Plasmon slot waveguides: Metal-Insulator-Metal (MIM)

*Towards chip-scale propagation with subwavelength-scale localization*

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PLASMON SLOT WAVEGUIDE DISPERSION

\[ E(x,z,t) = (E_x \hat{x} + E_y \hat{y} + E_z \hat{z}) e^{i(k_x x - \omega t)} \]

\[ B(x,z,t) = (B_x \hat{x} + B_y \hat{y} + B_z \hat{z}) e^{i(k_x x - \omega t)}, \]

with \( E_y, B_x, \) and \( B_z \) identically zero for transverse magnetic (TM) polarization \( E = (E_z, 0, E_x) \) \( B = (0, B_z, 0) \)

and \( E_x, E_z, \) and \( B_y \) identically zero for transverse electric (TE) polarization \( E = (0, E_y, 0) \) \( B = (B_x, 0, B_z) \)

Inside the waveguide, the field components
for the TM polarization

\[ E_x^{in} = e^{-ikz_1 z} \pm e^{ikz_1 z}, \]
\[ E_y^{in} = 0, \]
\[ E_z^{in} = \left( \frac{k_x}{k_{z1}} \right) (e^{-ikz_1 z} \mp e^{ikz_1 z}), \]
\[ B_x^{in} = 0, \]
\[ B_y^{in} = \left( \frac{-\omega \varepsilon_1}{ck_x} \right) (e^{-ikz_1 z} \mp e^{ikz_1 z}), \]
\[ B_z^{in} = 0, \]

by momentum conservation

\[ k_{z1,2}^2 = \varepsilon_{1,2} \left( \frac{\omega}{c} \right)^2 - k_x^2. \]

Inside the waveguide, the field components
for the TE polarization

\[ E_x^{in} = 0, \]
\[ E_y^{in} = e^{ikz_1 z} \pm e^{-ikz_1 z}, \]
\[ E_z^{in} = 0, \]
\[ B_x^{in} = \left( \frac{-k_{z1} c}{\omega} \right) (e^{ikz_1 z} \mp e^{-ikz_1 z}), \]
\[ B_y^{in} = 0, \]
\[ B_z^{in} = \left( \frac{k_x c}{\omega} \right) (e^{ikz_1 z} \pm e^{-ikz_1 z}). \]
Outside the guide, for the TM polarization

\[ E_{x}^{out} = (e^{-ikz_1d/2} \pm e^{ikz_1d/2})e^{ikz_2(z-d/2)}, \]
\[ E_{y}^{out} = 0, \]
\[ E_{z}^{out} = \left( \frac{\varepsilon_1 k_x}{\varepsilon_2 k_{z_1}} \right) (e^{-ikz_1d/2} \mp e^{ikz_1d/2})e^{ikz_2(z-d/2)}, \]
\[ B_{x}^{out} = 0, \]
\[ B_{y}^{out} = \left( -\frac{\omega \varepsilon_1}{ck_x} \right) (e^{-ikz_1d/2} \mp e^{ikz_1d/2})e^{ikz_2(z-d/2)}, \]
\[ B_{z}^{out} = 0, \]

Outside the guide, for the TE polarization

\[ E_{x}^{out} = 0, \]
\[ E_{y}^{out} = (e^{ikz_1d/2} \pm e^{-ikz_1d/2})e^{ikz_2(z-d/2)}, \]
\[ E_{z}^{out} = 0, \]
\[ B_{x}^{out} = \left( -\frac{k_{z_1}c}{\omega} \right) (e^{ikz_1d/2} \mp e^{-ikz_1d/2})e^{ikz_2(z-d/2)}, \]
\[ B_{y}^{out} = 0, \]
\[ B_{z}^{out} = \left( \frac{k_{z_1}c}{\omega} \right) (e^{ikz_1d/2} \pm e^{-ikz_1d/2})e^{ikz_2(z-d/2)}. \]

