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# Slow Propagation, Anomalous Absorption, and Total External Reflection of Surface Plasmon Polaritons in Nanolayer Systems

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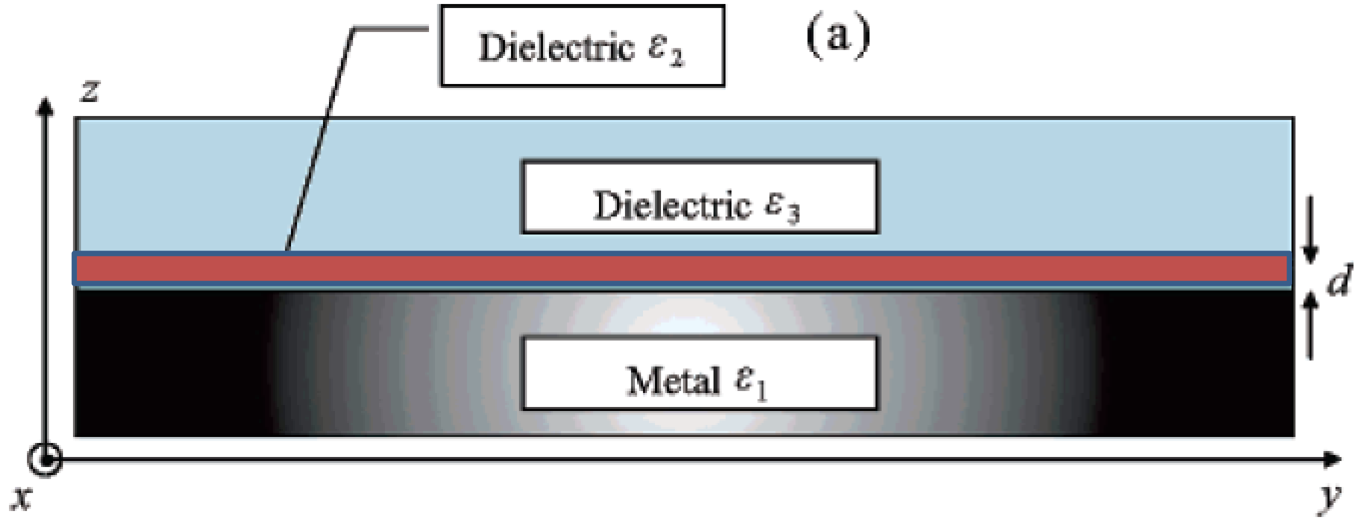
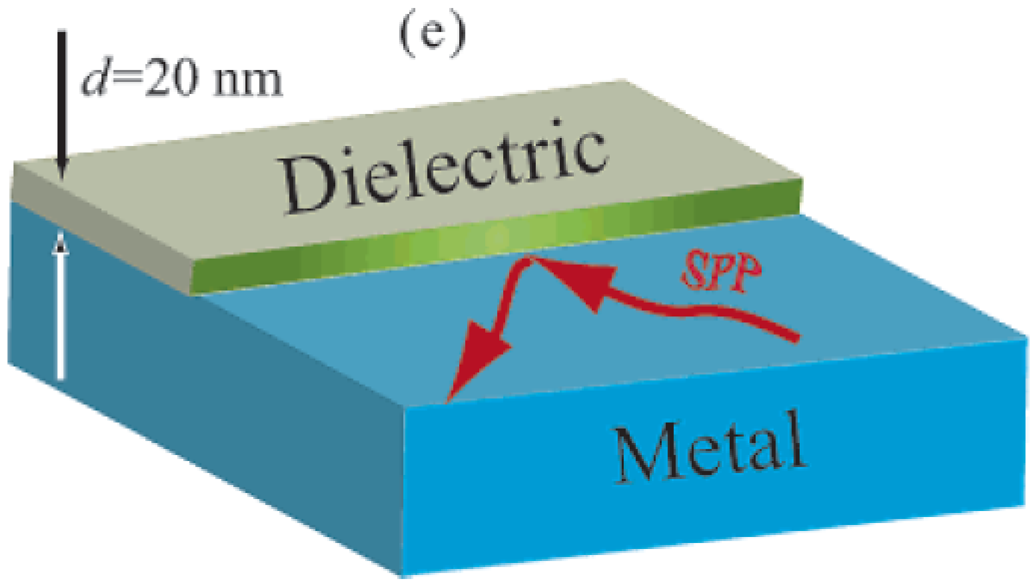
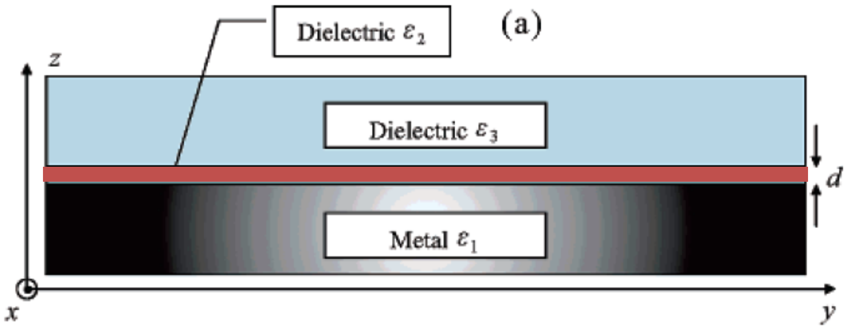
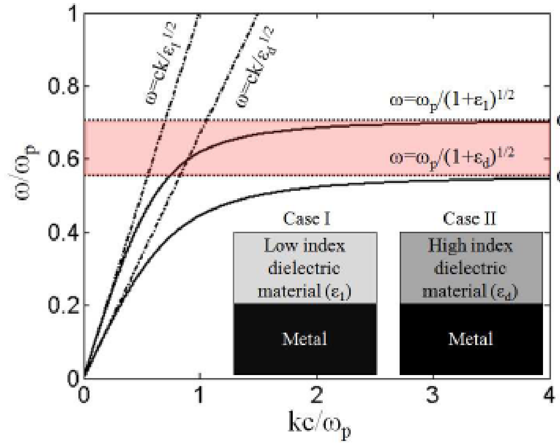



