Povrchové plazmony

v integrované fotonice

Povrchové plazmony v integrované fotonice

Typické aplikace:

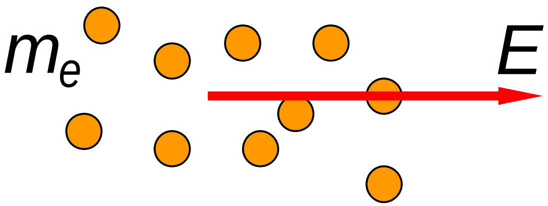
1. vlnovodné polarizátory

2. SPR senzory

3. povrchové plazmony pro přenos informace („plazmonika“)

Permitivita kovu (Drudeho model)

„volný“elektronový plyn v elektromagnetickém poli



Pohybová rovnice: $-m_e\ddot{x} - m_e\gamma\dot{x} - eE = 0$

Pro harmonické pole $E = E_0 \exp(-i\omega t)$

získáme ustálené řešení: $x_0 = \dfrac{-eE_0}{m_e\omega^2 + i m_e \gamma\omega}$

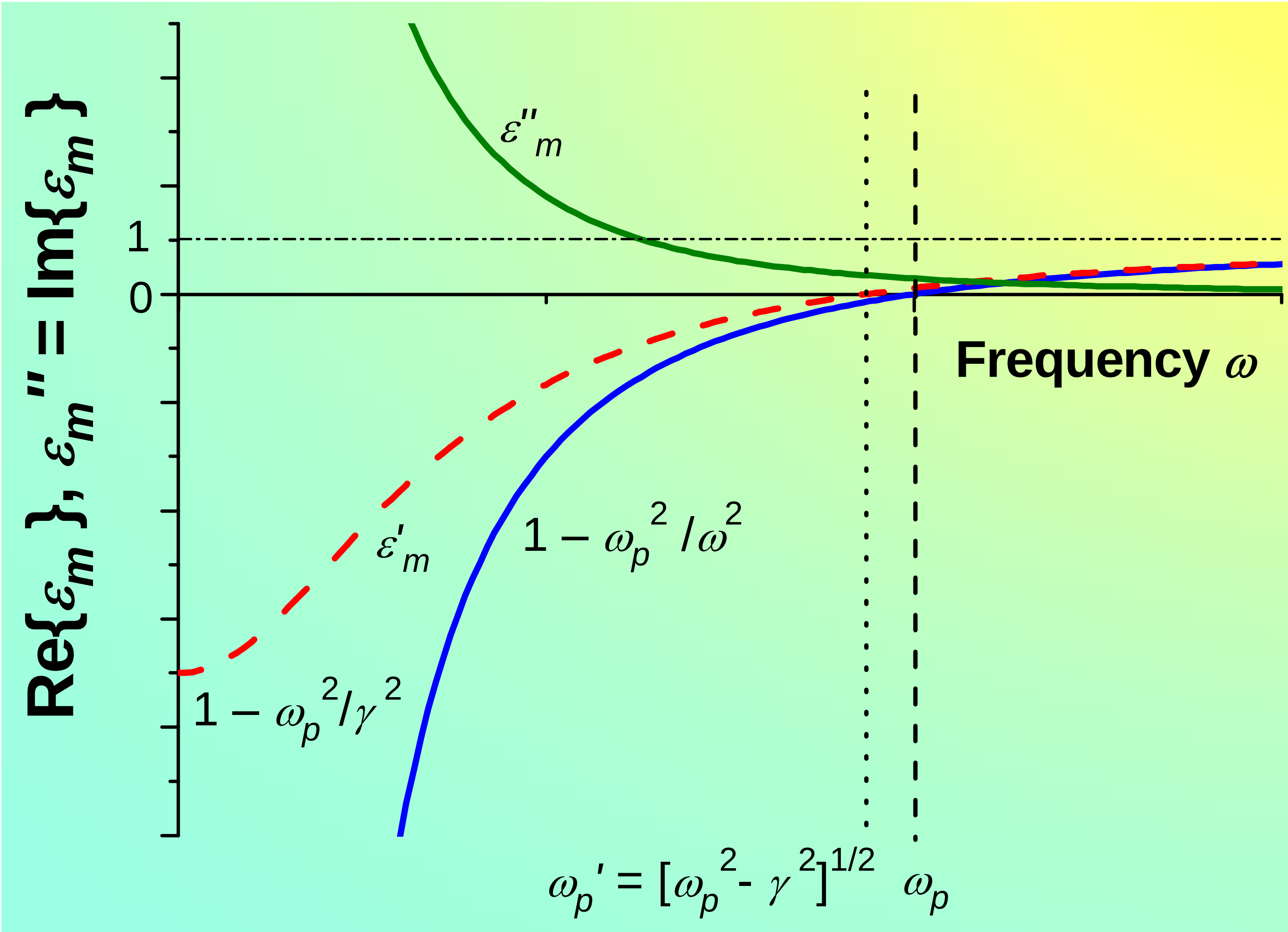
Polarizace: $P_0 = -n_e e x_0 = \dfrac{-e^2 n_e}{m_e\omega^2 + i m_e\gamma\omega} E_0 = \varepsilon_0 \chi E_0$

Permitivita: $\varepsilon_m = 1 + \chi = 1 - \dfrac{e^2 n_e / (m_e \varepsilon_0)}{\omega^2 + i\gamma\omega} = 1 - \dfrac{\omega_p^2}{\omega^2 + i\gamma\omega}$

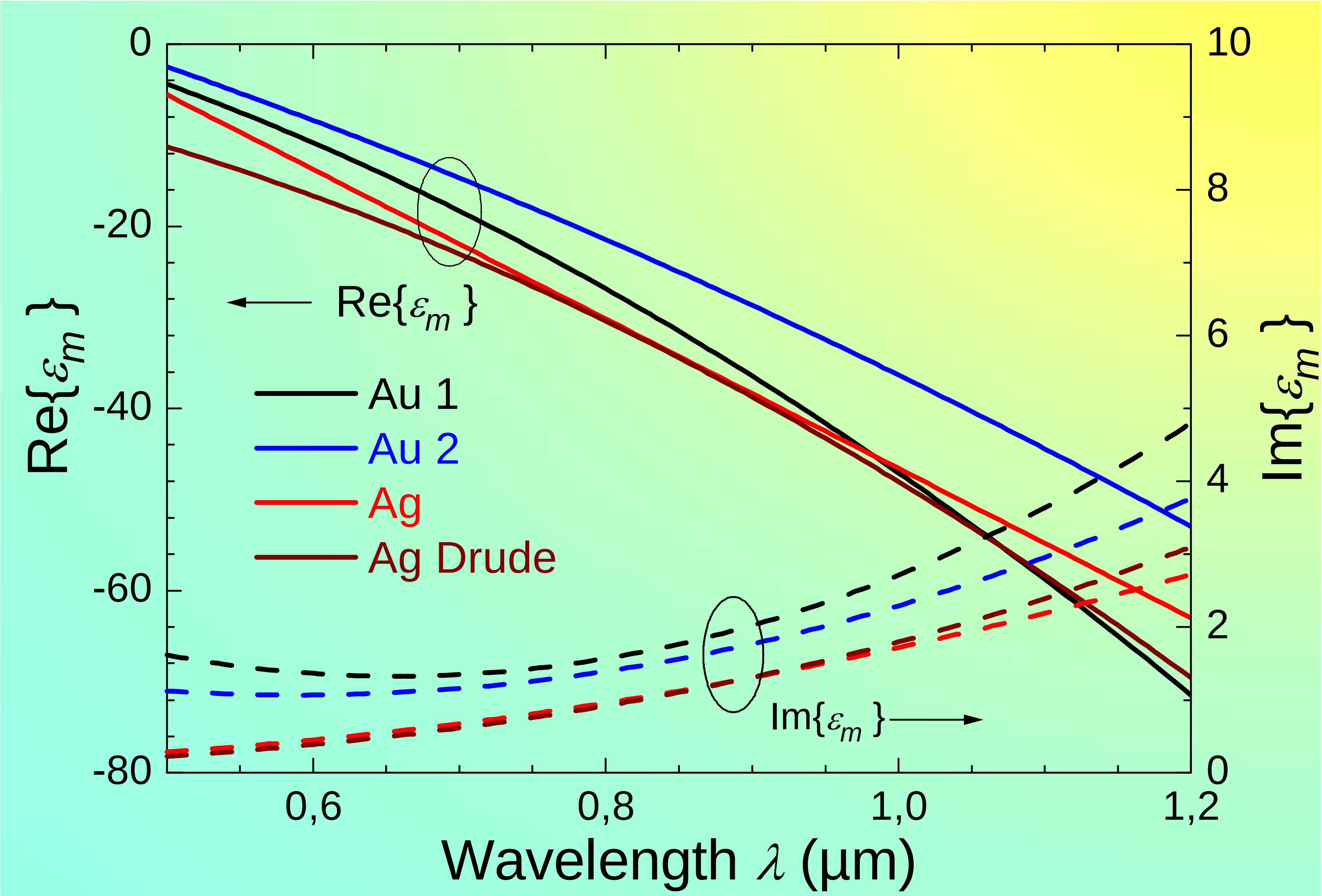
Plazmová frequence $\omega_p = e\sqrt{\dfrac{n_e}{m_e \varepsilon_0}}$

Disperze kovu (Drudeho model)

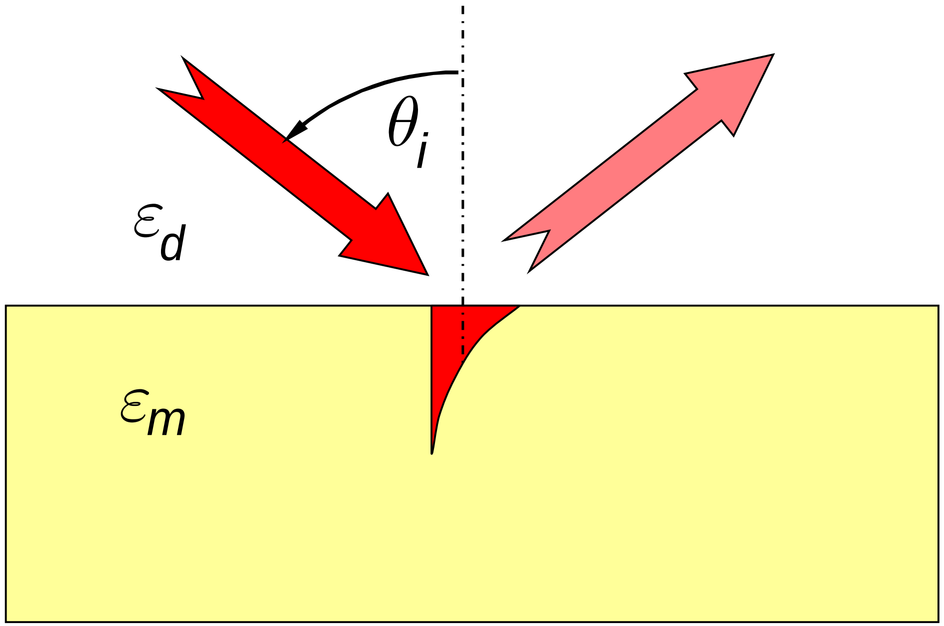
$$\varepsilon_m = \varepsilon_m' + i\varepsilon_m'' = 1 - \frac{\omega_p^2}{\omega^2 + \gamma^2} + i\frac{\omega_p^2\gamma}{\omega(\omega^2 + \gamma^2)}$$



Disperze kovu (experimentální data)



Odraz optického záření od rozhraní s kovem



$$R^{TE} = \frac{\sqrt{\varepsilon_d - N^2} - \sqrt{\varepsilon_m - N^2}}{\sqrt{\varepsilon_d - N^2} + \sqrt{\varepsilon_m - N^2}}$$

$$R^{TM} = \frac{\dfrac{\sqrt{\varepsilon_d - N^2}}{\varepsilon_m} - \dfrac{\sqrt{\varepsilon_m - N^2}}{\varepsilon_d}}{\dfrac{\sqrt{\varepsilon_d - N^2}}{\varepsilon_m} + \dfrac{\sqrt{\varepsilon_m - N^2}}{\varepsilon_d}}$$

$$N = \sqrt{\varepsilon_d}\,\sin\theta_i$$

Pro reálná $\varepsilon_m < 0$,

$$\sqrt{\varepsilon_m - N^2} = i\sqrt{N^2 - \varepsilon_m}$$

and $\left|R^{TE}\right| = \left|R^{TE}\right| = 1.$

Pro komplexní ε_m,

$$\left|R^{TE}\right| < 1,\ \left|R^{TE}\right| < 1.$$

Povrchová plazmová vlna
(povrchový plazmon-polariton, povrchový plazmon)

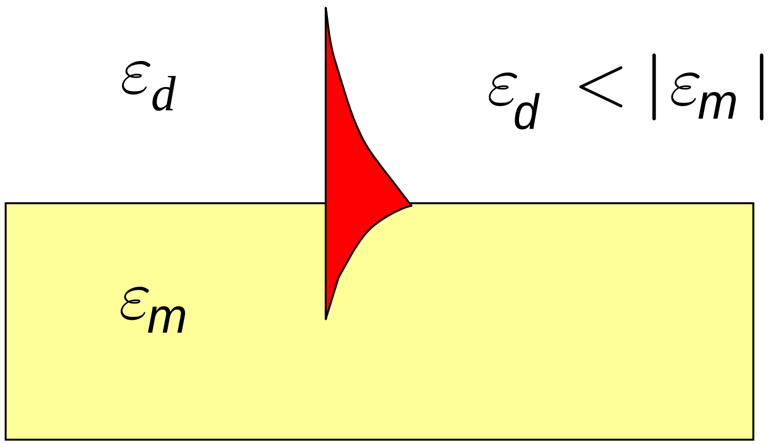
Vzájemně vázaná elektromagnetická a nábojová povrchová vlna localizovaná na rozhraní mezi dielectrikem a kovem

Pól $R(N^2) \Rightarrow N^2$ povrchové vlny

TE: $\sqrt{\varepsilon_d - N^2} + \sqrt{\varepsilon_m - N^2} = 0$ neexistuje řešení

TM: $\varepsilon_m \sqrt{\varepsilon_d - N^2} + \varepsilon_d \sqrt{\varepsilon_m - N^2} = 0$ povrchový plazmon

$$N_{SP} = \sqrt{\frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m}}$$



Rozložení pole povrchového plazmonu

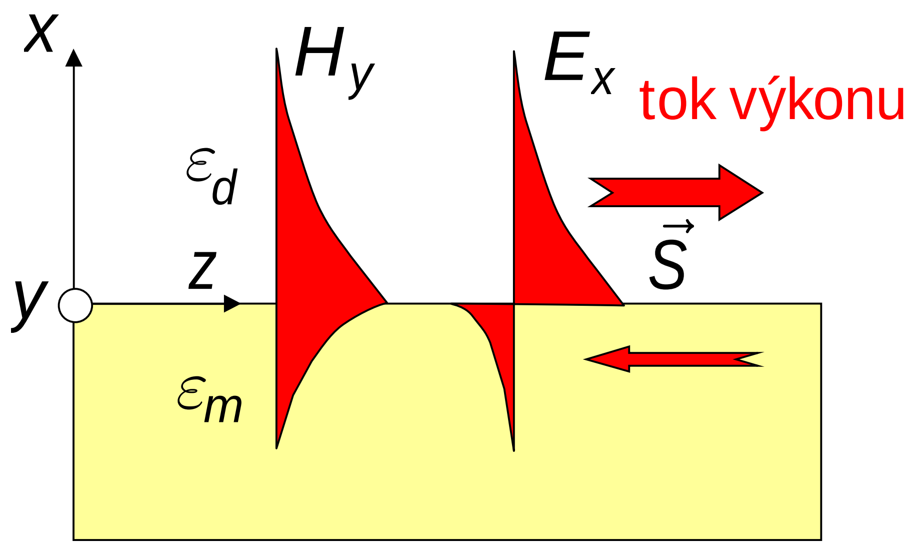
$$H_y(x,z) = H_0 e^{ik_0 N z} \begin{cases} e^{-k_0\sqrt{N^2-\varepsilon_d}\,x}, & x > 0 \\ e^{k_0\sqrt{N^2-\varepsilon_m}\,x}, & x < 0 \end{cases}$$

$$1\big/ k_0\sqrt{N^2 - \varepsilon_d} = 265\ \text{nm}$$

$$1\big/ k_0\sqrt{N^2 - \varepsilon_m} = 26\ \text{nm}$$

$$E_x(x,z) = Z_0 N H_0 e^{ik_0 N z} \begin{cases} \dfrac{1}{\varepsilon_d} e^{-k_0\sqrt{N^2-\varepsilon_d}\,x}, & x > 0 \\ \dfrac{1}{\varepsilon_m} e^{k_0\sqrt{N^2-\varepsilon_m}\,x}, & x < 0 \end{cases}$$

Pro $\gamma = 0,\ \mathrm{Im}\{N\} = 0$



Uvažujme *reálné* rozhraní zlato-vzduch a vlnovou délku záření 1 μm.