TE surface plasmon waves do not generally exist in planar metallo-dielectric structures, since continuity of \( E_y \) forbids charge accumulation at the interface.
The in-plane wave vector $k_x$ is defined by the dispersion relations:

\[
\begin{align*}
\text{Field antisymmetric mode } L^+ : \\
\epsilon_1 k_{z2} + \epsilon_2 k_{z1} \tanh \left( \frac{-ik_{z1}d}{2} \right) = 0 \text{ TM} \\
k_{z2} + k_{z1} \tanh \left( \frac{-ik_{z1}d}{2} \right) = 0 \text{ TE}
\end{align*}
\]

\[
\begin{align*}
\text{Field symmetric mode } L^- : \\
\epsilon_1 k_{z2} + \epsilon_2 k_{z1} \coth \left( \frac{-ik_{z1}d}{2} \right) = 0 \text{ TM} \\
k_{z2} + k_{z1} \coth \left( \frac{-ik_{z1}d}{2} \right) = 0 \text{ TE}
\end{align*}
\]

Tangential ($E_x$) Electric Field Profiles

(TM modes)
TM dispersion relations for an MIM waveguide of a three-layer metallodielectric stack with a SiO\textsubscript{2} core and a Ag cladding.

- \(a_b\) : antisymmetric bound
- \(s_b\) : Symmetric bound

Electric Field Profiles (Tangential (\(E_y\)))

- \(\lambda = 410\text{nm}\) 
  \(~3.0\text{eV}\)

- \(\lambda = 650\text{nm}\)
  \(~1.9\text{eV}\)

- \(\lambda = 1.7\mu\text{m}\)
  \(~0.73\text{eV}\)

Stack dimensions:
- \(d = 250\text{ nm}\)
- \(d = 100\text{ nm}\)
In insulator-metal-insulator (IMI) structures,
electrons of the metallic core screen the charge configuration at each interface and maintain a near-zero (or minimal) field within the waveguide.
As a result, the surface polarizations on either side of the metal film remain in phase and a cutoff frequency is not observed for any transverse waveguide dimension.

In metal-insulator-metal (MIM) structures,
surface polarizations arise and evolve independently of the other interface, and plasma oscillations need not be energy- or wave-vector-matched to each other. Therefore, interface SPs may not remain in phase but will exhibit a beating frequency; as transverse core dimensions are increased, “bands” of allowed energies or wave vectors and “gaps” of forbidden energies will be observed.
The allowed $a_b$ modes follow the light line for energies below $\sim 1$ eV and resemble conventional dielectric core, conducting cladding waveguide modes for energies above $\sim 2.8$ eV.

The $s_b$ modes are only observed for energies between 1.5 and 3.2 eV. For energies exceeding $\sim 2.8$ eV, wave vectors of the $s_b$ mode are matched with those of the SP and the tangential electric field transits from a core mode to an interface mode.
$D = 100 \text{ nm}$

- Conventional waveguide modes within $\Delta E \sim 1 \text{ eV}$
- SP modes
The dispersion of the 50-nm-thick sample lies completely to the left of the decoupled SP mode. Low-energy asymptotic behavior follows a light line of $n = 1.5$. It suggests that polariton modes of MIM more highly sample the imaginary dielectric component. In the low energy limit, the $S_b$ SP truly represent a photon trapped on the metal surface.
Purely plasmonic nature of the mode

The cutoff frequencies remains essentially unchanged, possibly by the Goos-Hanchen effect. As waveguide dimensions are decreased, energy densities are more highly concentrated at the metal surface. This enhanced field magnifies Goss-Hanchen contributions significantly. In the limit of $d \ll s$ (skin depth), complete SP dephasing could result.
**MIM (Ag/SiO$_2$/Ag) TM-polarized propagation and skin depth (D = 250 nm)**

Forbidden band

Note that only a slight relation correlation between propagation distance and skin depth ($\sigma$).