$\varepsilon_2 > \varepsilon_3$






two characteristic frequencies

Case I $\epsilon_1(\omega_3)+\epsilon_3=0 \quad \hbar\omega_3 = 3.68$ eV

Case II $\epsilon_1(\omega_2)+\epsilon_2=0, \quad \hbar\omega_2 = 3.02$ eV

The dispersion equation for the SPP dispersion relation *k(ω)* can be cast into the form

$$d = f(k,\omega)$$

$$f(k,\omega) = \frac{1}{\epsilon_2 v_2}\left\{-\text{Arctan}\left[\frac{v_2(u_1+u_3)}{u_1u_3 - v_2{}^2}\right] + n\pi\right\},$$

$n = 0, 1, 2, ...,$ where

$$u_i = \frac{1}{\epsilon_i}\sqrt{q^2-\epsilon_i}, \quad v_i = \sqrt{\epsilon_i - q^2}, \quad k = \frac{\omega}{c}q$$

$$v_i = \frac{1}{\varepsilon_i}\sqrt{\varepsilon_i - q^2} = iu_i$$ 논문이 틀린 듯

$$\tanh(u_2\varepsilon_2 d) = -\left(\frac{1+u_1/u_3}{u_2/u_3+u_1/u_2}\right)$$ [PRL 95, 063901 (2005)]