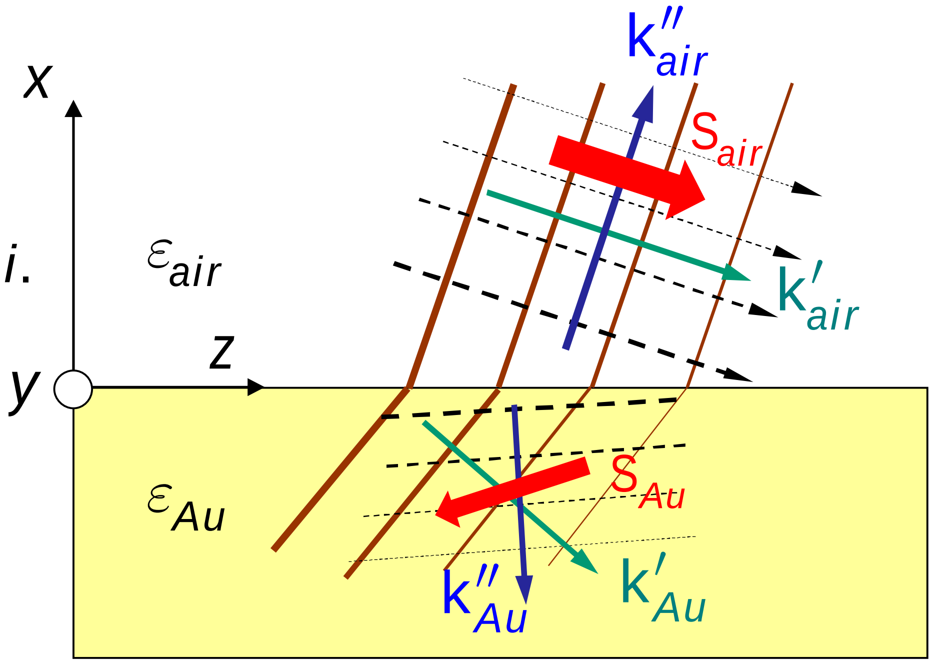
$$\varepsilon_{Au} = -115.13 + 10.742i, \quad \varepsilon_{air} = 1.0; \text{ Pak}$$

$$\mathrm{H} = \mathrm{y}^0 H, \; H = H_0 e^{ik_0(px+Nz)};$$

$$N = \sqrt{\frac{\varepsilon_{air}\varepsilon_{Au}}{\varepsilon_{air} + \varepsilon_{Au}}} = 1.00433 + 4.2627 \times 10^{-5} i.$$

$$p_{air} = \sqrt{\varepsilon_{air} - N^2} = -0.004381 + 0.09330i;$$

$$p_{Au} = \sqrt{\varepsilon_{Au} - N^2} = -0.49782 - 10.78826i;$$



$$\mathrm{E} = \frac{Z_0 H_0}{\varepsilon_m} e^{ik_0(px+Nz)} \left(N\mathrm{x}^0 - p\mathrm{z}^0\right);$$

$$\mathrm{S} = \frac{1}{2}\mathrm{Re}\left\{\mathrm{E} \times \mathrm{H}^*\right\} = \frac{1}{2}\mathrm{Re}\{\mathrm{E}\} \times \mathrm{y}^0 =$$

$$= \frac{Z_0 |H_0|^2}{2} \mathrm{Re}\left\{\frac{1}{\varepsilon}\left(N\mathrm{x}^0 - p\mathrm{z}^0\right)\right\} \times \mathrm{y}^0;$$

Ve ztrátovém prostředí se tok výkonu (Poyntingův vektor) *nešíří rovnoběžně s reálnou částí vlnového vektoru*!!!

$$S_{Au} = \frac{Z_0 |H|^2}{2} \mathrm{Re}\left\{\frac{1}{\varepsilon_{Au}}\left(p_{Au}\mathrm{x}^0 + N\mathrm{z}^0\right)\right\} = \frac{Z_0 |H|^2}{2}(-0.004381\mathrm{x}^0 - 0.0086478\mathrm{z}^0)$$

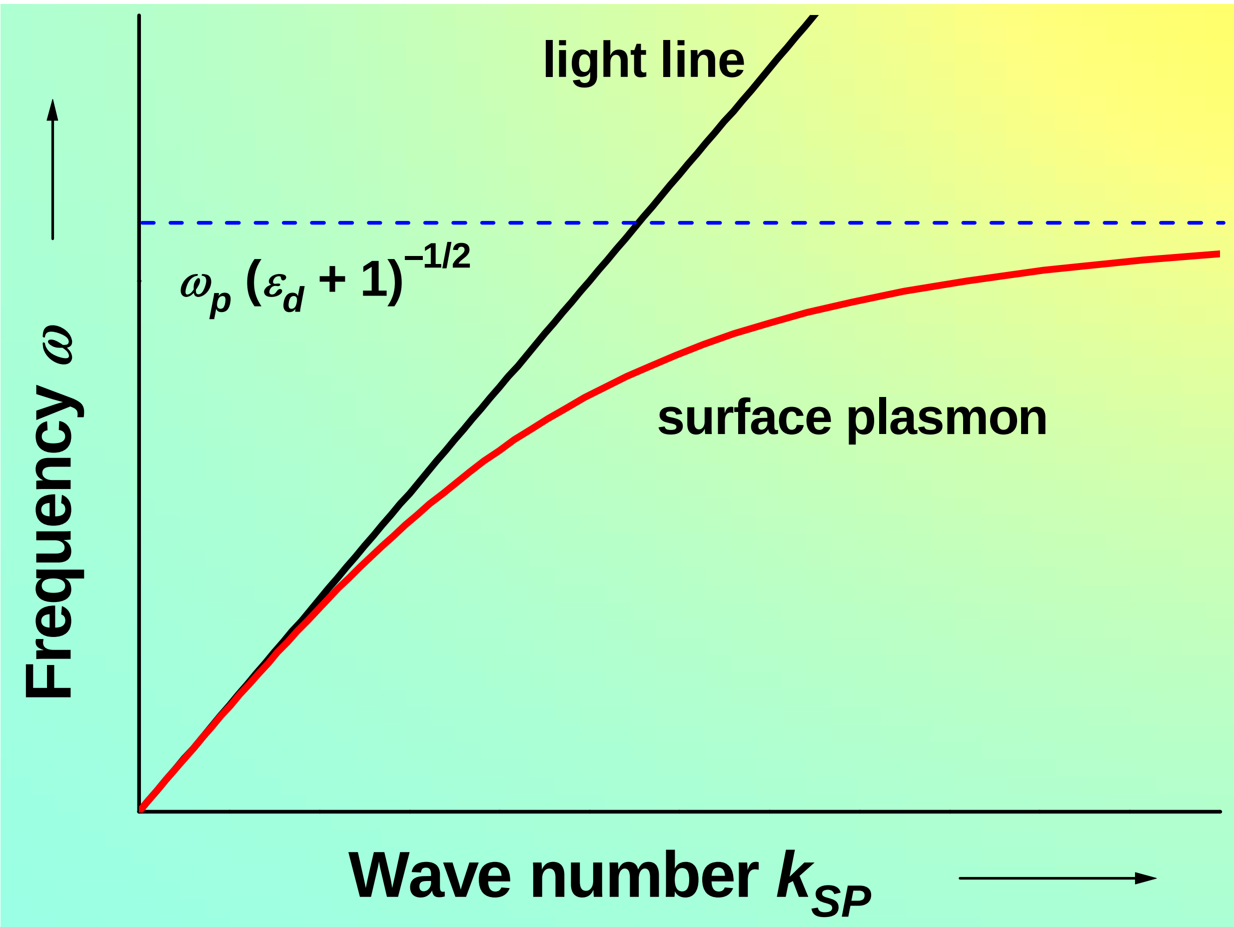
Sklon S_{air} vůči rozhraní je jen asi 0,25°, sklon S_{Au} je asi 27°. Musí rovněž platit $S_{air,x} = S_{Au,x}$.

Disperzní vlastnosti povrchového plazmonu

Pro $\gamma = 0,\ \omega < \omega_p / \sqrt{(\varepsilon_d + 1)}$

$$k_{SP} = \frac{\omega}{c} N_{SP} = \frac{\omega n_d}{c} \underbrace{\sqrt{\frac{\omega_p^2 - \omega^2}{\omega_p^2 - \omega^2(\varepsilon_d + 1)}}}_{\text{faktor } <1}$$

"light line" → $\frac{\omega n_d}{c}$



$\mathrm{Re}\{N_{SP}\} > n_d \ \Rightarrow$

PP je pomalá vlna

nemůže být excitována zářením z dielektrika

Vidy vlnovodů s PP

Metoda příčné rezonance

i. vrstevnatá struktura – metoda přenosových matic

$$\begin{pmatrix} H_{y,j}(\pm d_j) \\ -iE_{z,j}(\pm d_j) \end{pmatrix} = \begin{pmatrix} \cos\gamma_j d_j & \pm\left(\varepsilon_j/\gamma_j\right)\sin\gamma_j d_j \\ \mp\left(\gamma_j/\varepsilon_j\right)\sin\gamma_j d_j & \cos\gamma_j d_j \end{pmatrix} \cdot \begin{pmatrix} H_{y,j}(0) \\ -iE_{z,j}(0) \end{pmatrix}$$

$$\gamma_j = k_0\sqrt{\varepsilon_j - N^2}$$

ii. difúzní vlnovody: metoda příčné immitance
(Riccatiho rovnice, integrace metodou Rungeho a Kutty)

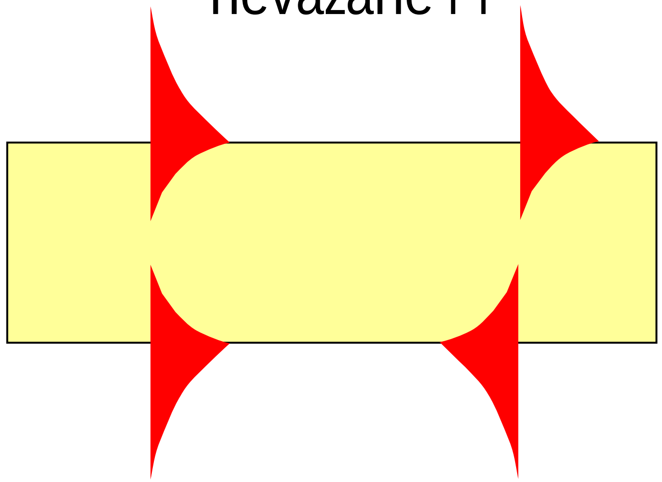
$$\frac{1}{k_0}\frac{dv}{dx} = -\frac{\varepsilon(x) - N^2}{\varepsilon(x)} - v^2 \qquad v(x) = \frac{1}{k_0\varepsilon(x)}\frac{1}{H_y(x)}\frac{dH_y}{dx} = -i\sqrt{\frac{\varepsilon_0}{\mu_0}}\frac{E_z(x)}{H_y(x)}$$

$$\frac{1}{k_0}\frac{dH_y}{dx} = v(x)\,\varepsilon(x)H_y$$

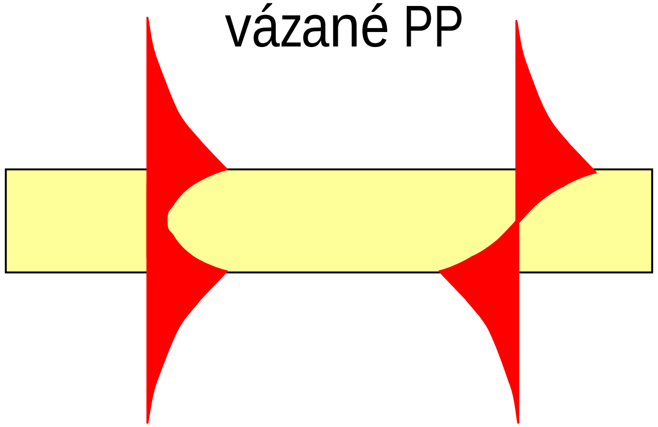
normovaná příčná impedance

Povrchové plazmony na kovové vrstvě

nevázané PP

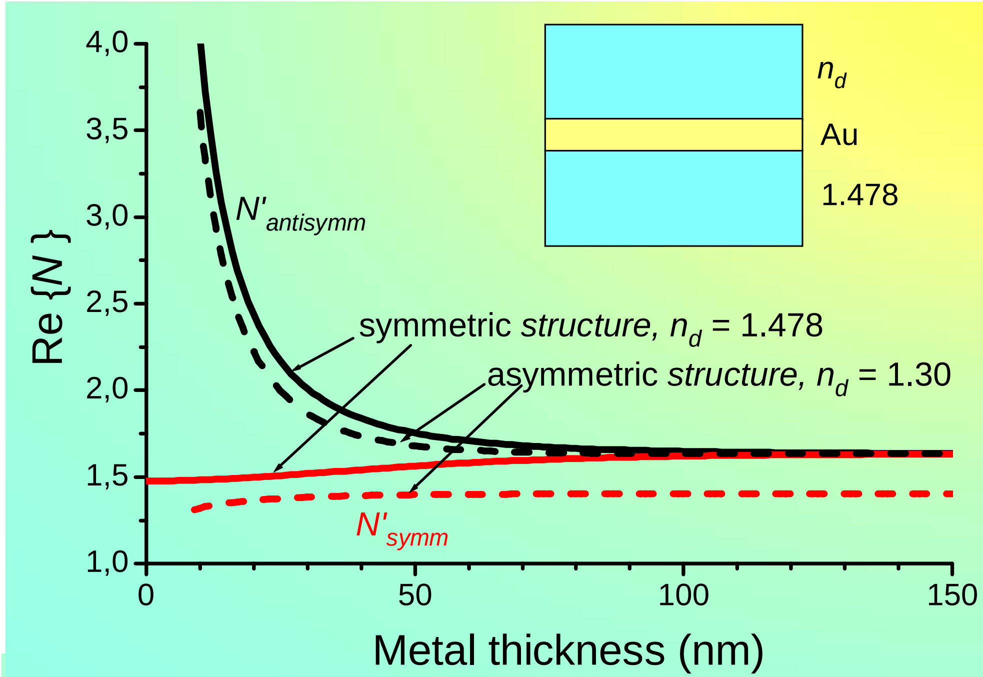


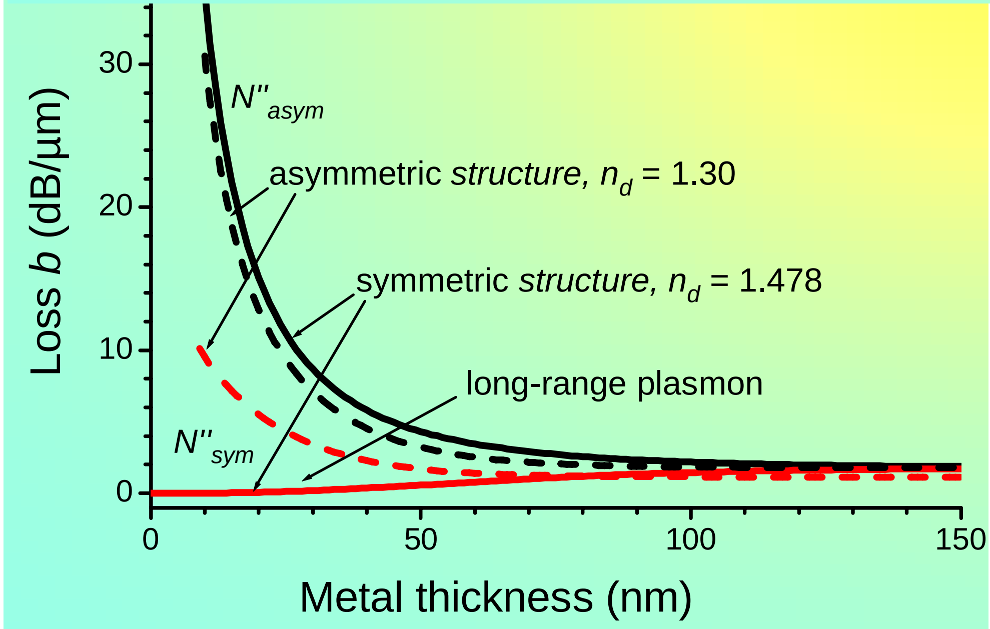
vázané PP



symetrický (vůči H_x)