- The metal absorption is not the limiting loss mechanism in MIM structures.
MIM (Ag/SiO$_2$/Ag) TM-polarized propagation and skin depth

( $D = 12$ nm, 20 nm, 35 nm, 50 nm, and 100 nm )

- Approximately constant in the Ag cladding. Thus, MIM can achieve micron-scale propagation with nanometer-scale confinement.
- Evanescent within 10 nm for all wavelength

Local minima corresponding to the transition between quasibound modes and radiation modes

Unlike IMI, extinction (prop. distance) is determined not by ohmic loss (metal absorption) but by field interference upon phase shifts induced by the metal.
In planar IMI waveguides, transverse electric SP modes are not supported since $E_y$ is continuous. However, the existence of conventional and SP modes in MIM guides suggests that TE waves might propagate for certain oxide core thicknesses and excitation wavelengths.

As wavelengths approach the regime of anomalous Ag dispersion, (~4 eV: ~300 nm) all modes become evanescent.

As oxide thickness is decreased, the TE polarization is filtered, and only TM waves can propagate in the guide. This mixed TM-TE mode characteristic may be an important consideration in MIM tapered waveguides.
**EM energy density profiles of MIM structures (Ag/SiO2/Ag)**

In an electrostatics limit, MIM waveguides locally serve as parallel-plate capacitors. At each metal-dielectric interface, localized charges will either interact with nearest neighbors in the conductor or across the dielectric. While the former situation is indicative of a surface charge wave, the latter suggests strong field concentration within the dielectric. Thus, unlike skin depth, the distribution of energy density in each media is a prime discriminator of wave propagation in MIM structures.

\[
\begin{align*}
u_{\text{SiO}_2} &= \frac{1}{2} (\hat{E} \cdot \hat{D}^* + \hat{B} \cdot \hat{H}^*) = \frac{1}{2} (\varepsilon_1 \hat{E} \cdot \hat{E}^* + \hat{B} \cdot \hat{B}^*) \\
u_{\text{Ag}} &= \frac{1}{2} \left( \text{Re} \left[ \frac{d(\omega \varepsilon_2)}{d\omega} \right] \hat{E} \cdot \hat{E}^* + \hat{B} \cdot \hat{B}^* \right)
\end{align*}
\]
CONCLUSIONS

Depending on transverse dimensions, MIM waveguides can support both conventional and plasmonic modes; cutoff wave vectors are not observed until the core diameter is reduced below ~20 nm or exceeds ~100 nm. This superposition of modes results in wide tunability of energy density throughout the electromagnetic spectrum. While energy densities are generally high at the metal interface, intensities within the waveguide can be comparable to values observed in nanoparticle array gaps.

Judicious arrangement of IMI and MIM plasmon waveguides promises potential for two-dimensional planar loss-localization balance. When combined with the recent remarkable progress in nanoscale fabrication, the aforementioned results might inspire an alternative class of waveguide architectures—ultimately, a class of subwavelength plasmonic interconnects, not altogether different from the silicon-on-insulator networks of today.
We demonstrate that, to achieve subwavelength pitches, a metal–insulator–metal geometry is required with higher confinement factors and smaller spatial extent than conventional insulator–metal–insulator structures. The resulting trade-off between propagation and confinement for surface plasmons is discussed, and optimization by materials selection is described.
Consider the isotropic wave equation for a generic three-layer plasmonic slab waveguide with metallic and dielectric regions,

\[
k_{x,\text{metal}}^2 + k_{y,\text{metal}}^2 + k_z^2 = \frac{\omega^2}{c^2} \varepsilon_{\text{metal}}
\]

\[
k_{x,\text{dielec}}^2 + k_{y,\text{dielec}}^2 + k_z^2 = \frac{\omega^2}{c^2} \varepsilon_{\text{dielec}}
\]

where \( z \) is the propagation direction and thus \( k_z \) is the conserved quantity.