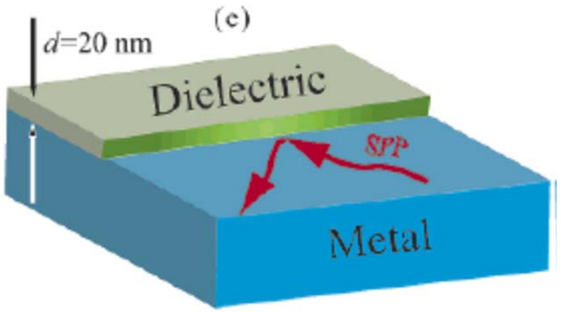
$$\rightarrow \tan(v_2\varepsilon_2 d) = \frac{v_2(u_1+u_3)}{u_1u_3 - v_2^2}$$

$$\rightarrow v_2\varepsilon_2 d + n\pi = \tan^{-1}\left[\frac{v_2(u_1+u_3)}{u_1u_3-v_2^2}\right]$$

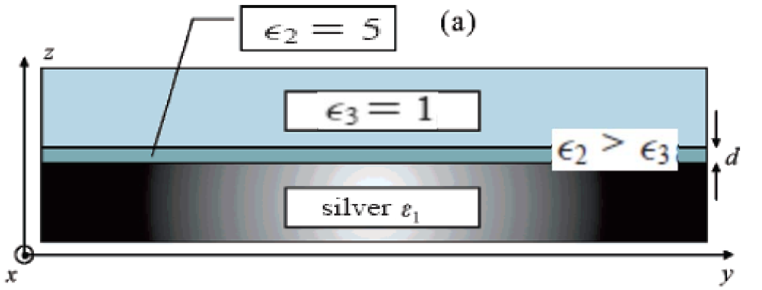
$$\rightarrow d = f(k,\omega) = \frac{1}{\varepsilon_2 v_2}\left\{n\pi - \tan^{-1}\left[\frac{v_2(u_1+u_3)}{u_1u_3-v_2^2}\right]\right\}$$

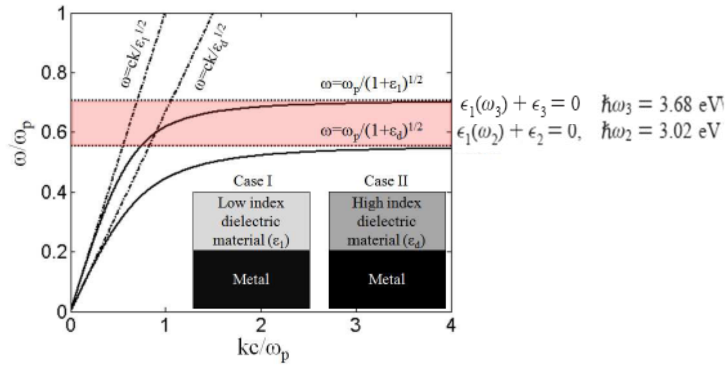
$$\omega_3 > \omega > \omega_2.$$

A layer of a high-permittivity dielectric on the surface of a metal plays the role of a near-perfect mirror causing the total reflection of SPPs from it. → total external reflection