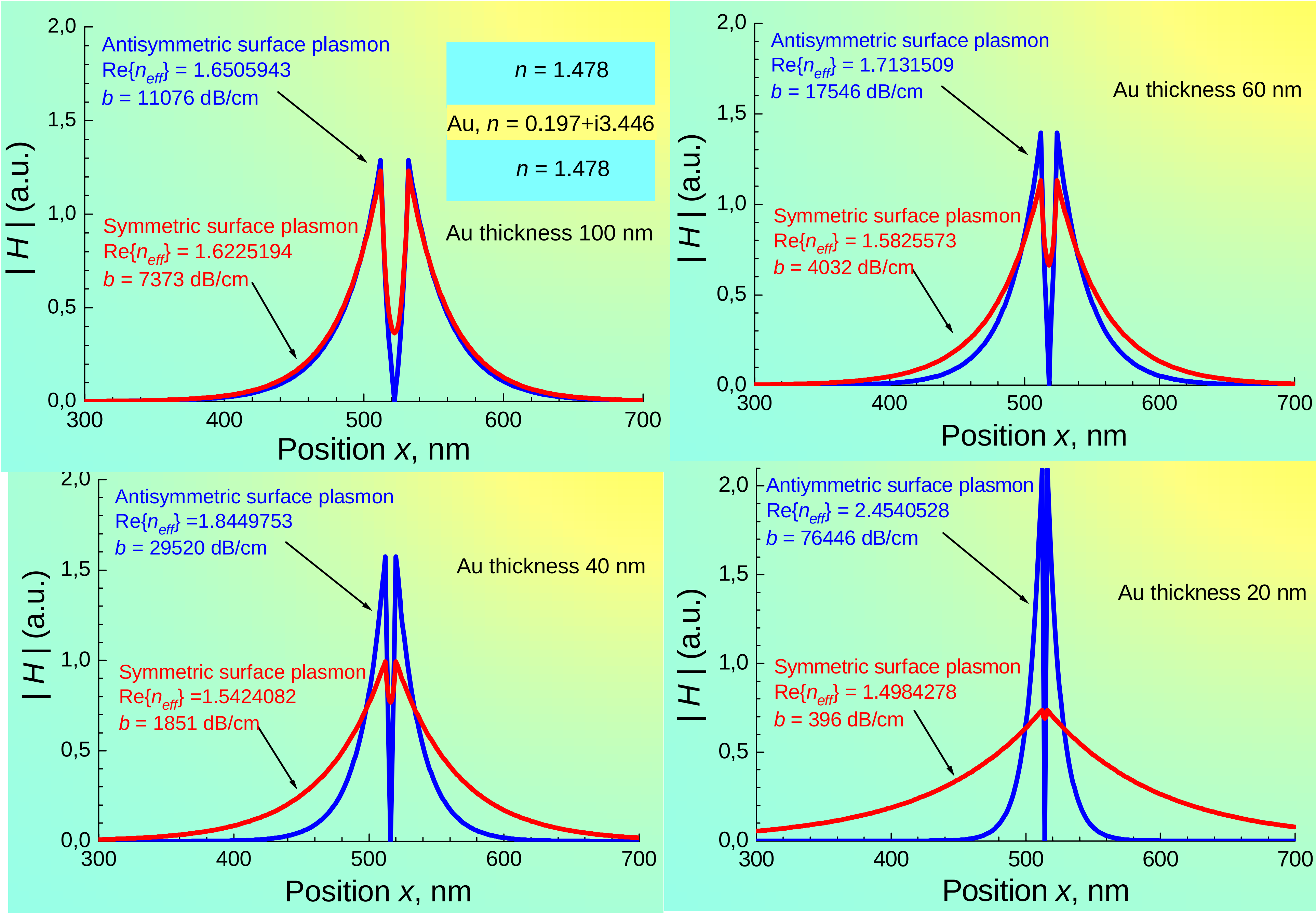
antisymetrický PP





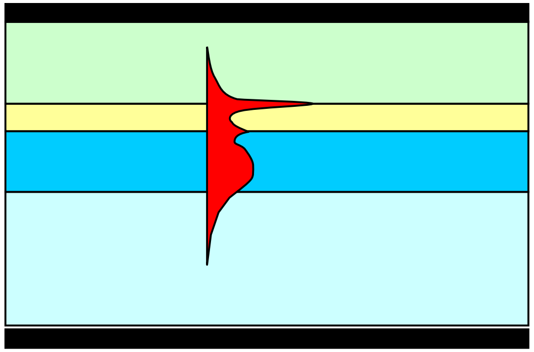
Rozložení polí PP na kovových vrstvách

Závislost na tloušťce kovové vrstvy

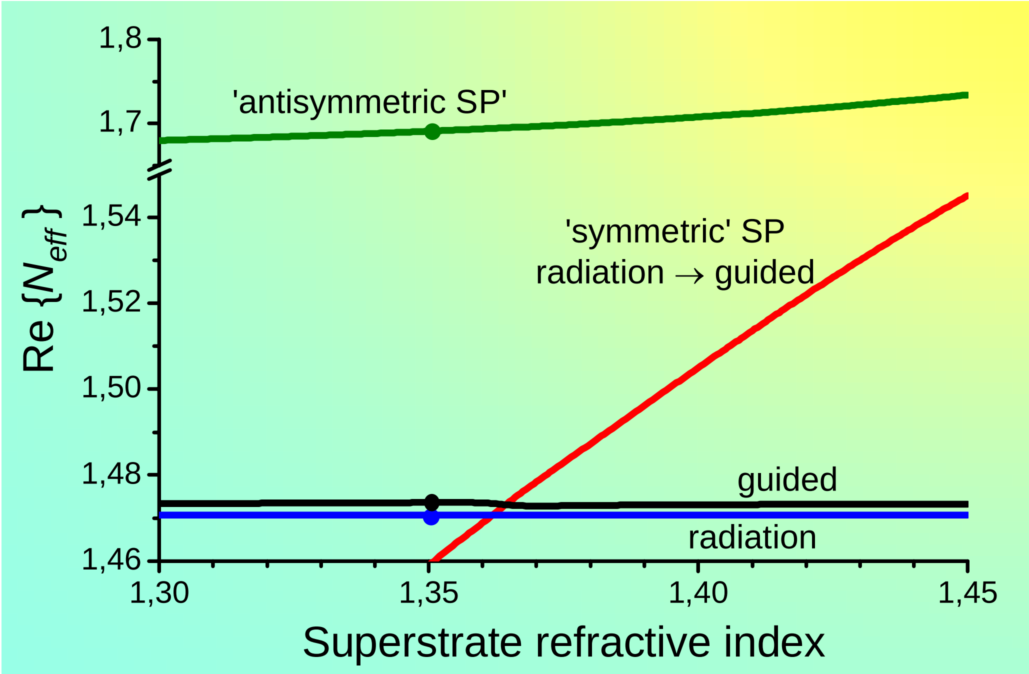


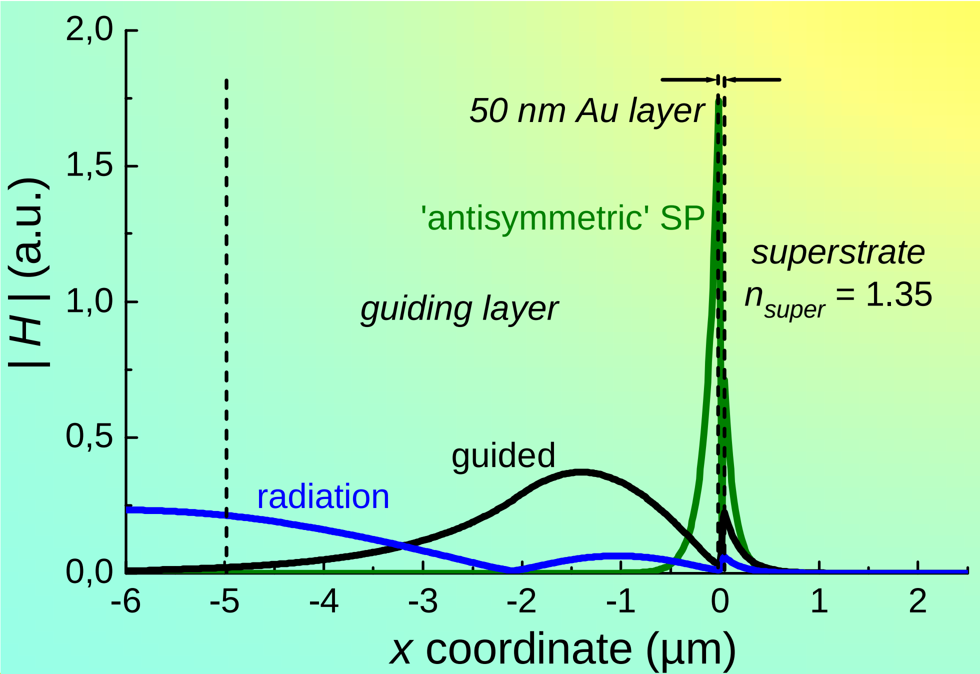
Vidy planárních vlnovodů s kovovou vrstvou

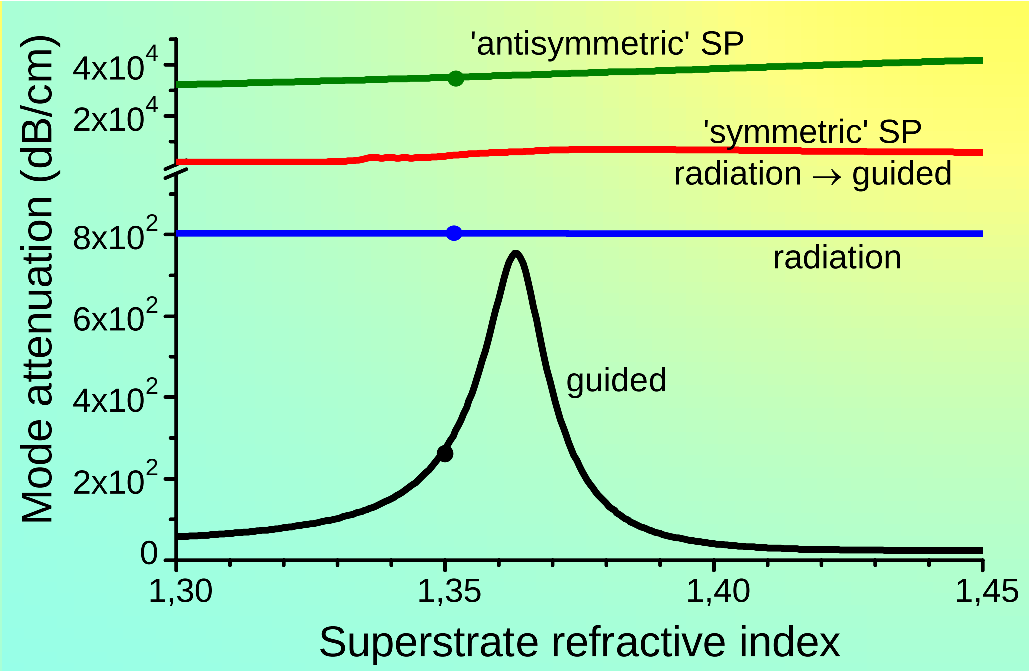
1.



$$d_{Au} = 50\ \text{nm}$$

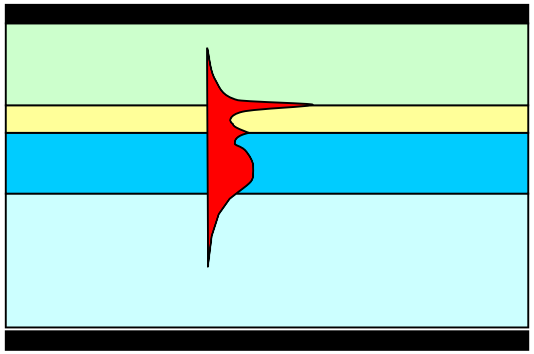




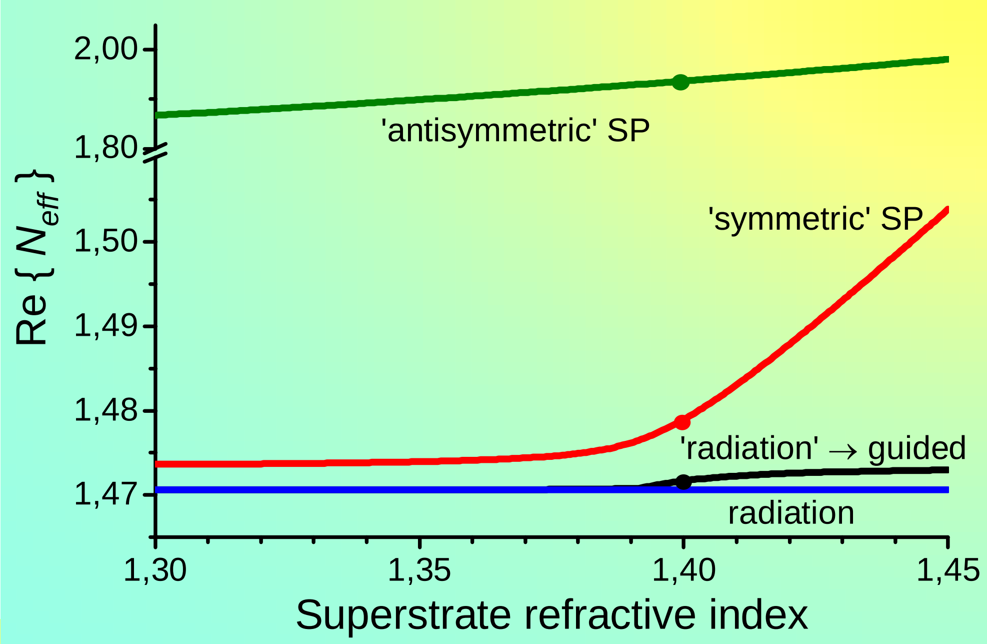


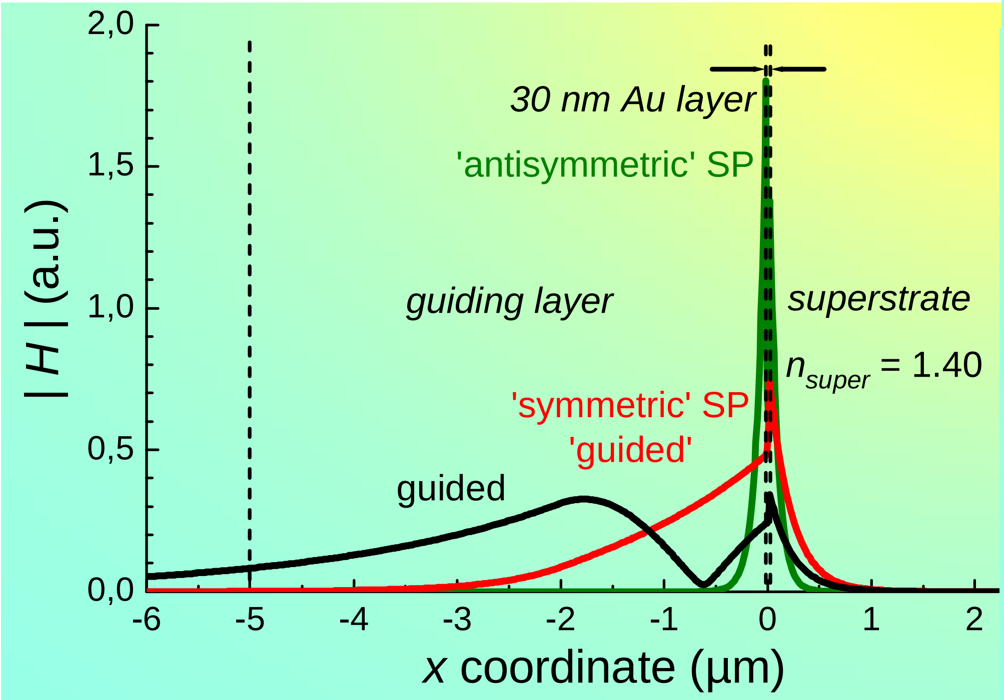
Vidy planárních vlnovodů s kovovou vrstvou

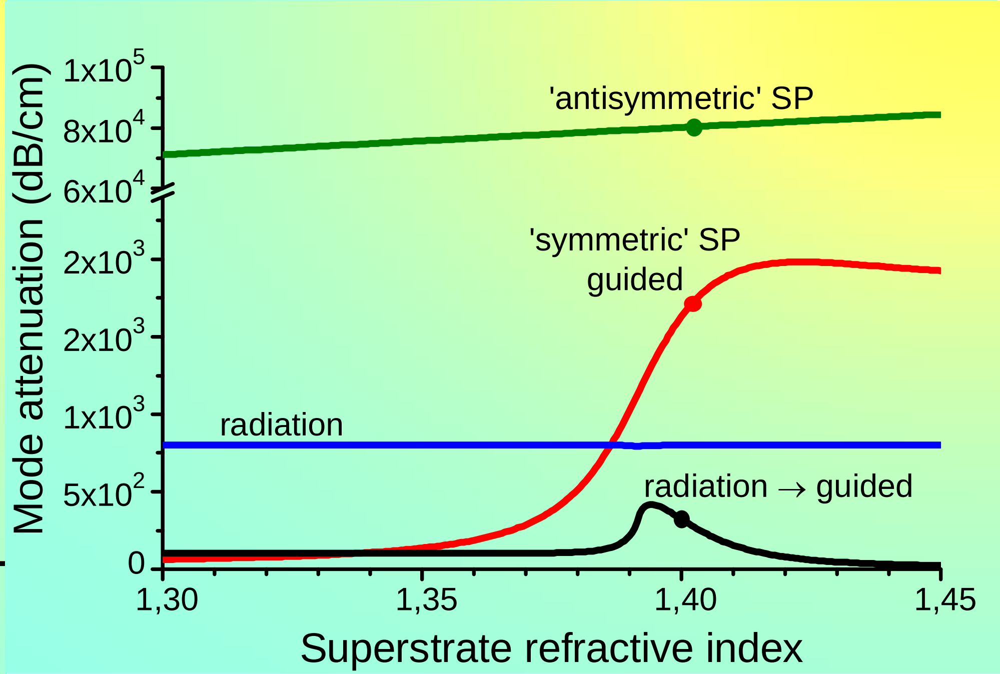
2.



