of the total mode energy resides inside the metal
  - Propagation loss increases due to Ohmic heating.
- Guiding of electromagnetic energy with sub/wavelength mode confinement
  - Micro-meter even sub/micron propagation lengths.
- The LRSPP modes of metal stripes can show 1/e attenuation lengths approaching 1 cm in the near-infrared, due to the low confinement for a film thickness on the order of 20 nm.

IMI vs. MIM SPP Waveguides

IMI vs. MIM SPP Waveguides

IMI vs. MIM SPP Waveguides

IMI vs. MIM SPP Waveguides
Experimental Demonstration of SPP in Metal Stripes

- The first experimental demonstration of the long-ranging mode [Charbonneau et al., 2000].

Metal film embedded in a polymer host with a propagation loss of only 8 dB/cm

SPP Propagates Along Sub-wavelength Nanowires

- Nanowires (160 nm height, λ=1550 nm)
  - Propagation loss
  - Coupling loss (to SMF)

SPP Propagates Along Sub-wavelength Nanowires

- Metal film embedded in a polymer host with a propagation loss of only 8 dB/cm

- Nanowire VOAs
  - Nom. wire width
    - 180 nm
    - 240 nm
    - 360 nm
    - 440 nm

Nom. wire width [nm]
Micron-sized widths of stripe waveguides have already enabled the demonstration of useful optical elements such as bends and couplers.

**Metal Stripe SPP Waveguides**

- For metal stripes embedded in an asymmetric environment
  - Usually the SPP excited by Prism
  - LRSPP mode is absent in this case, due to the phase mismatch between the SPPs at the two different metal/insulator interfaces [Berini, 2001].

The modes excited on the metal/air interface in stripes using prism coupling are inherently leaky modes.

- The stripe width has a a lower bound below which no propagating leaky modes exists.
Surface Plasmon Propagation in Micro-Scale Metal Stripes

- Lamprecht et al., 2001
- Zia et al., 2005b

![Diagram](Image)

Surface Plasmon Propagation in Micro-Scale Metal Stripes

- Zia et al., 2005b

![Diagram](Image)

Surface Plasmon Propagation in Micro-Scale Metal Stripes

- Zia et al., 2005b

![Diagram](Image)

Surface Plasmon Propagation in Micro-Scale Metal Stripes

- 70 nm Ag Stripes on Glass Substrate
- 70 nm Ag Stripes with Al Screen
- Data from Lamprecht et al. [Ref. 9]

![Diagram](Image)
Optical near-field distributions of SPP waveguide modes

Optical near-field distributions of SPP waveguide modes

Optical near-field distributions of SPP waveguide modes

Optical near-field distributions of SPP waveguide modes

Weeber et al. 2003
Integrated Plasmon and Dielectric Waveguides

Summary of 7.1-7.3

- Well-established dielectric waveguide theory can be applied to SPP waveguides if the effective index \( n_{\text{eff}} \) is calculated via the SPP dispersion as \( n_{\text{eff}} = \frac{\beta}{k_0} \).
- The transverse dimensions of SPP stripe waveguides have to obey a diffraction limit \( \Delta x \geq \lambda_0/2n_{\text{eff}} \), limiting the amount of transverse confinement and thus the integration density of such waveguides.

References