**➔ How thin the dielectric 2 (d) should be to cause such a total external reflection?**



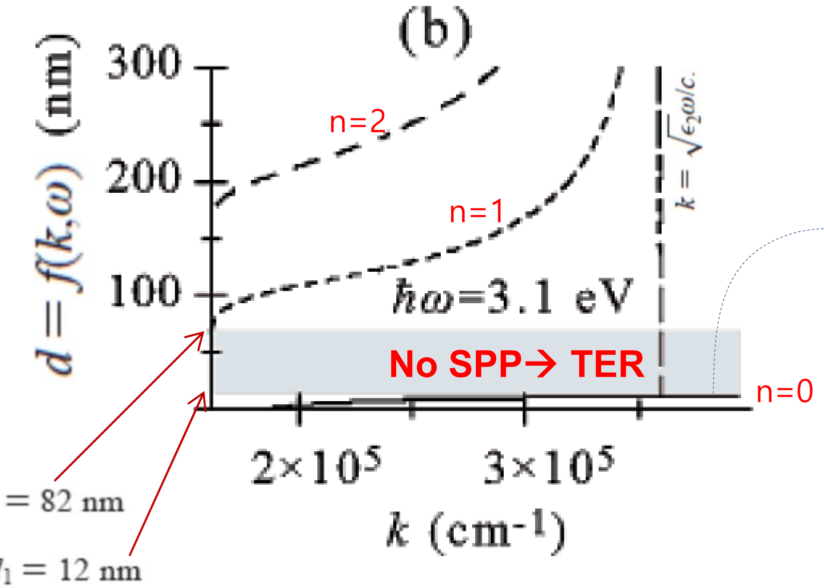

$$d = f(k,\omega) = \frac{1}{\varepsilon_2 v_2}\left\{ n\pi - \tan^{-1}\left[\frac{v_2(u_1+u_3)}{u_1u_3 - v_2^2}\right]\right\}$$

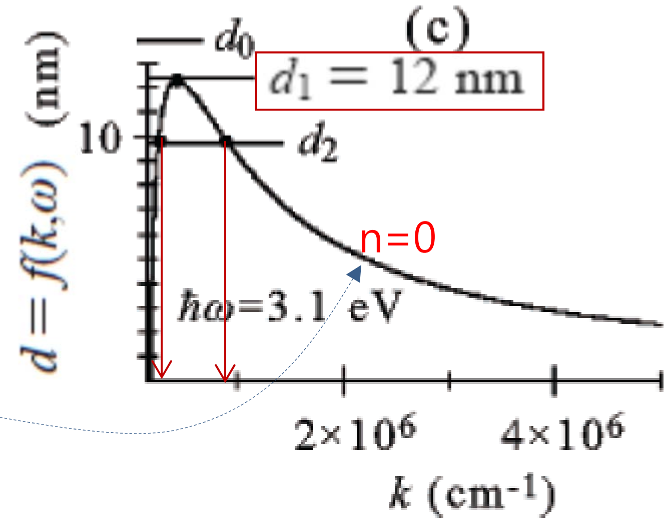
$$u_i = \frac{1}{\epsilon_i}\sqrt{q^2-\epsilon_i},$$

$$v_i = \frac{1}{\varepsilon_i}\sqrt{\varepsilon_i - q^2} = iu_i$$

$$k = \frac{\omega}{c}q$$

$\omega_3 > \omega > \omega_2.$ for $\omega = 3.1$ eV



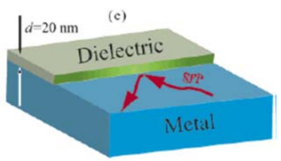

$d_0 > d_1 = 12$ nm, there are no propagating SPPs.

$d = d_1 = 12$ nm a bifurcation point

$d_2 < d_1 = 12$ nm, two solutions.

a long wavelength (small $k$), → **fast SPP**

a short wavelength (large $k$) → **slow SPP**



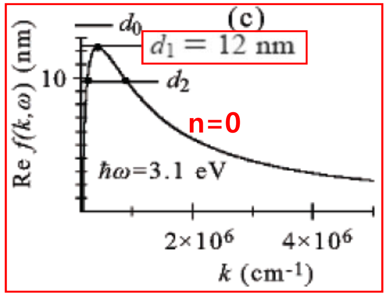

For layer thickness: 82 nm $> d >$ 12 nm total external reflection.

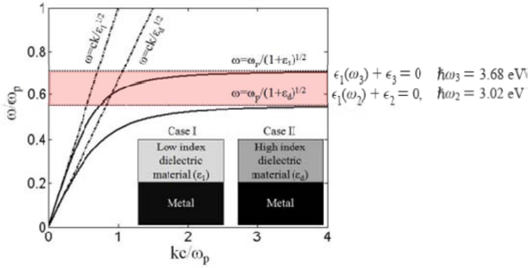
high-efficiency two-dimensional (2d) mirror for SPPs can find applications in nanotechnology to create 2d resonant cavities for SPPs. Among possible applications will be optical nanofilters, nanospectrometers, nanolasers, and spasers.