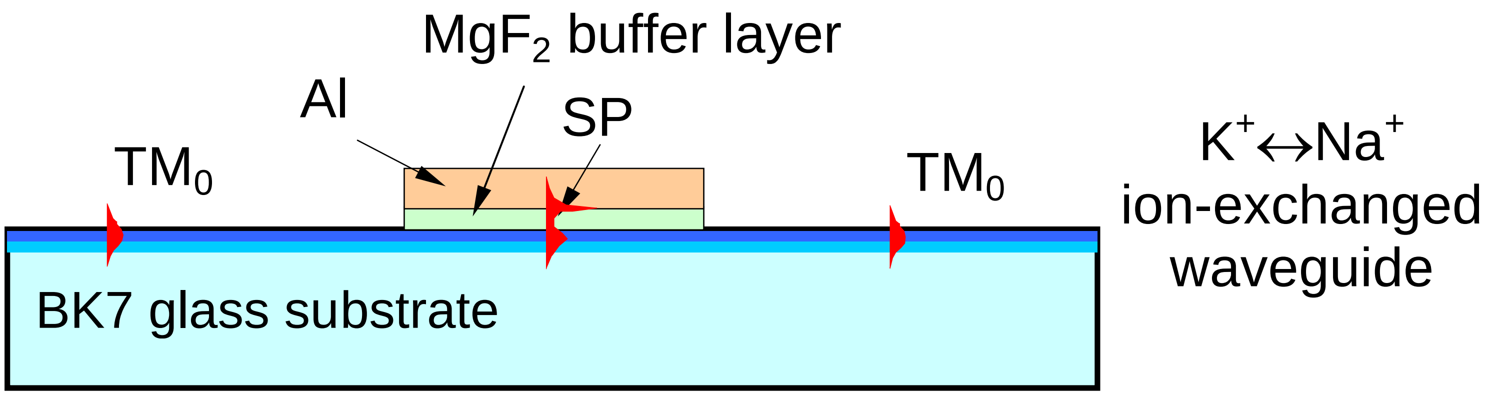
$$d_{Au} = 30\ \text{nm}$$

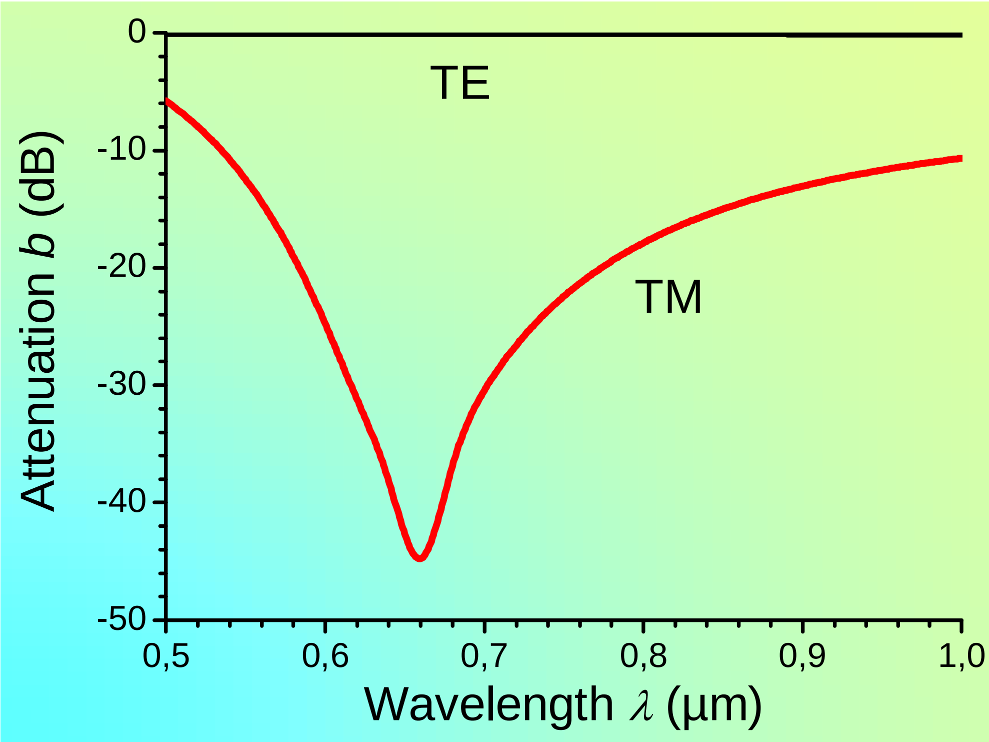


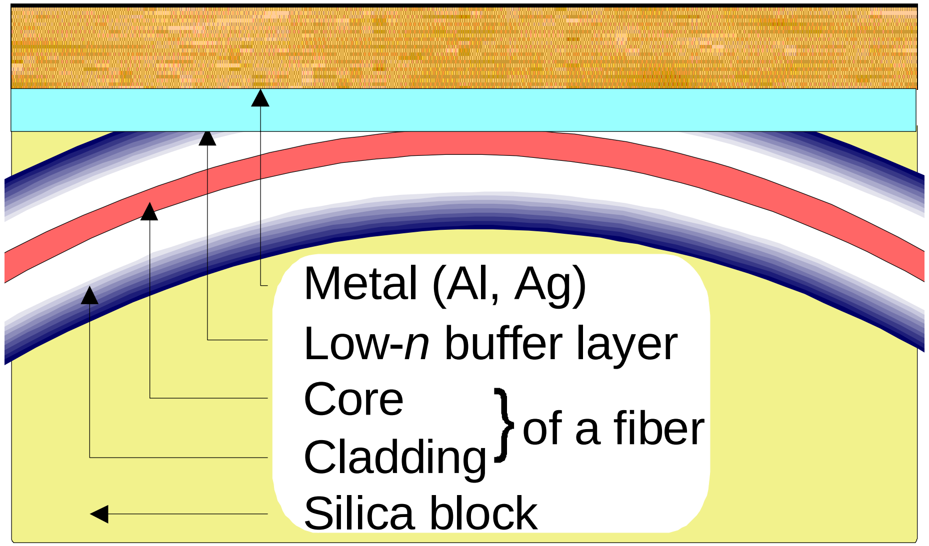




Vlnovodný polarizátor založený na rezonanční excitaci PP



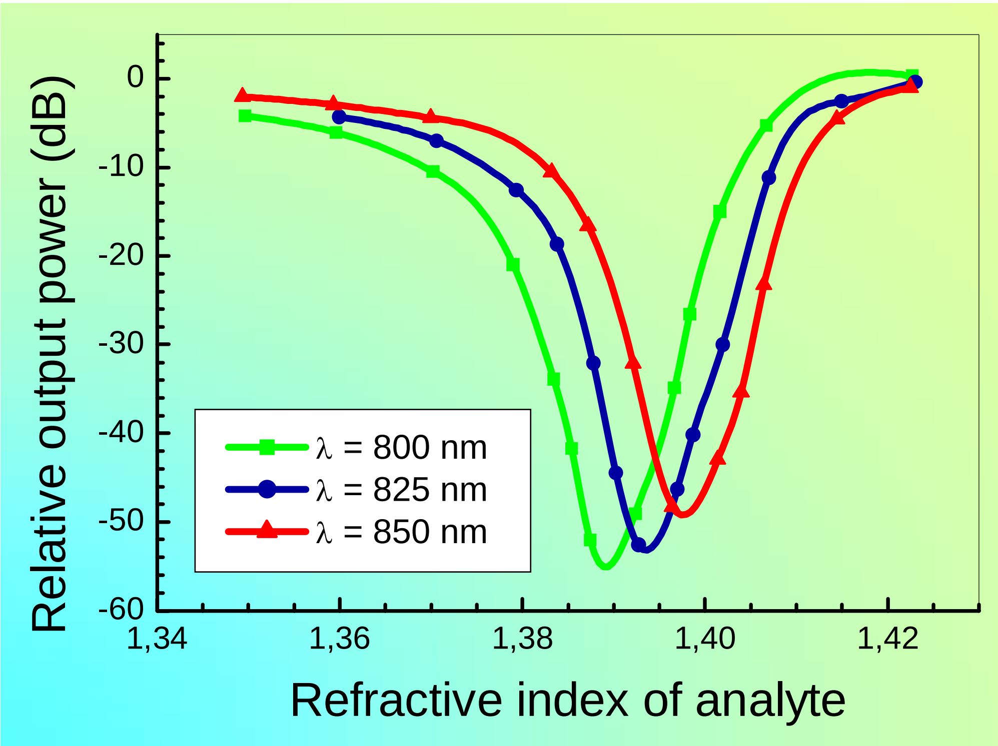


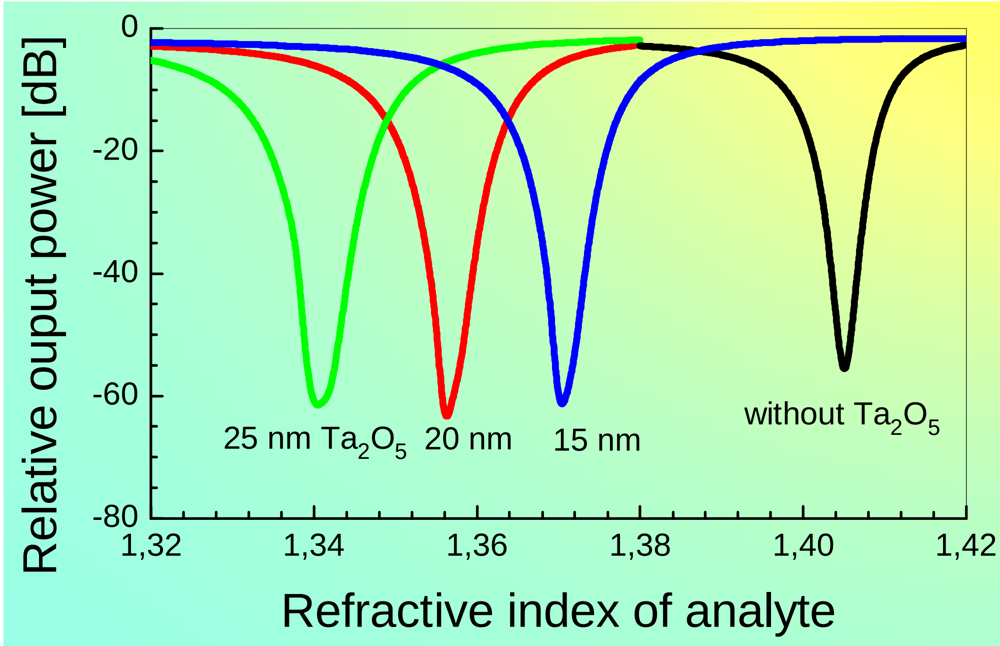


Průchod optického záření senzorem s PP

1. závislost na indexu lomu analytu (zkoumaného prostředí)

2D (planární) model



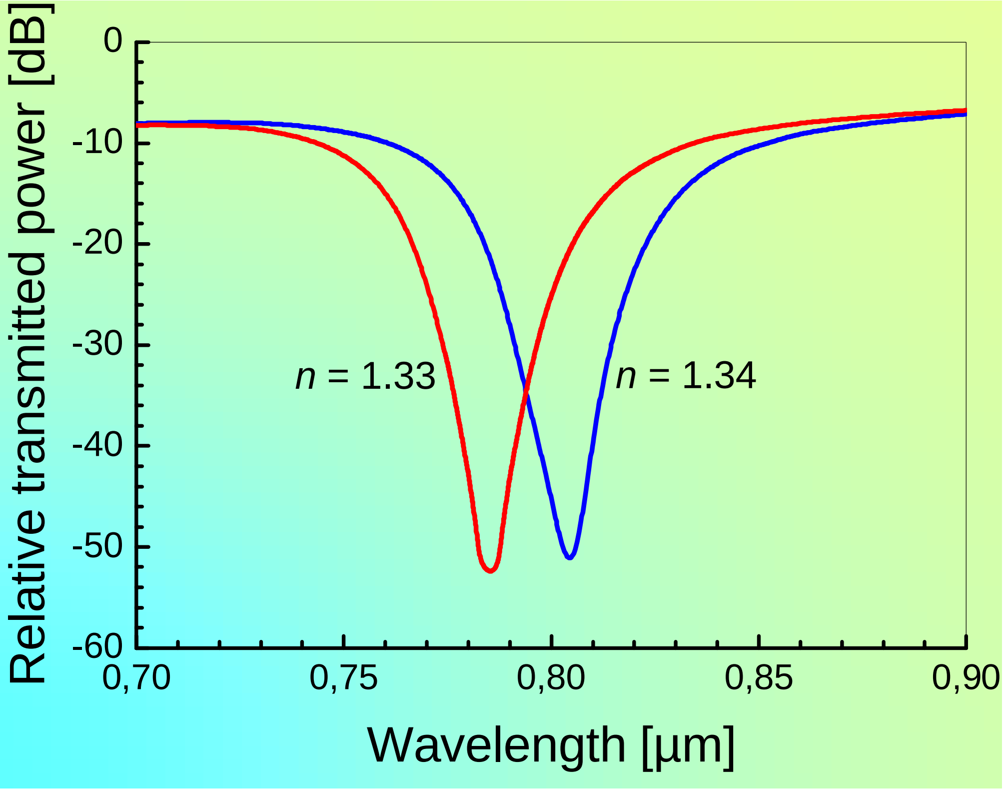


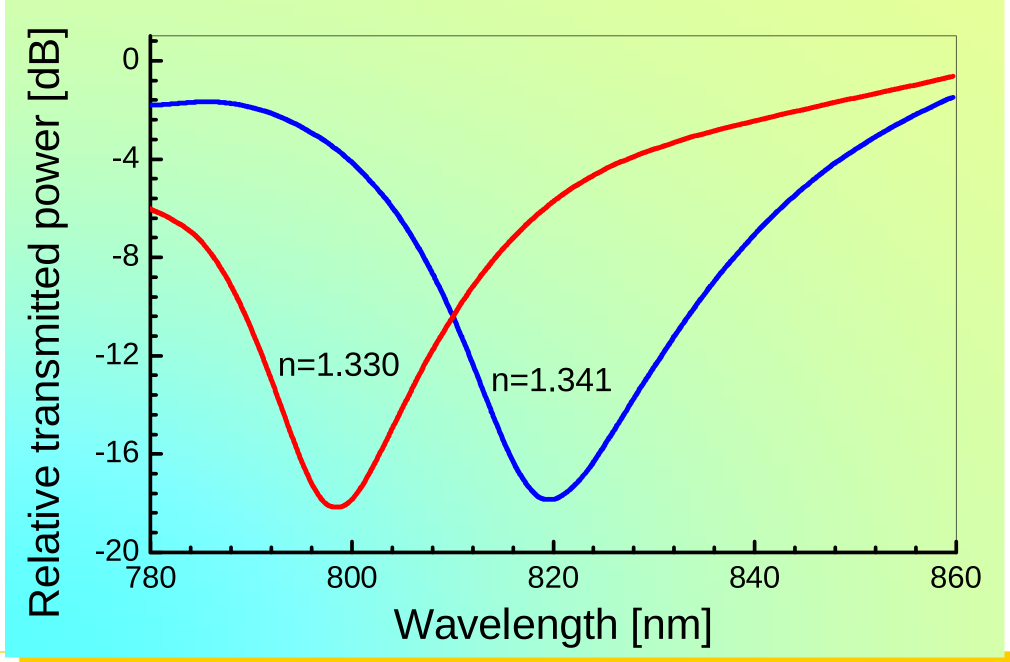
měření laditelným Ti:safírovým laserem

Průchod optického záření IO senzorem s PP

2. spektrální závislost

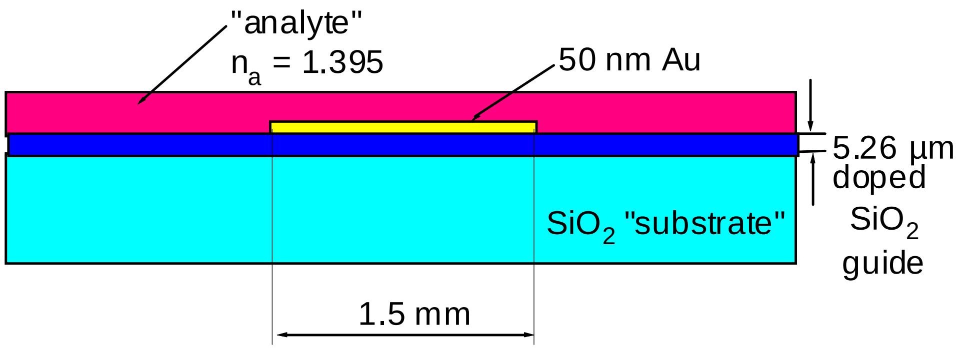
2D (planární) model

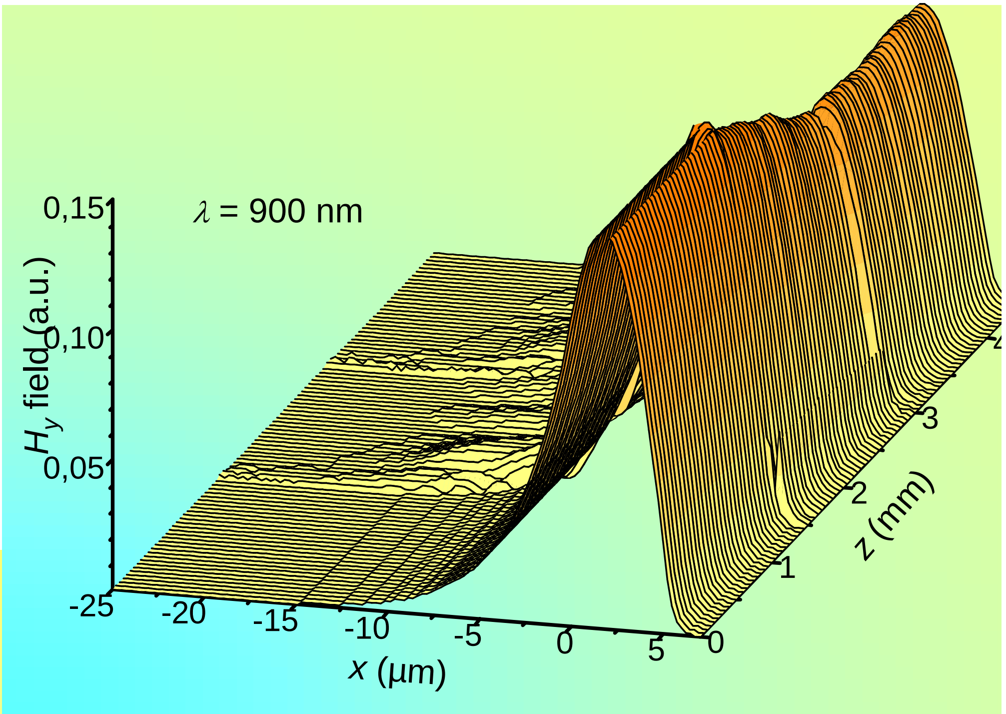


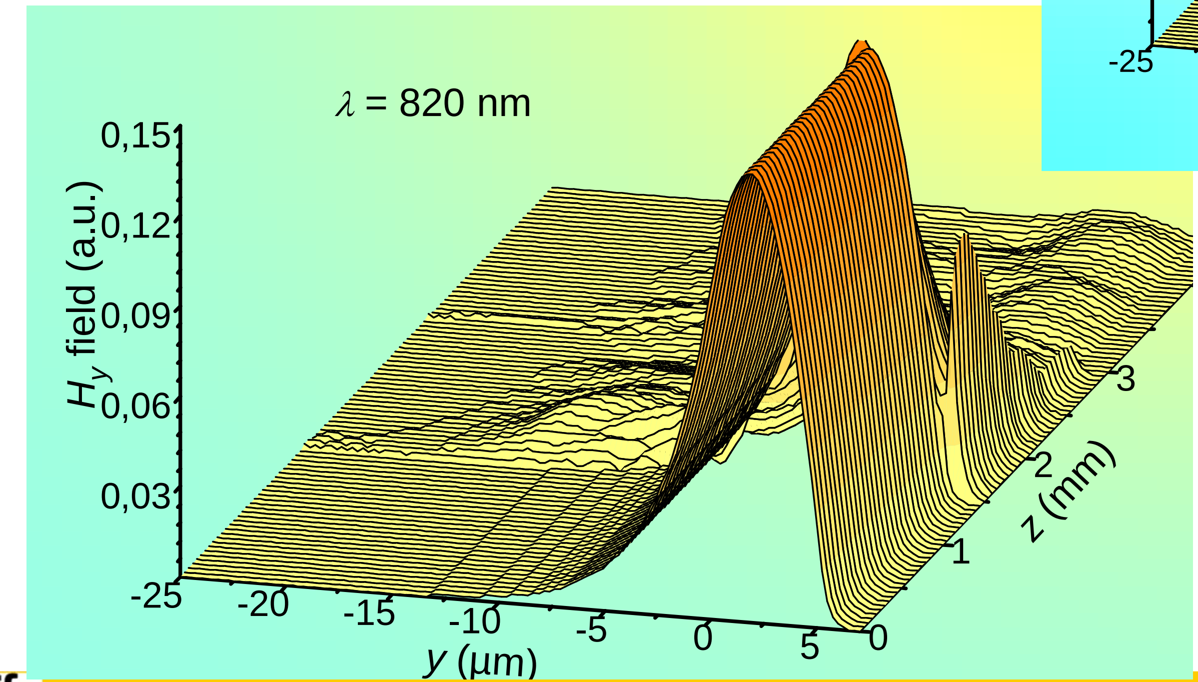


měřeno s širokopásmovou SLD a spektrálním analyzátorem

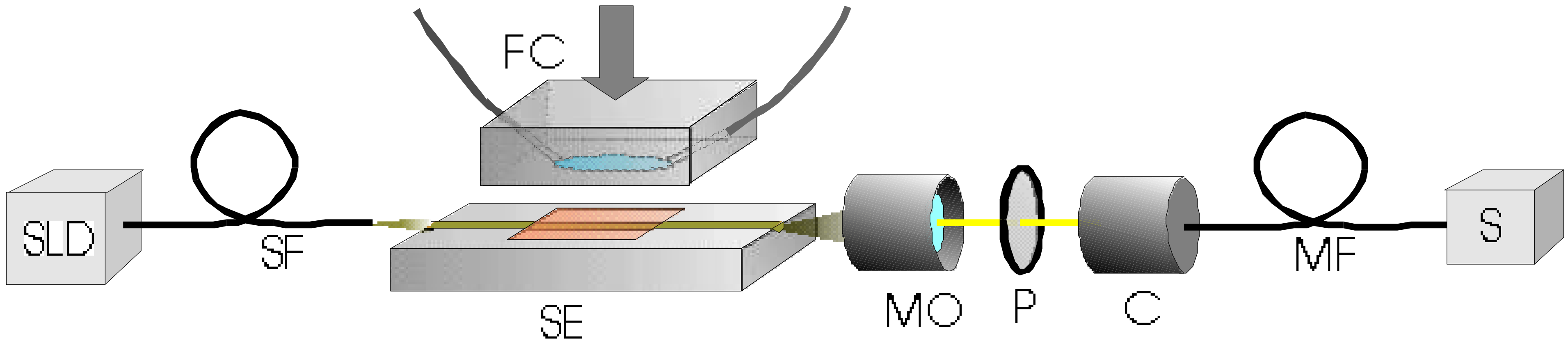
Rozložení optického záření ve vlnovodu s úsekem, na němž se může šířit PP