For a guided surface-plasmon mode to exist,

\[
k_z \geq \frac{\omega}{c} \sqrt{\varepsilon_{\text{dielec}}}
\]

If the radiation is unconfined in the \( y \) dimension (i.e., \( k_y = 0 \)),

\[
k_{x,\text{metal}} = i \left( k_z^2 - \frac{\omega^2}{c^2} \varepsilon_{\text{metal}} \right)^{1/2}
\]

\[
k_{x,\text{dielec}} = i \left( k_z^2 - \frac{\omega^2}{c^2} \varepsilon_{\text{dielec}} \right)^{1/2}
\]
**Ultimate confinement of the IMI structure** is limited by the decay length into the dielectric cladding. For confinement below the limit of a conventional dielectric waveguide ($\lambda/2n$),

$$2\pi x \left(1/k_{x,\text{dielectric}}\right) < (\lambda/2n)$$

$$|k_{x,\text{dielec}}| \geq \frac{2\pi n_{\text{dielec}}}{\lambda} = \frac{\omega}{c} \sqrt{\varepsilon_{\text{dielec}}}, \quad \therefore k_z = \frac{\omega}{c} \sqrt{2\varepsilon_{\text{dielec}}}.$$

Note that this condition is met only near the surface plasmon resonance frequency.

**Confinement of the MIM structure** is limited by the decay length into the metallic regions, which can be approximated as follows for metals below the surface-plasmon resonance:

$$\Re\{\varepsilon_{\text{metal}}\} < -\varepsilon_{\text{dielec}},$$

$$\therefore |k_{x,\text{metal}}| > \frac{\omega}{c} \sqrt{2\varepsilon_{\text{dielec}}} > \frac{2\pi n_{\text{dielec}}}{\lambda}.$$

$$k_{x,\text{metal}} = \frac{\omega}{c} \left(\frac{\varepsilon_{\text{metal}}^2}{\varepsilon_{\text{metal}} + \varepsilon_d}\right)^{1/2} > \frac{\omega}{c} \left(\varepsilon_d\right)^{1/2}.$$
Power confinement factor ($\Gamma$) of field-symmetric TM modes - MIM and IMI plasmonic waveguides - (Au–air, $\lambda = 1.55$ $\mu$m)

The figure illustrates the confinement factor ($\Gamma$) as a function of the center layer thickness for both MIM and IMI geometries. The confinement factor is defined as:

$$\Gamma = \frac{\int_{\text{cent lay}} |E_x H_y^*| \, dx}{\int_{-\infty}^{+\infty} |E_x H_y^*| \, dx}$$

If plasmonic waveguides are intended to propagate light in subwavelength modes, MIM geometries with higher confinement factors and shorter spatial extents are much better suited for this purpose.
Waveguiding in nanoscale metallic apertures

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\[ n_{1D} = \frac{\kappa}{k_0} = \sqrt{\varepsilon_d \left( 1 + \frac{\lambda}{\pi w \sqrt{-\varepsilon_m}} \sqrt{1 + \frac{\varepsilon_d}{-\varepsilon_m}} \right)^{1/2}} \]

\[ n_{2D} = \frac{\kappa}{k_0} = \sqrt{\varepsilon_d' - \left( \frac{\lambda}{2 w_x} \right)^2} \]

\[ w_x' = w_x \left( 1 + \frac{\lambda}{\pi w_x \sqrt{\left( \varepsilon_d' - \varepsilon_m \right) + \left( \frac{\lambda}{2 w_x} \right)^2}} \right) \]

\[ w_x' = w_x + 2\delta \]

\[ \delta \text{ is the metal skin depth} \]

Red-shift of the cut-off wavelength due to the finite permittivity of the metal

\[ \lambda_c = 2(w_x + 2\delta) \sqrt{\varepsilon_d \left( 1 + \frac{2\delta}{w_y} \right)} \]

\[ \text{Real part of } n_{2D} \]

\[ \text{Wavelength } \lambda(\mu m) \]

\[ \text{Cut-off wavelength } \lambda_c(\mu m) \]
an optical range resonator based on single mode metal-insulator-metal plasmonic gap waveguides. A small bridge between the resonator and the input waveguide can be used to tune the resonance frequency.

\[ FDTD \text{ with the perfectly matched layer boundary conditions} \]
Negative Refraction at Visible Frequencies

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