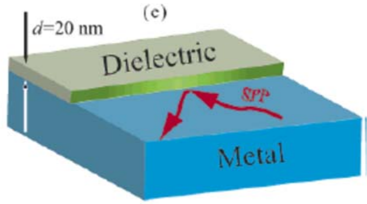
For relatively thick layers ($d > d_u = 82$ nm), there will be oscillations of the propagation properties of the SPP because of the higher bands involved corresponding to modes in the *z direction.*

for $\omega = 3.1$ eV

$\omega_3 > \omega > \omega_2.$



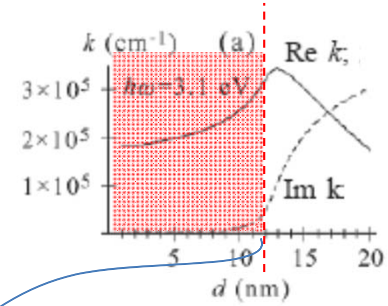




(b) For the lower-frequency range where the SPP propagation is possible for arbitrary *d*.

for $\omega = 3.1$ eV

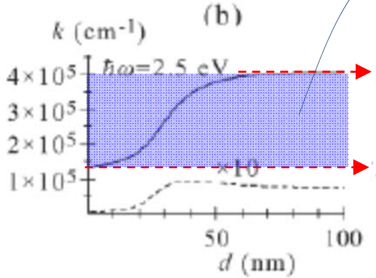
$\omega_3 > \omega > \omega_2.$

(a) As the thickness of the dielectric layer over the silver increases from 0 to 12 nm, the real part of the wavevector increases by a factor of 2 while its imaginary part stays small,
→ **suggesting a good propagation with small losses**.




$\omega < \omega_2$

The large interval of change of $n_{\rm eff}$ used efficiently in adiabatic nanooptics

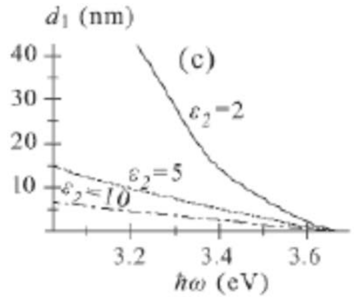


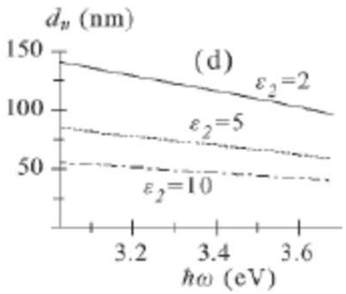

$k = (\omega/c)[\epsilon_1\epsilon_2/(\epsilon_1 + \epsilon_2)]^{1/2}$

→ no total external reflection $\text{Im } k \ll |\text{Re } k|$

$k = (\omega/c)[\epsilon_1\epsilon_3/(\epsilon_1 + \epsilon_3)]^{(1/2)}$

(a) When thickness *d riches* the critical value (12 nm), the propagation terminates: the imaginary part of *k starts to* dominate, which implies the evanescent, exponentially decaying tail of the fields in the direction of the propagation. Such a layer can also be used as an efficient electrooptical or all-optical modulator in SPP nanooptics.

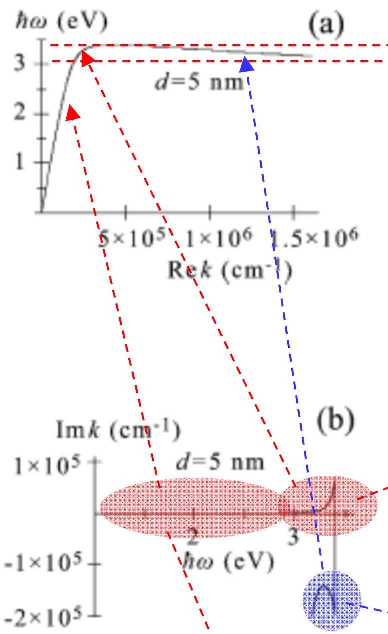



(c) Dependence of the critical thickness $d_1$ *(for which the total* external reflection sets on) on frequency for three values of ε2 (2, 5, 10)

(d) Dependence of the upper critical thickness, *du, for which* the total external reflection disappears and a continuous band of propagation begins.
This thickness is much greater, *du ~100 nm,* which corresponds to the formation of modal structure in the Fabri-Perot resonator formed by the layer.

for $d = 5$ nm.