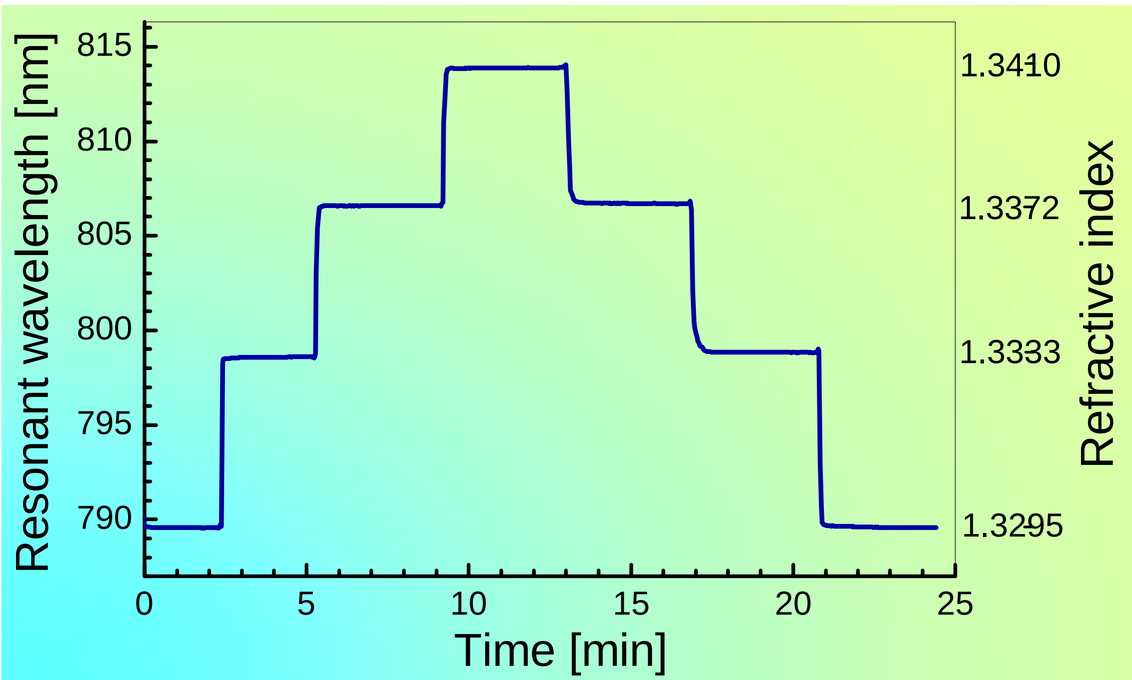






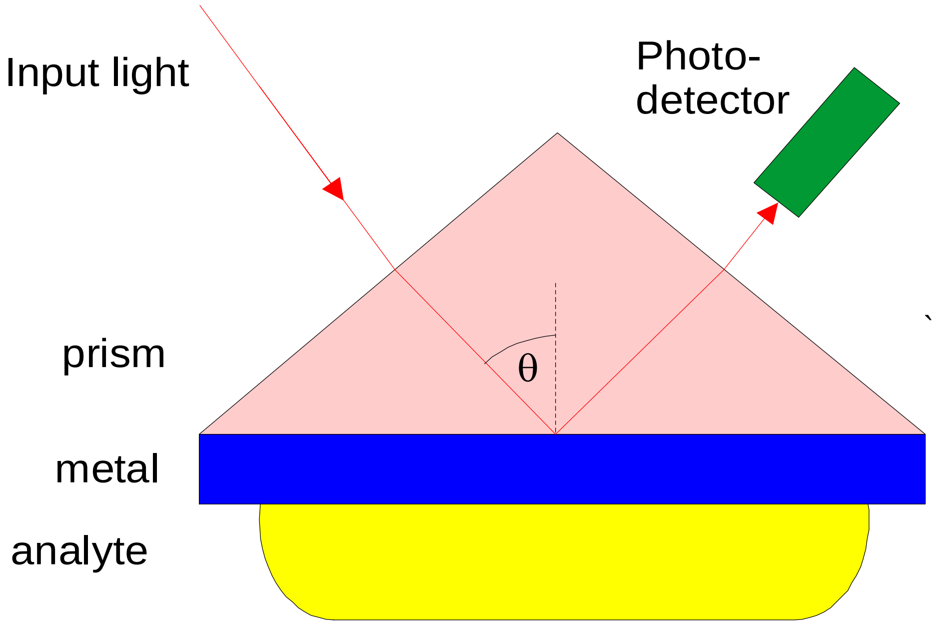
Experimentální uspořádání integrovaně-optického senzoru s PP



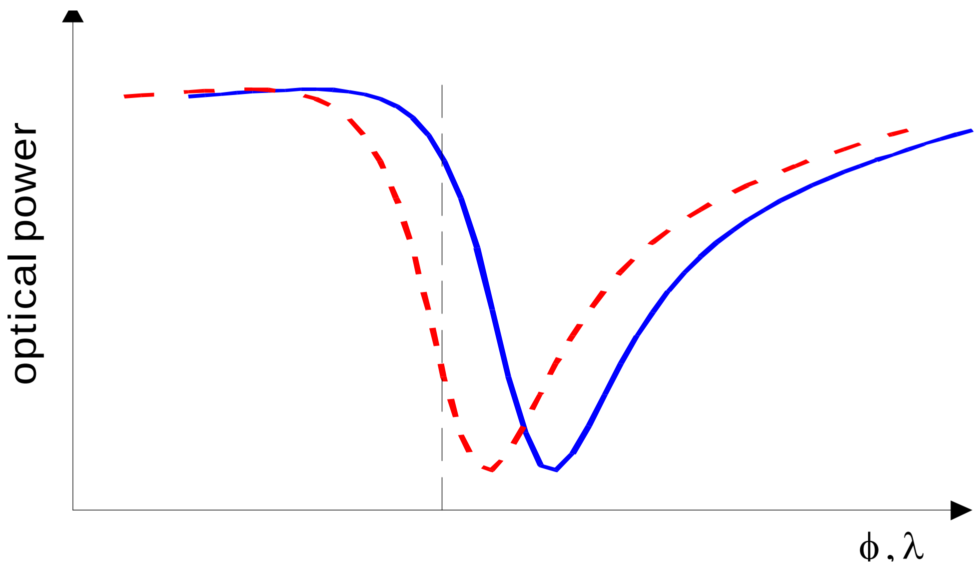


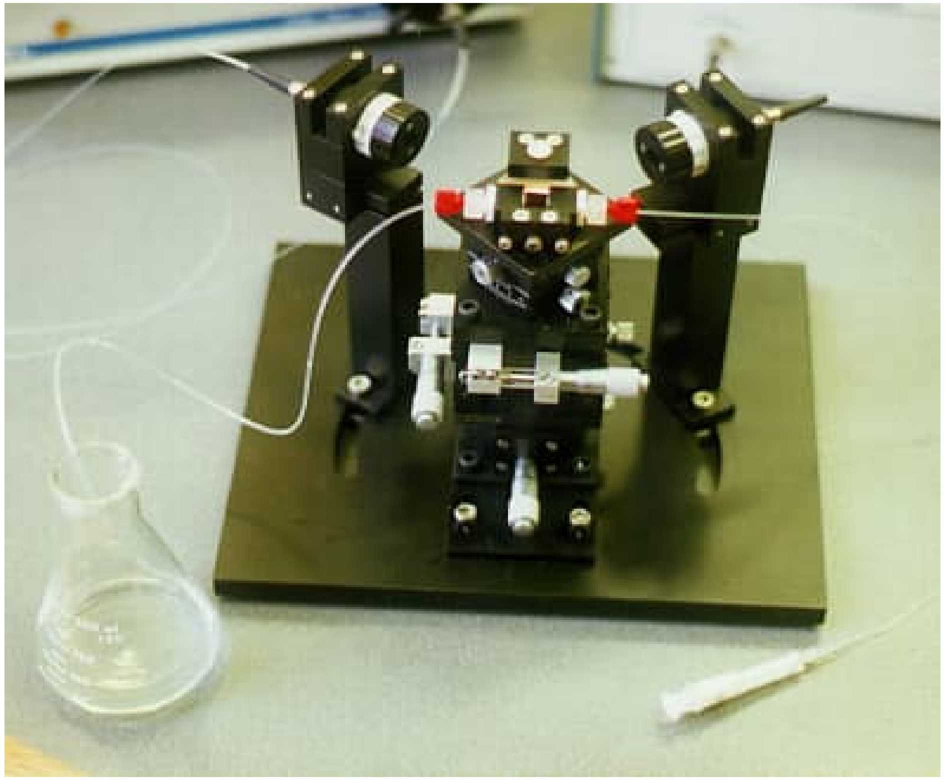
Rozlišení změn indexu lomu menších než 1.2×10^{-6}

Objemové senzory s PP



Rozlišení změn indexu lomu menších než 5×10^{-7}

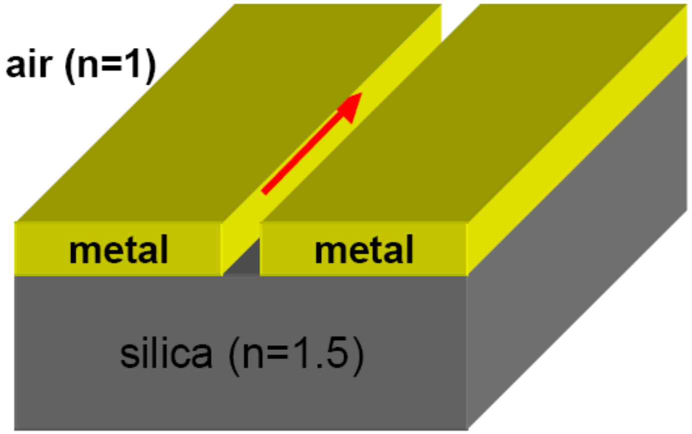


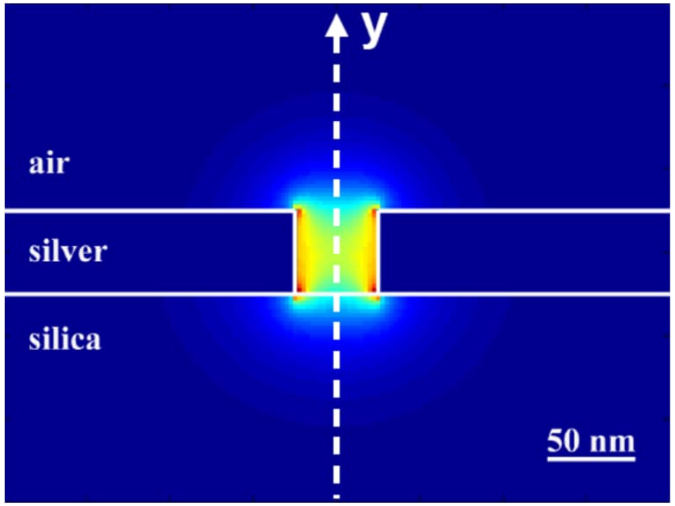


„Plazmonika“

(„fotonika“ využívající šíření povrchových plazmonů)

2D vedení povrchového plazmonu

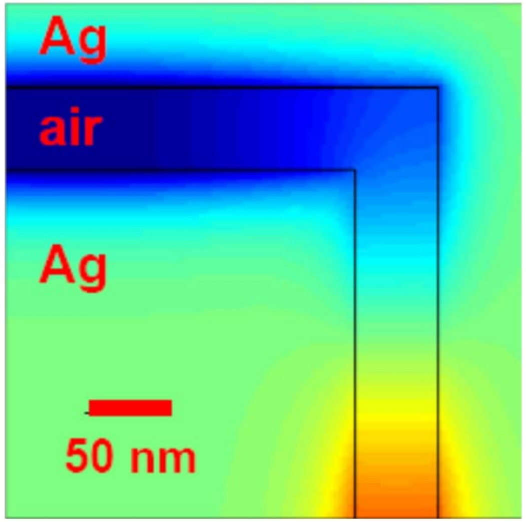




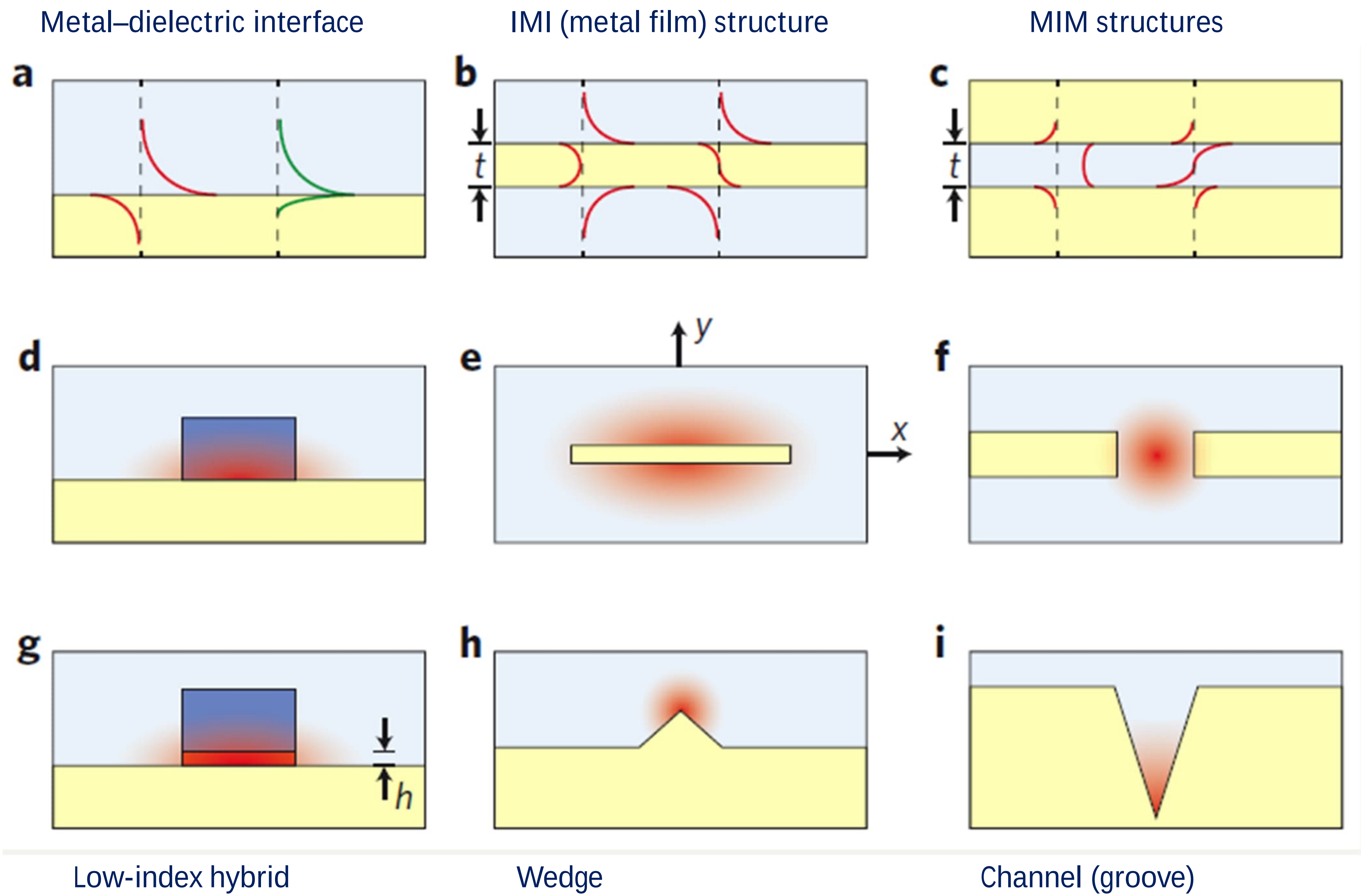
SP umožňuje lokalizovat optické záření ve velmi malém objemu,

Silný útlum v důsledku „ohmických“ ztrát v kovovém materiálu umožňuje šíření jen na vzdálenosti řádu 1-100 μm

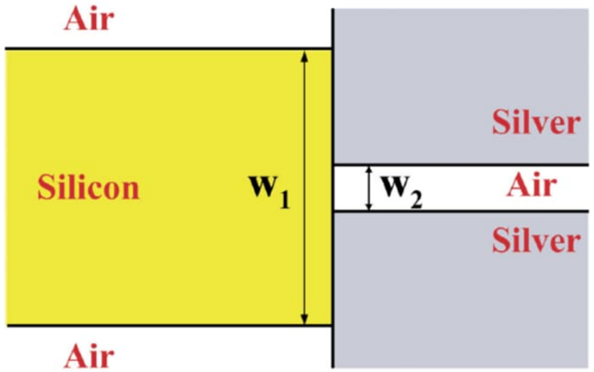
90° ohyb



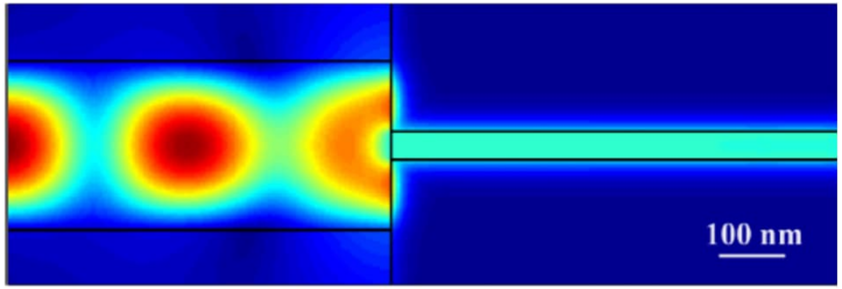
PLAZMONICKÉ VLNOVODY



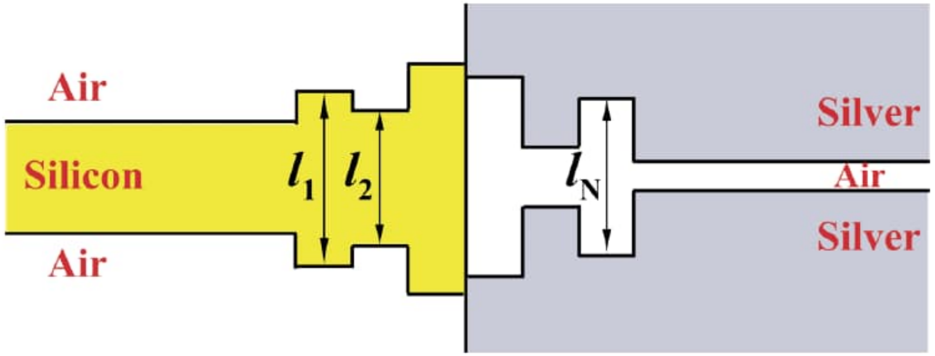
Přechod mezi vlnovodem SOI a plazmonovým vlnovodem