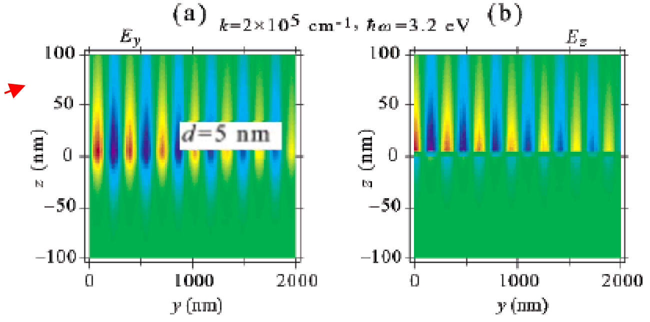

$\omega_m = 3.40$ eV

$\omega_2 = 3.02$ eV

$\omega_m > \omega > \omega_2$

two solutions:
The small-*k* root, fast SPP with normal dispersion (positive refraction),
The high-*k* root. slow SPPs with negative refraction ($v_g$ is anomalously low)

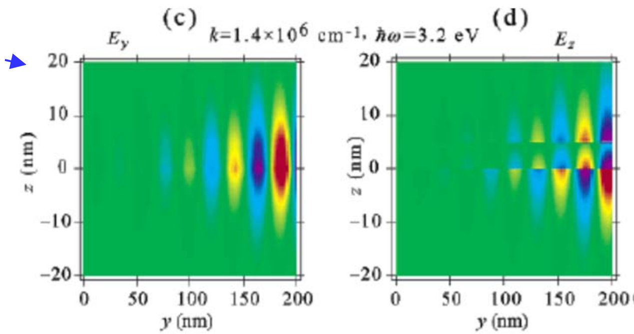
positive-refraction branch
no well-defined, propagating SPPs.




delocalized into the vacuum to distances 50 nm.
decay along the direction of propagation (*y*)

weakly absorbed,
well-propagating, long-range SPPs.

negative-refraction branch
have very large values of $|\text{Im } k| \sim \text{Re } k$




dramatically decay on a distance of ~50 nm
a strong absorption due to the Ohmic losses.

propagation trend from right to left.

# Summary

(i) **There is a range of thickness (typically between 10 nm and 100 nm) for which propagation of SPPs is forbidden.**
   **→ total external reflection of SPPs**
   **→ high-quality mirrors and resonators for plasmonic nanooptics.**

(ii) **The slow propagation of SPPs predicted earlier is intrinsically related to strong losses due to the localization of fields in the metal.**

(iii) **In the region of negative refraction, these losses cause dissipation of SPPs at distances on order of their wavelength.**

(iv) **I trust that the much better way to achieve small group velocity and, in addition, small phase velocity (slowing down and stopping) of SPPs with acceptable losses is using the adiabatically tapered plasmonic waveguides.**

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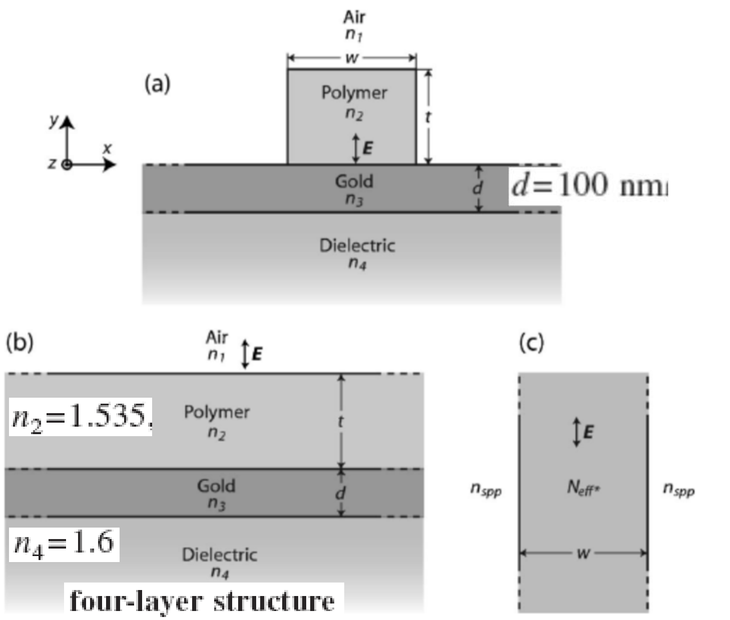
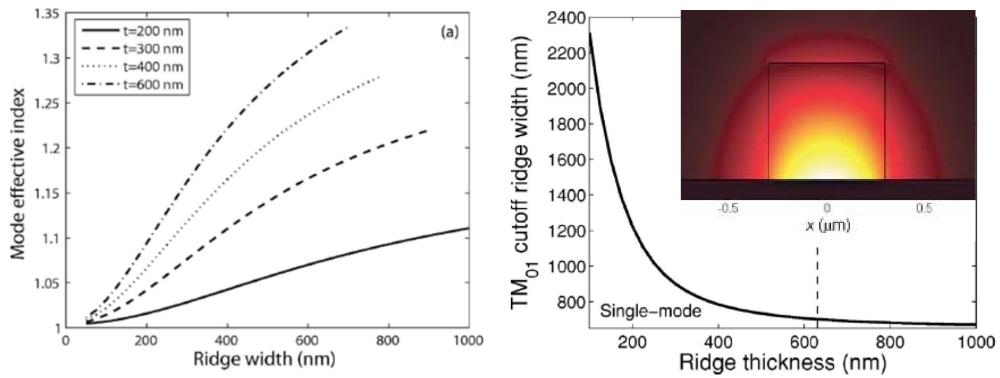
# Theoretical analysis of dielectric-loaded surface plasmon-polariton waveguides

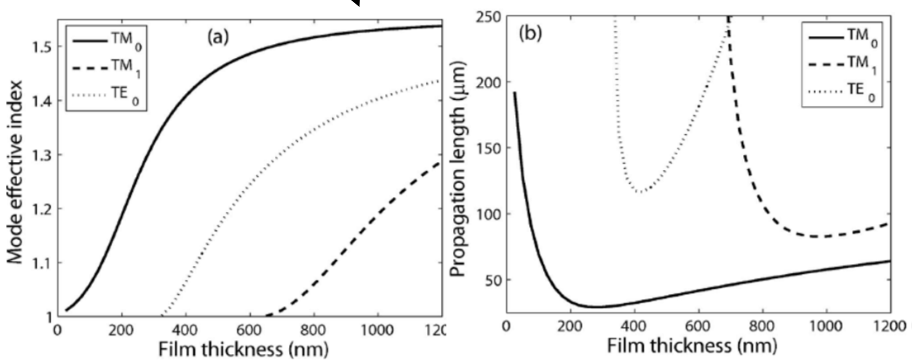
Tobias Holmgaard* and Sergey I. Bozhevolnyi *Aalborg University, Denmark*

**the mode effective index, confinement, and propagation length, are calculated at the telecom wavelength =1.55 um for different widths and thicknesses of a polymer ridge with the refractive index of 1.535 placed on a gold film surface.**