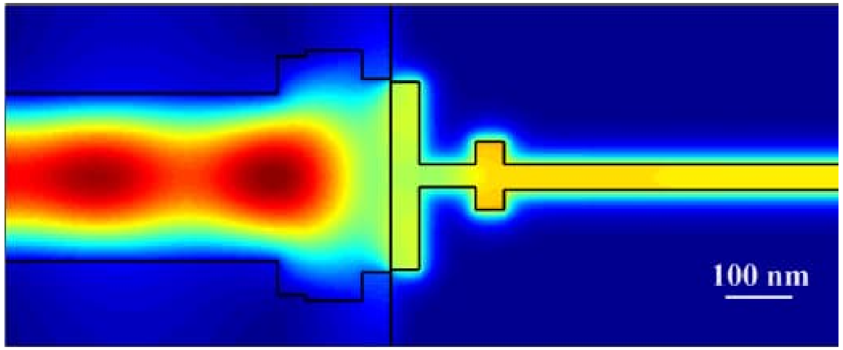


Účinnost vazby cca 64%



Účinnost vazby cca 90%





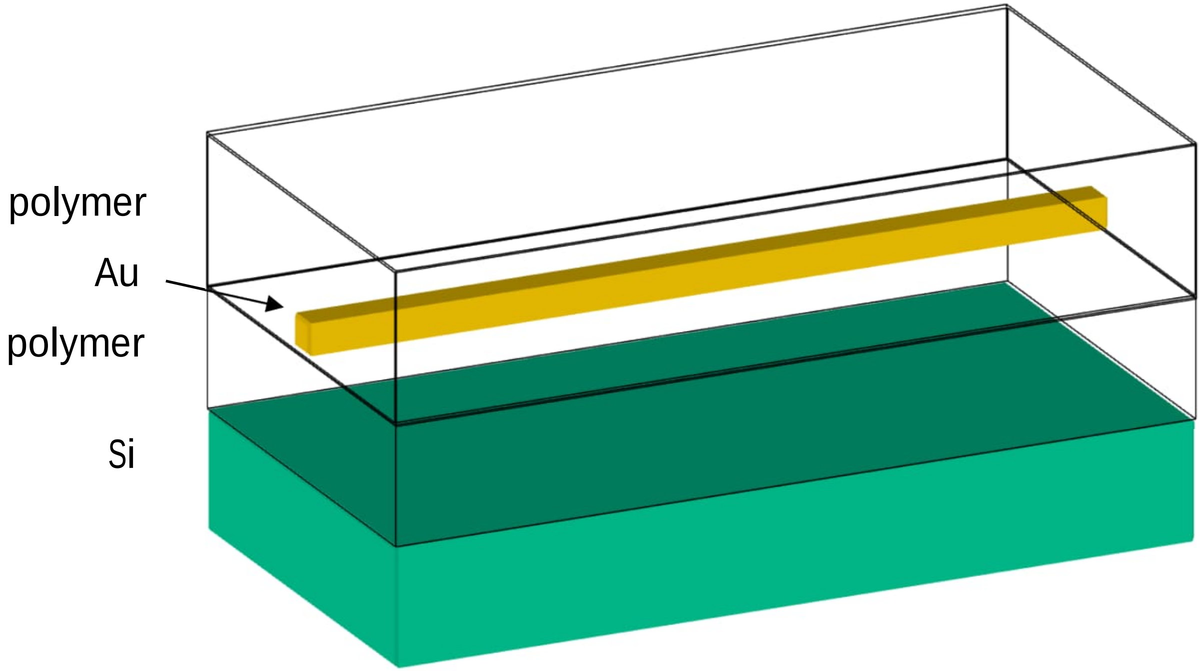
G. Veronis, S. Fan, OWTNM 2006, p. 12
(Stanford university)

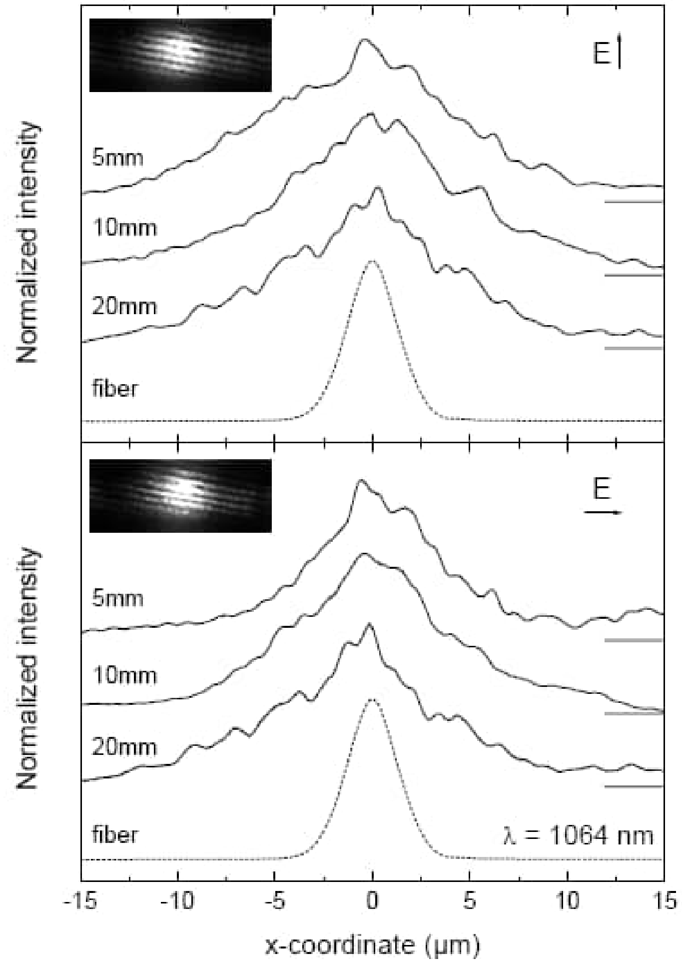
„Zlatý nanodrát“ jako vlnovod pro povrchové plazmony

(T. Rosenzveig, ECIO 2007)

Průřez „nanodrátu“
100×100 nm,

útlum 4.3 dB/cm





Rozložení blízkého pole
„plazmonů dalekého dosahu“

„Vlnovod“ tvořený řadou kovových nanočástic – vázané lokalizované plazmony

(S.A.Maier, ECIO 2007)

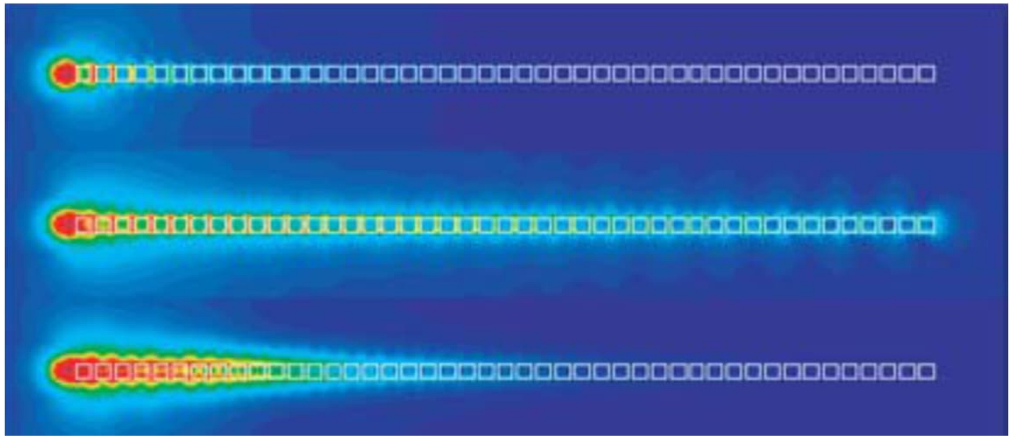
„Řetízek“ Au krychliček o straně 45 nm vzdálených od sebe 20 nm

Excitační vlnová délka

500 nm

429 nm

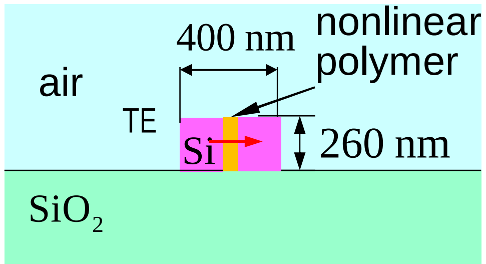
390 nm



Na vlnové délce 429 je „překlenutelná vzdálenost“ pro pokles výkonu na $1/e^2$ celkem 2,2 mm (útlum cca 40 dB/cm)

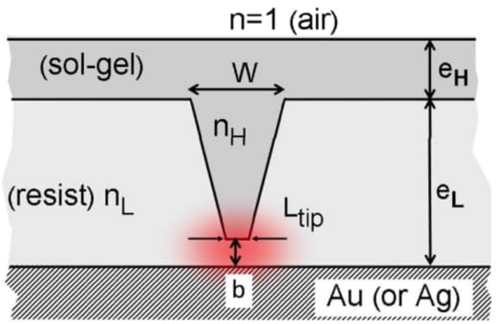
Nové typy plazmonických vlnovodů

SOI "slot waveguide"



C. Koos & al., *Nat. Photonics* 3(4), 16–219 (2009)

PIROW – plasmonic inverted rib optical waveguide



H. Benisty and M. Besbes, *J. Appl. Phys.* 108(6), 063108 (2010).

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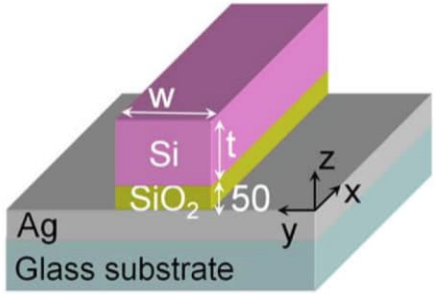
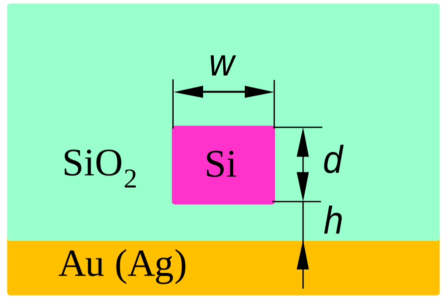
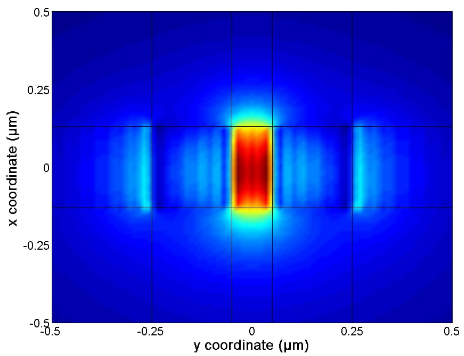


H.-S. Chu & al., *J. Opt. Soc. Am. B* 28(12), 2895 (2011) (others, too)

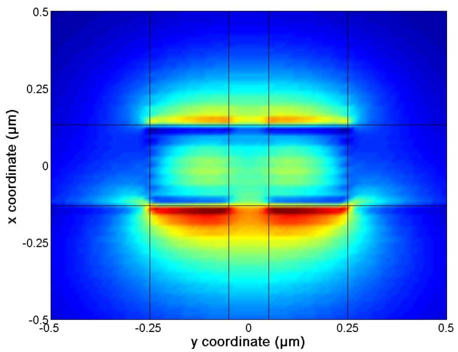
Hybrid dielectric-plasmonic slot waveguide (HDPSW)



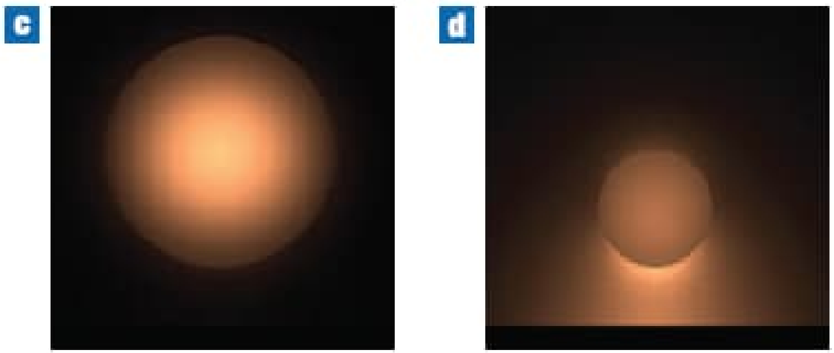
R. F. Oulton & al., *New J. Phys.* 10, 105018 (2008)



TE_{00} E_y

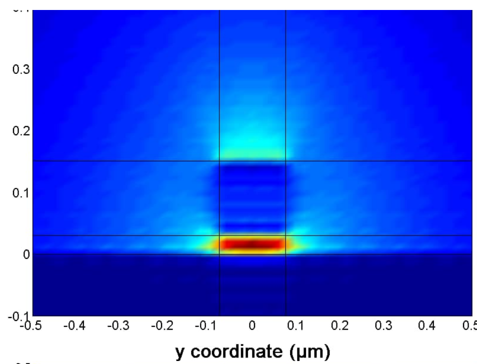


TM_{00} E_x

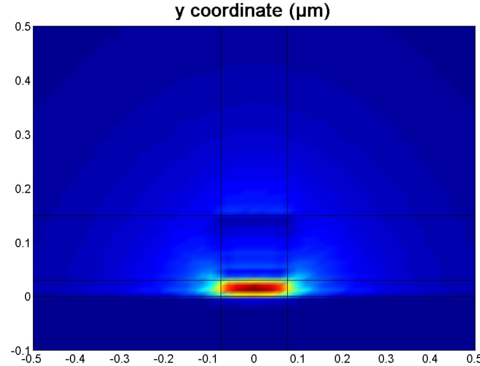


R. F. Oulton & al., *Nat. Photonics* 2, 496 (2008);

E_x

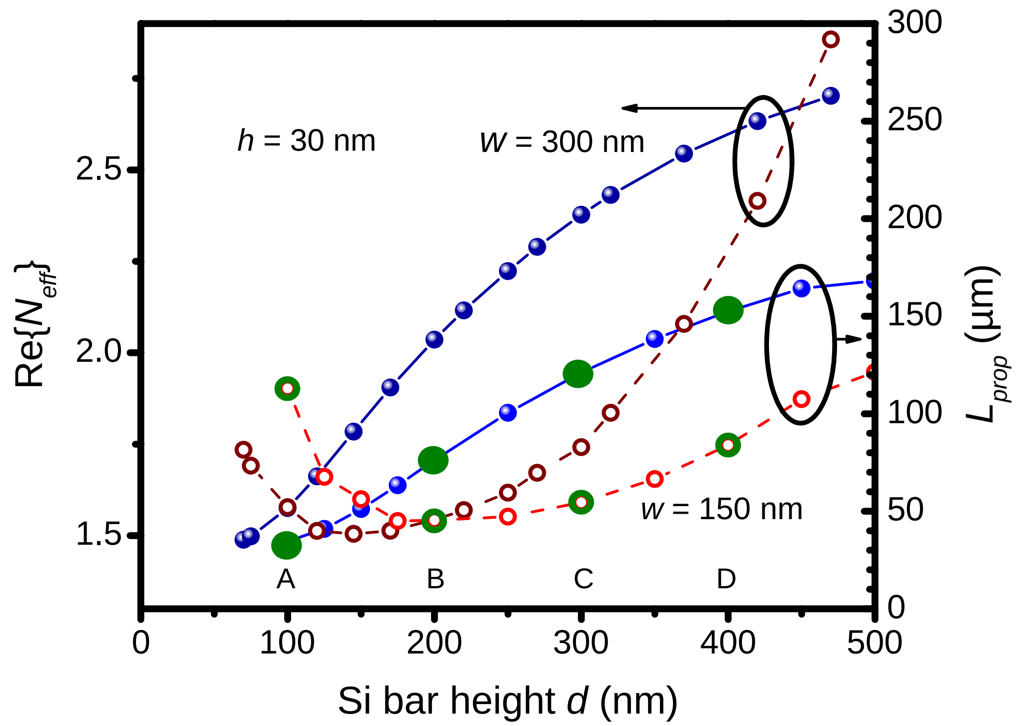


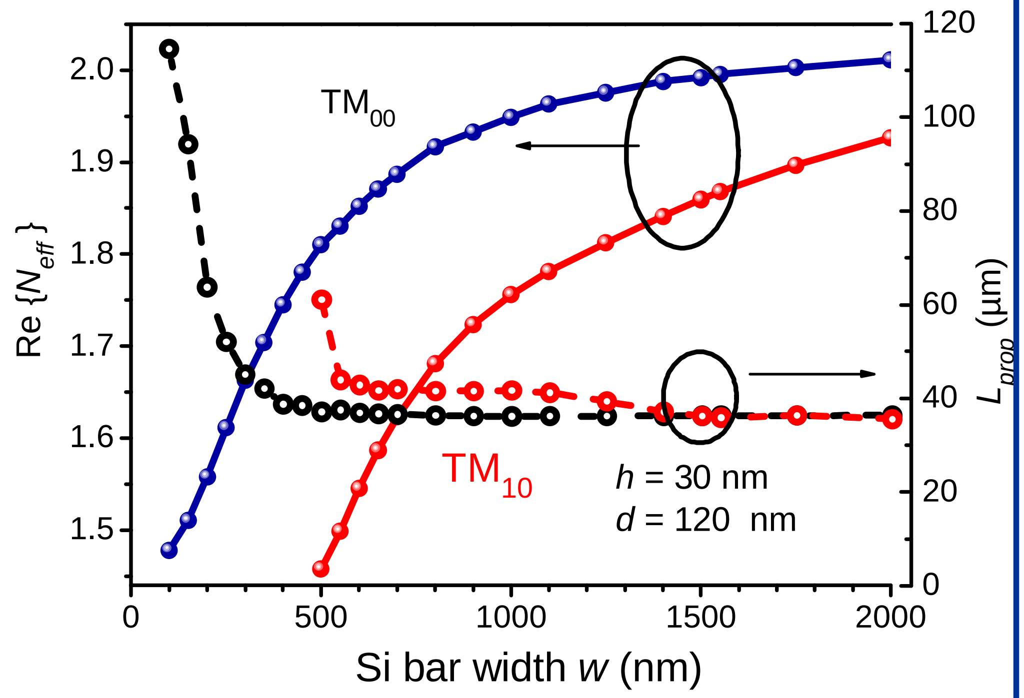
P_z



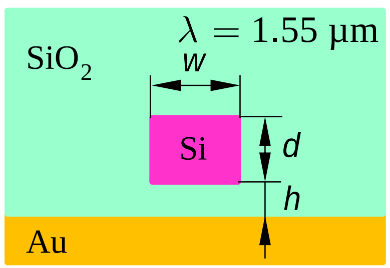
Hybrid dielectric-plasmonic slot waveguide

Influence of basic geometric parameters

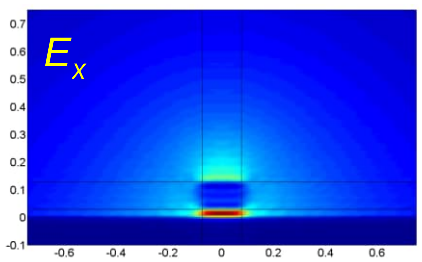




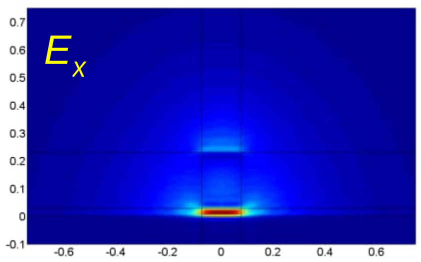
w = 150 nm



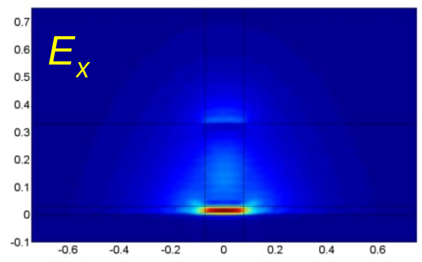
A: d = 100 nm



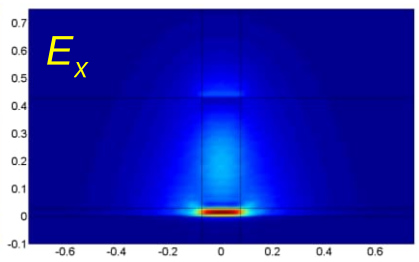
B: d = 200 nm



C: d = 300 nm

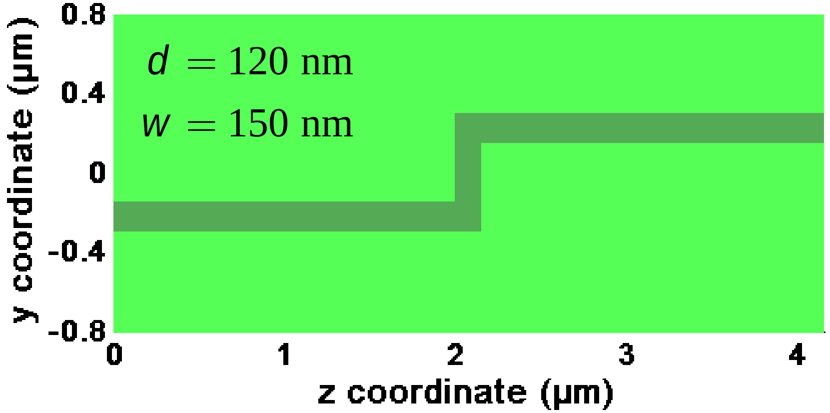


D: d = 400 nm

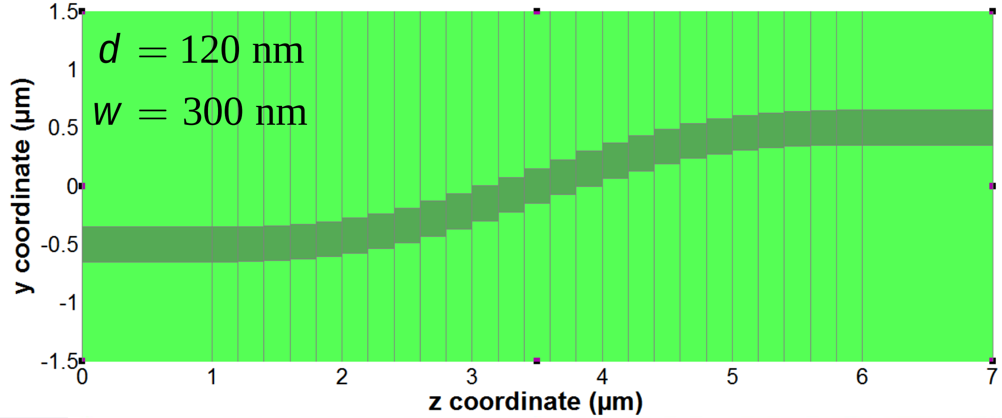


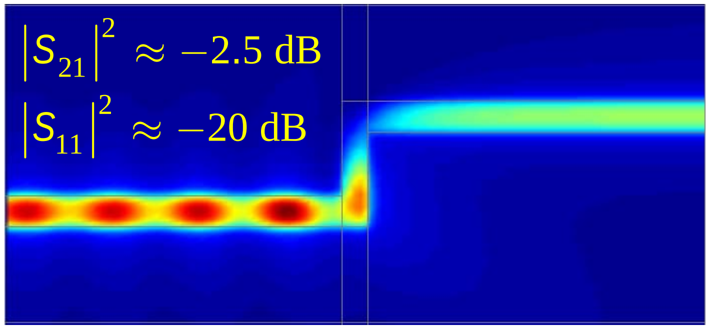
HDPSW DEVICES

HDPSW sharp S bend

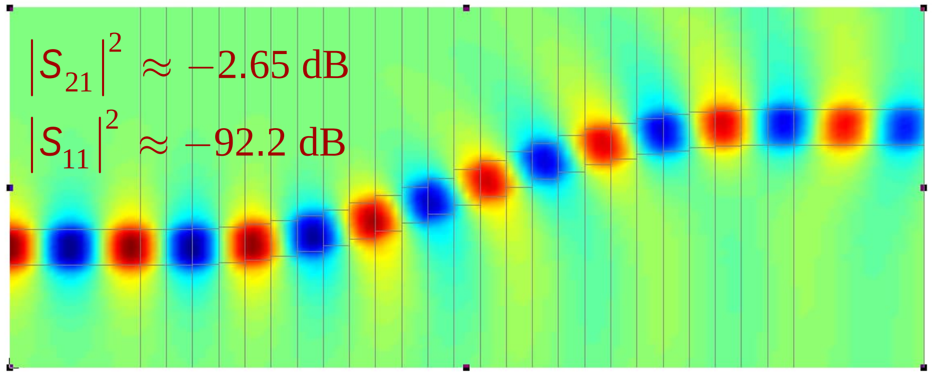


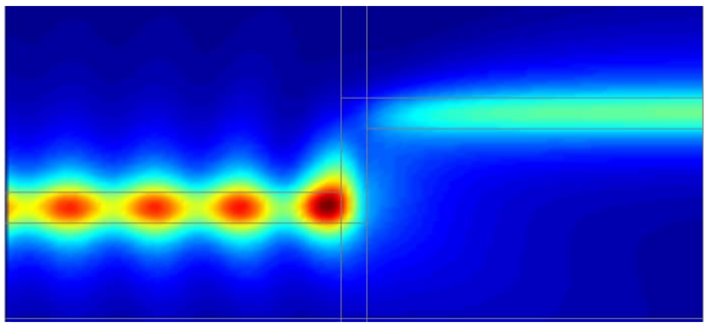
HDPSW smooth S bend



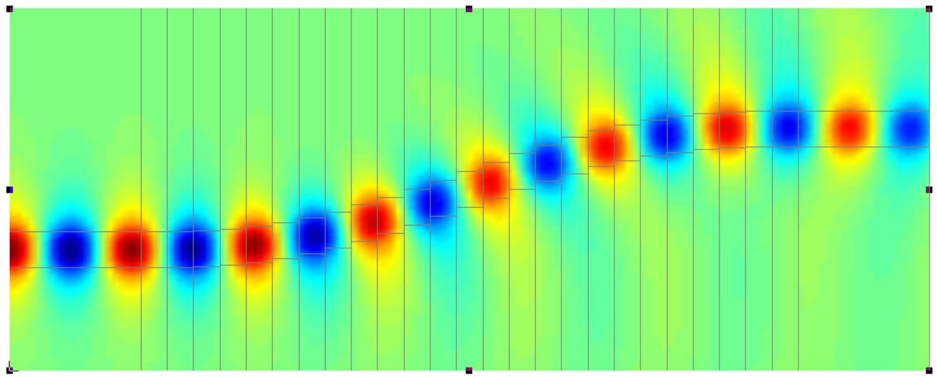


E_x

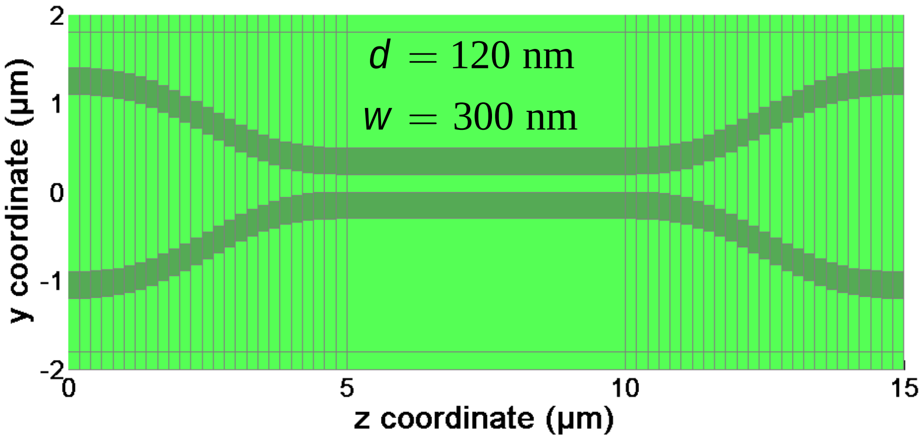


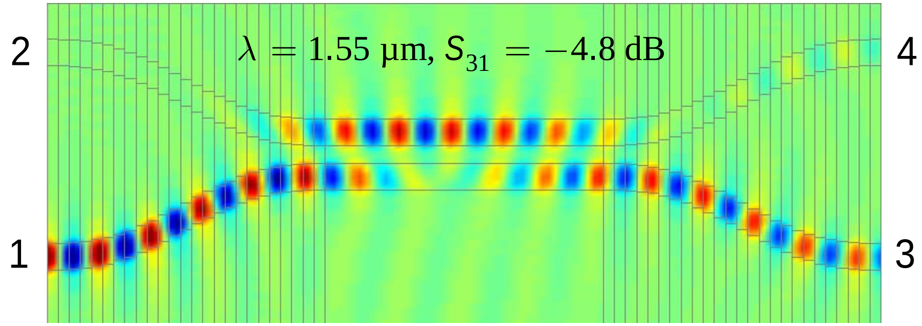


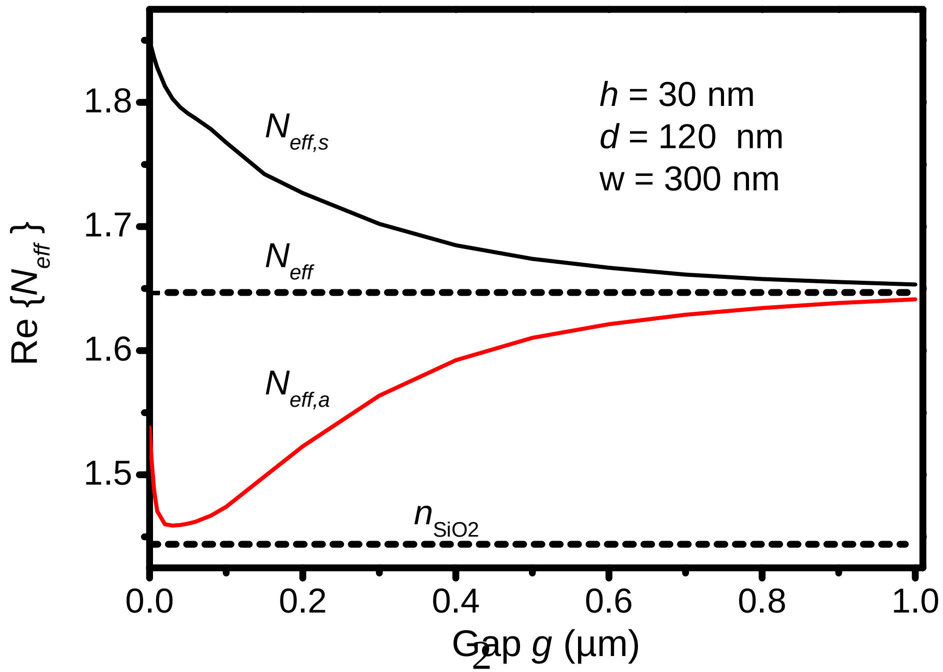
H_y

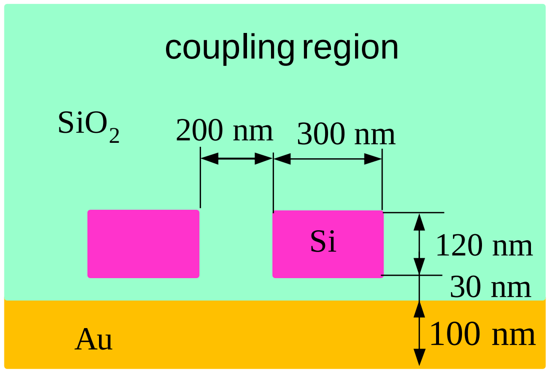


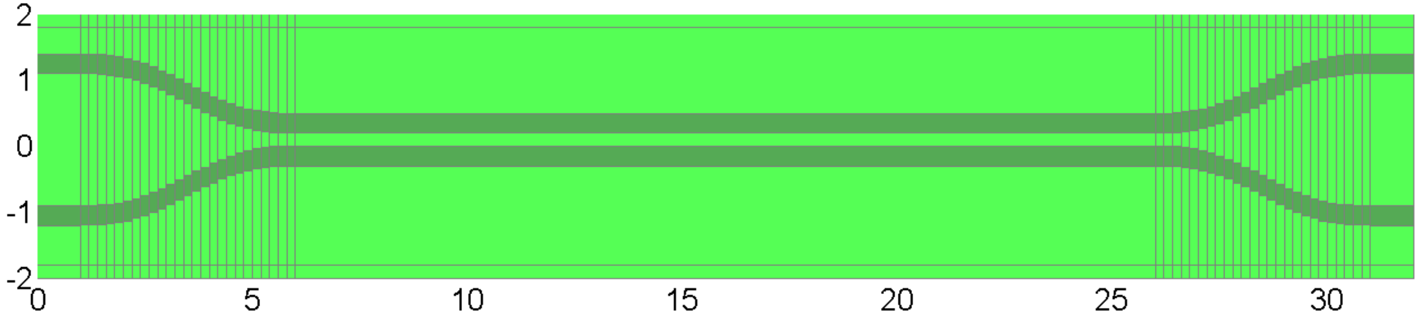
DIRECTIONAL COUPLER

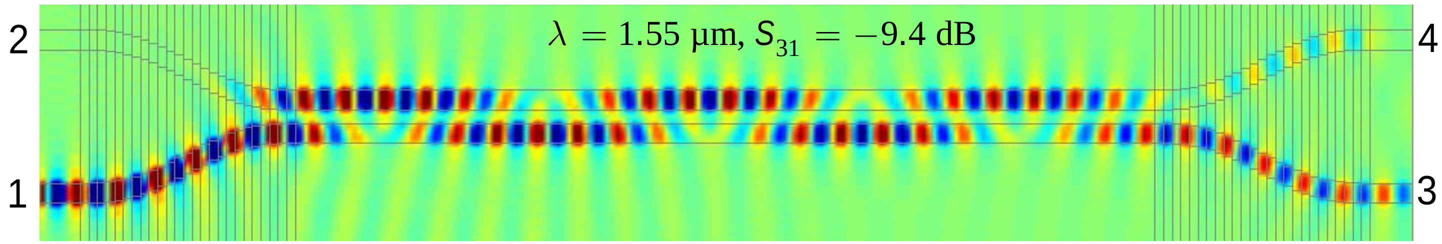






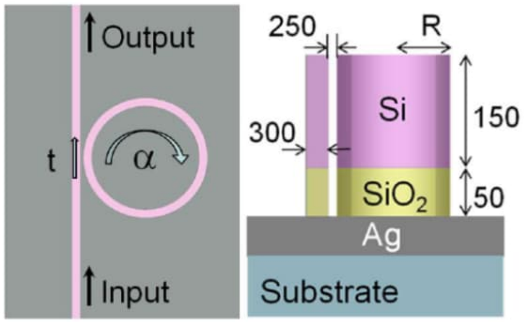






RING MICRORESONATOR

H.S. Chu et al., JOSA B 28, 2895 (2011)



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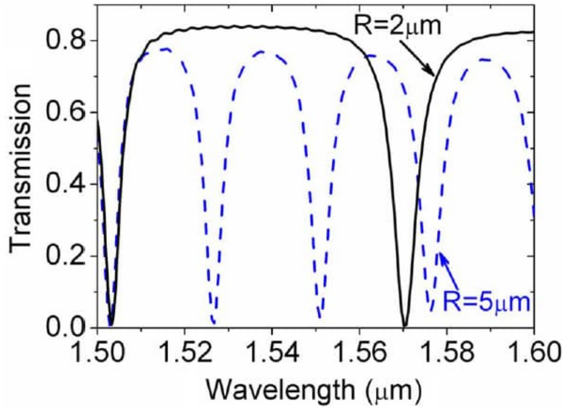
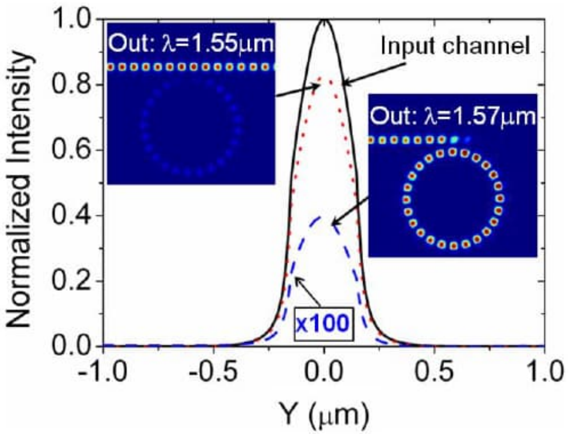
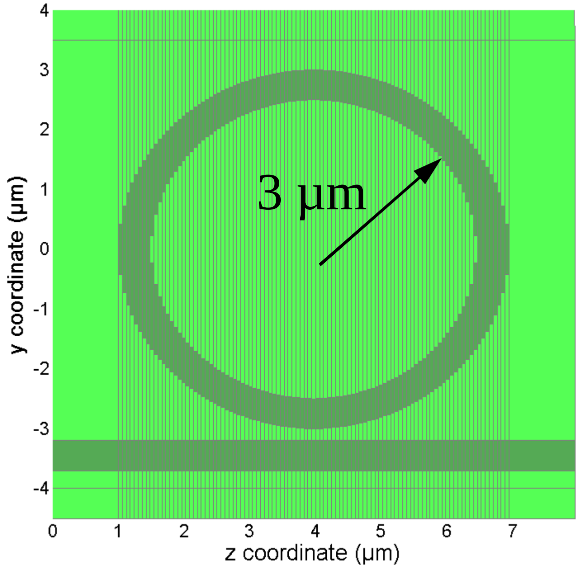
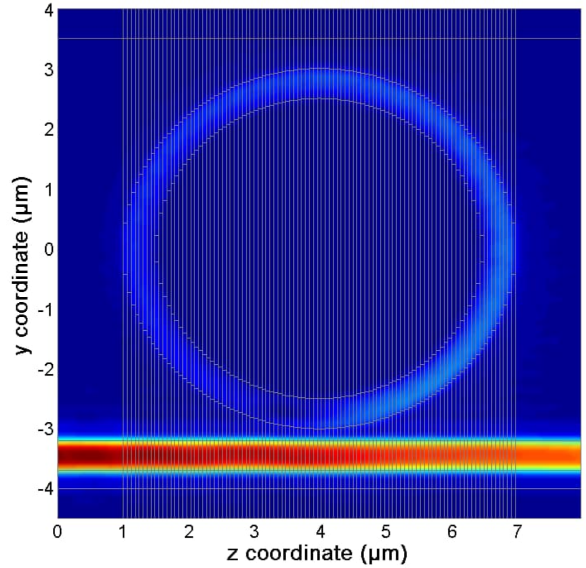