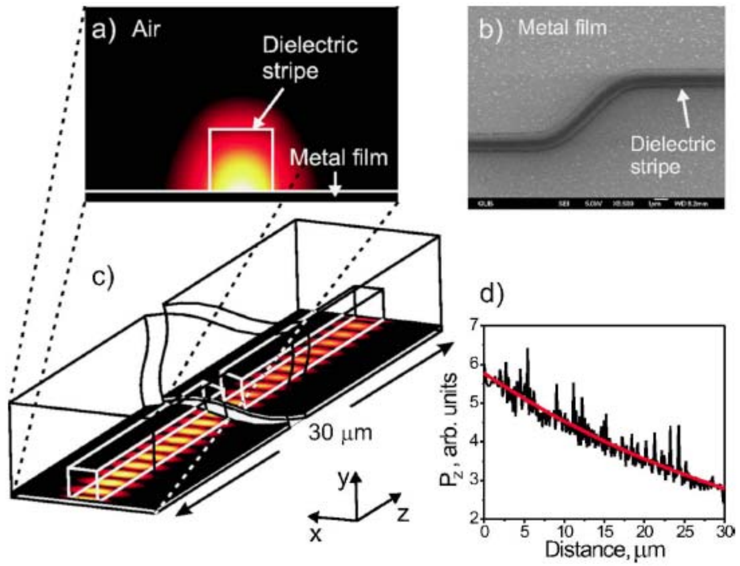



$\lambda=1.55\ \mu m$, finite element method (FEM)




various polymer film thicknesses,

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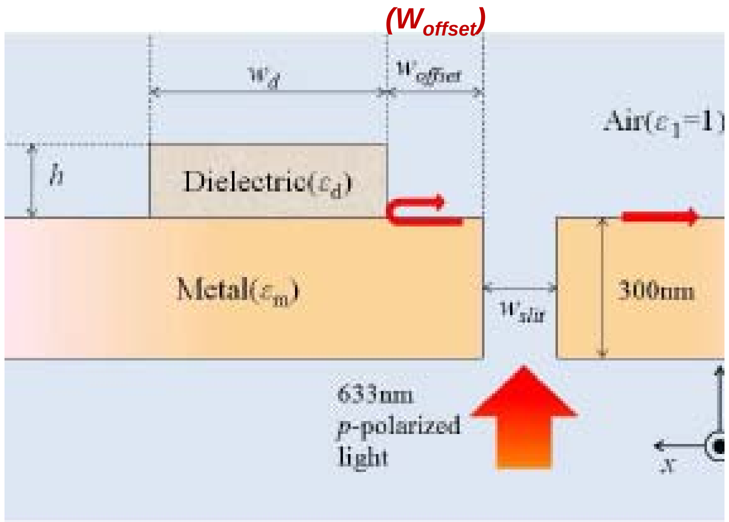


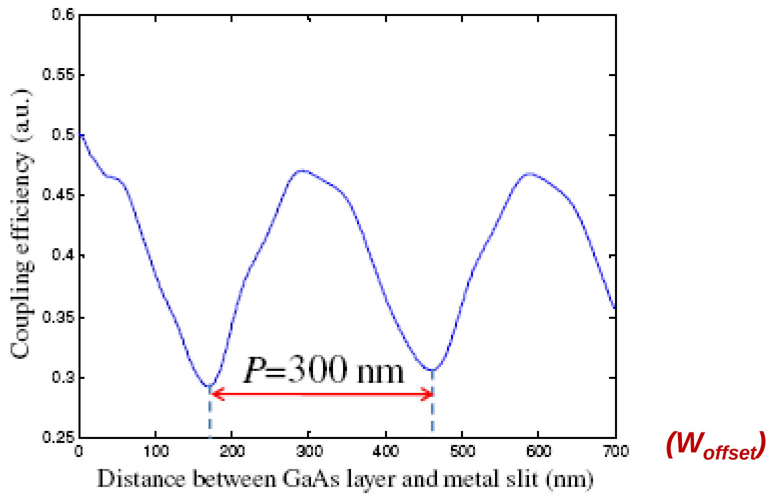


Fig. 3. Coupling efficiency as a function of the offset distance between metal slit and GaAs barrier ($\varepsilon_d$=14.753). $h$ and $w_d$ are 14 nm and 640 nm, respectively.