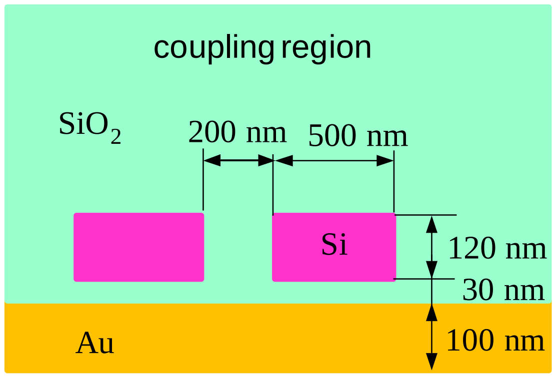
Present work



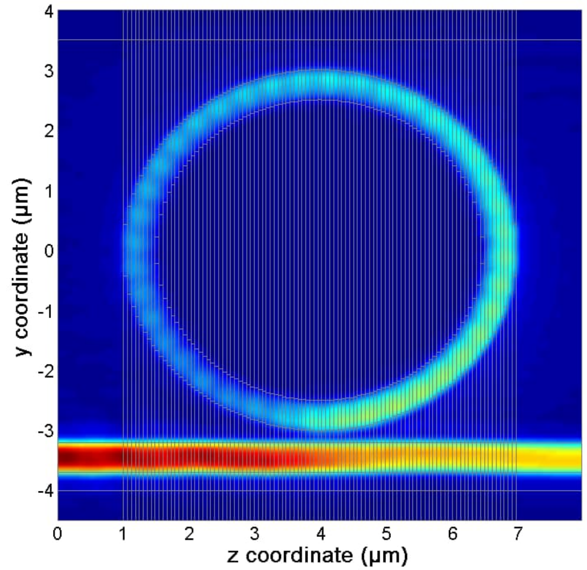
Off-resonance: $\lambda = 1.55$ μm, $S_{21} = -2$ dB



E_x



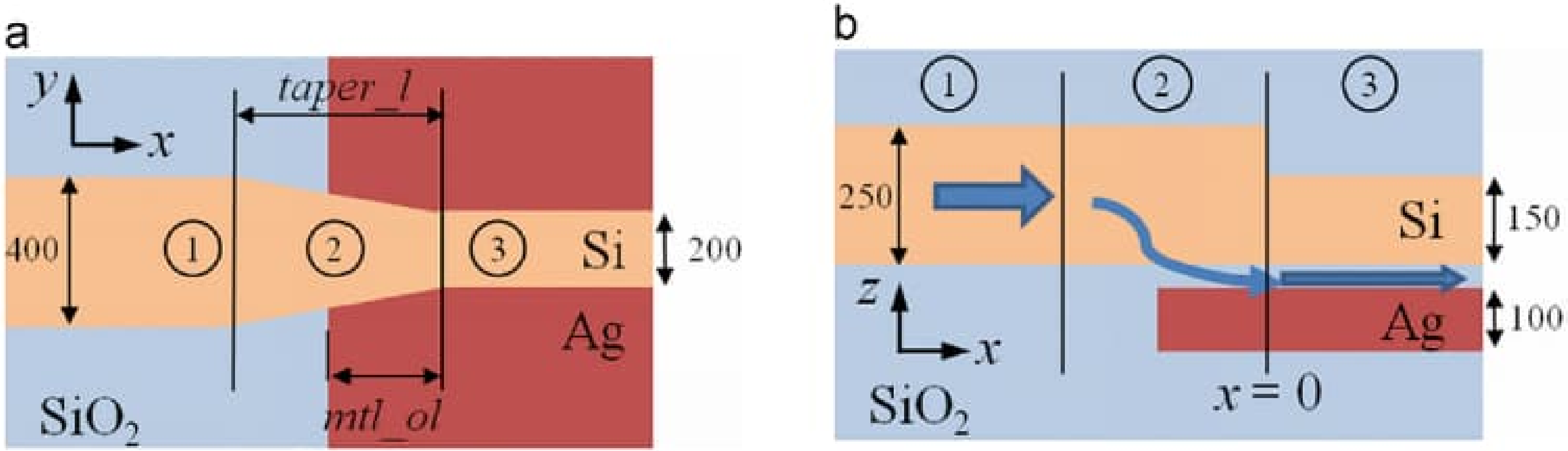
≈ On-resonance: $\lambda = 1.57$ μm, $S_{21} = -4$ dB

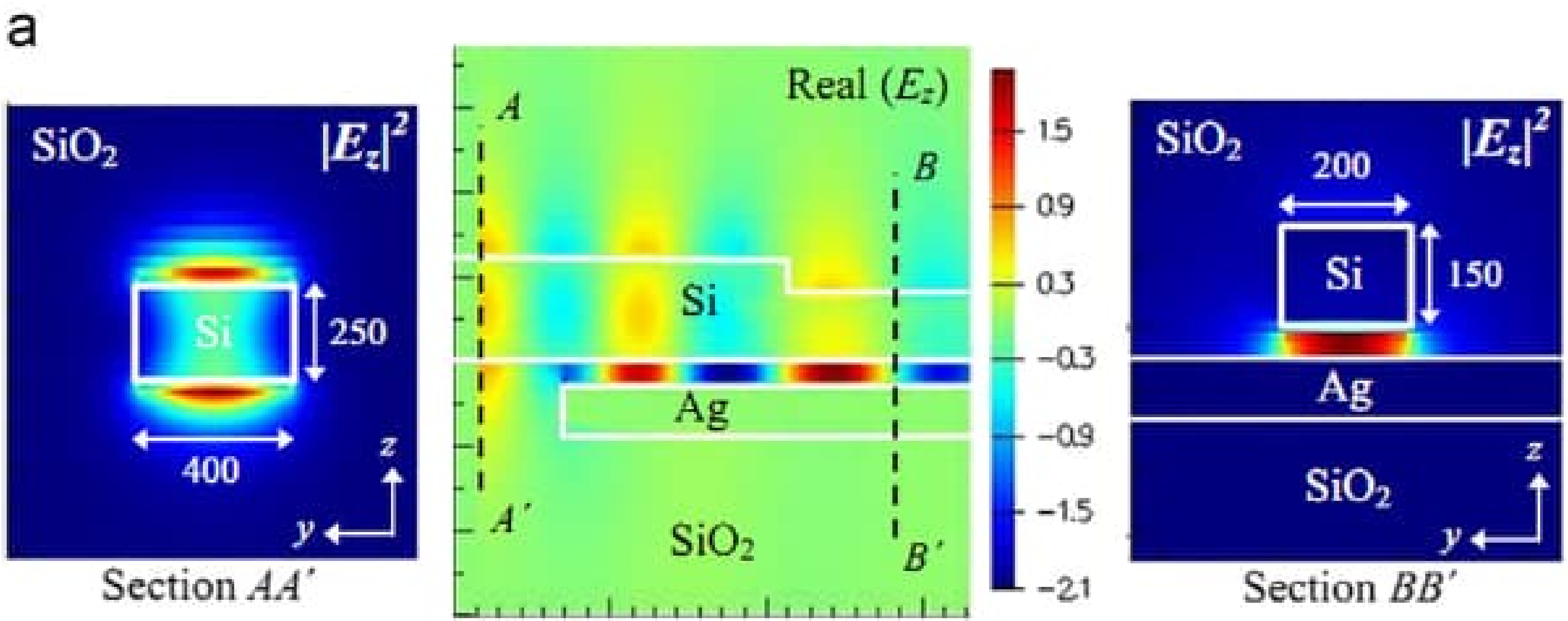


E_x

VAZBA MEZI SOI NANODRÁTEM A HDPSW

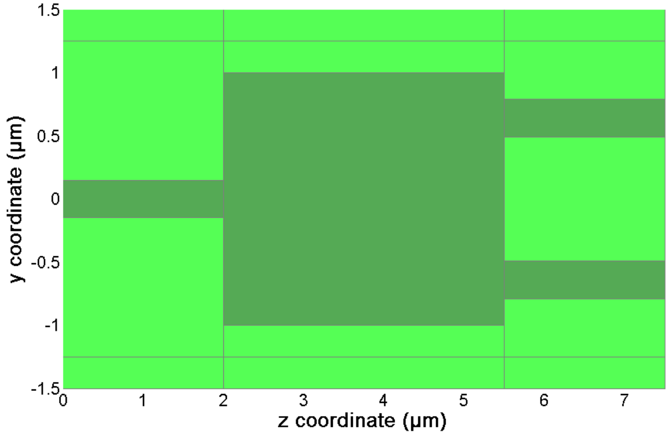
R. Mote et al., *Optics Communications* 285 (2012) 3709–3713

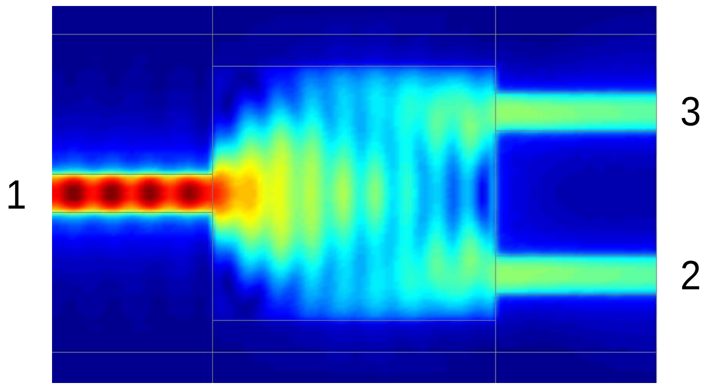




MULTIMODE INTERFERENCE COUPLER

1x2 MMI – simple configuration

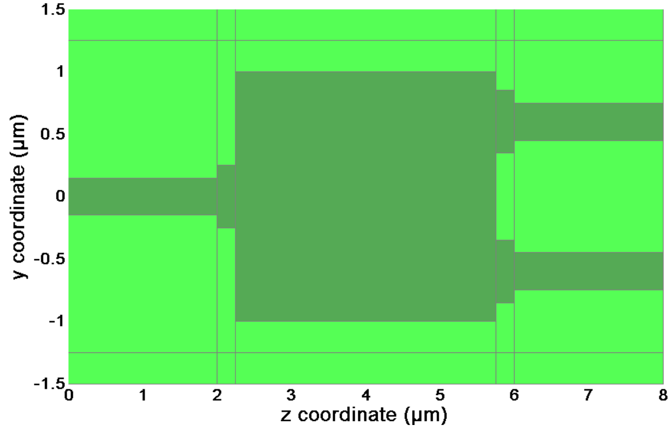


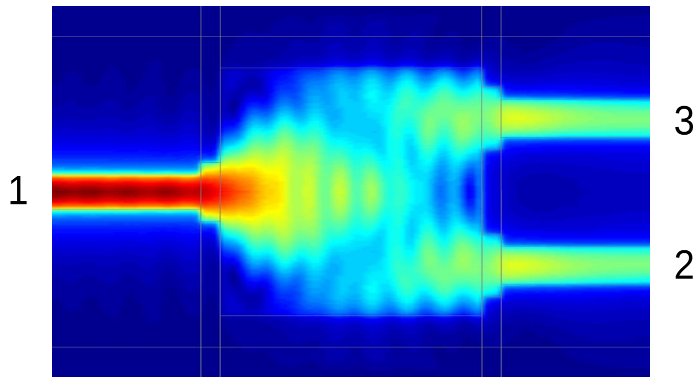


$$S_{11} = -24 \text{ dB},$$
$$S_{21} = -6 \text{ dB}$$

E_x

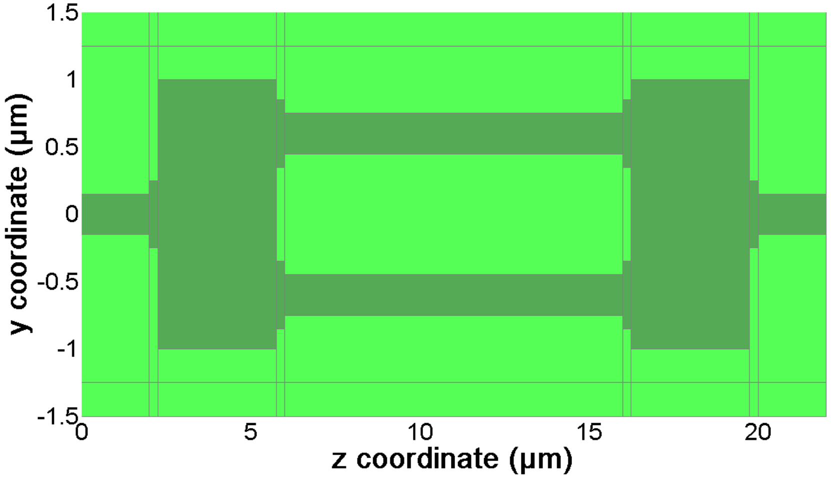
1x2 MMI – improved configuration

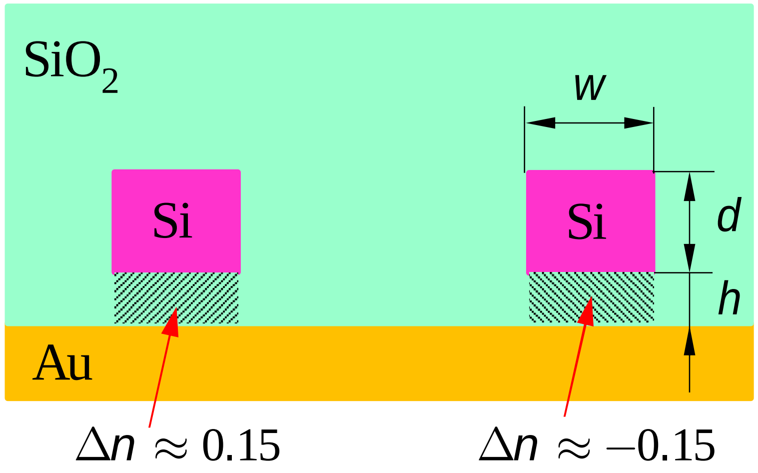




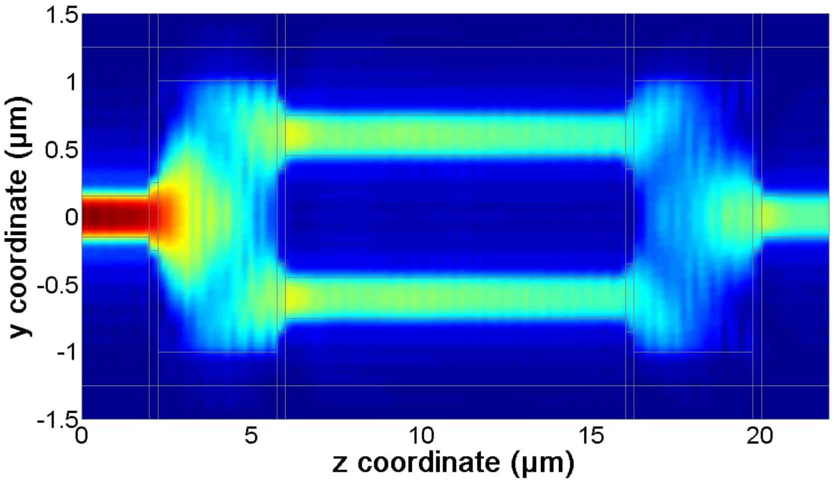
$$S_{11} = -51 \text{ dB},$$
$$S_{21} = -5.5 \text{ dB}$$

MACH-ZEHNDER INTERFEROMETER





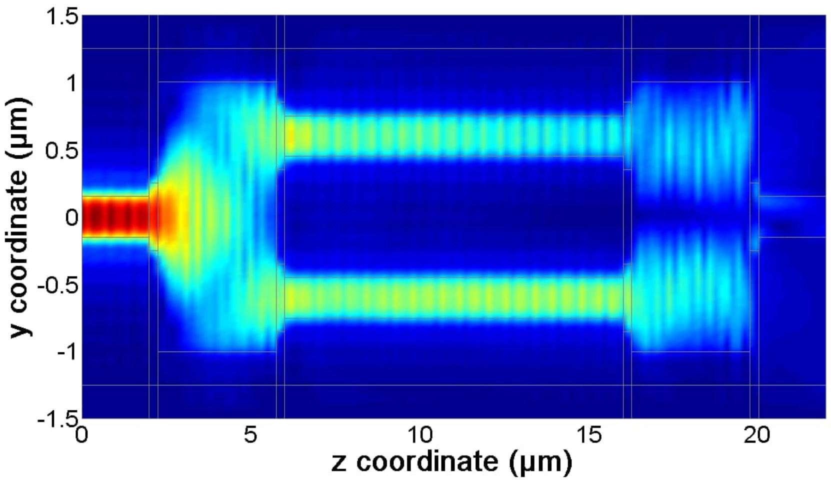
"On" state



$S_{11} = -37$ dB

$S_{21} = -6$ dB

"Off" state

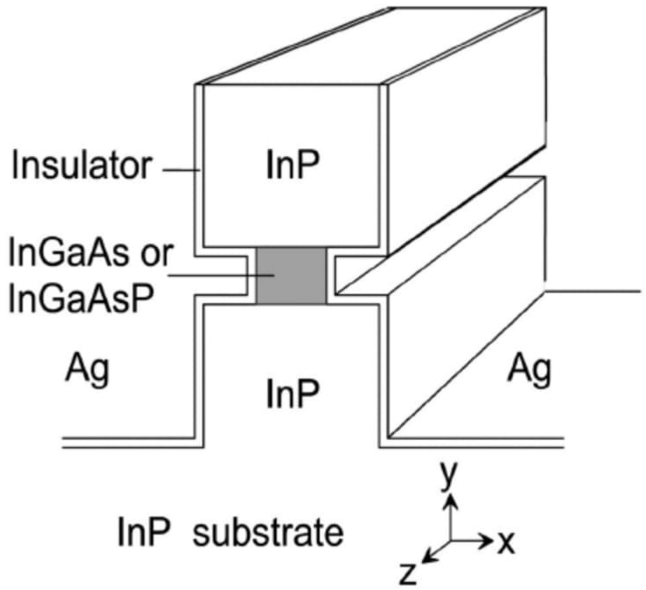


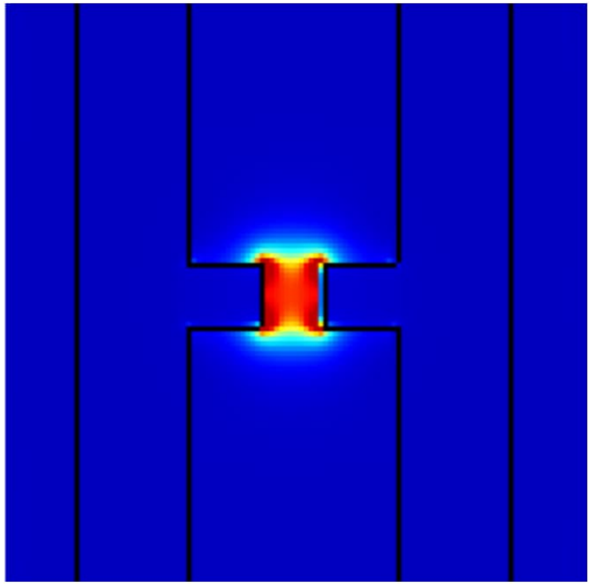
$S_{11} = -25$ dB

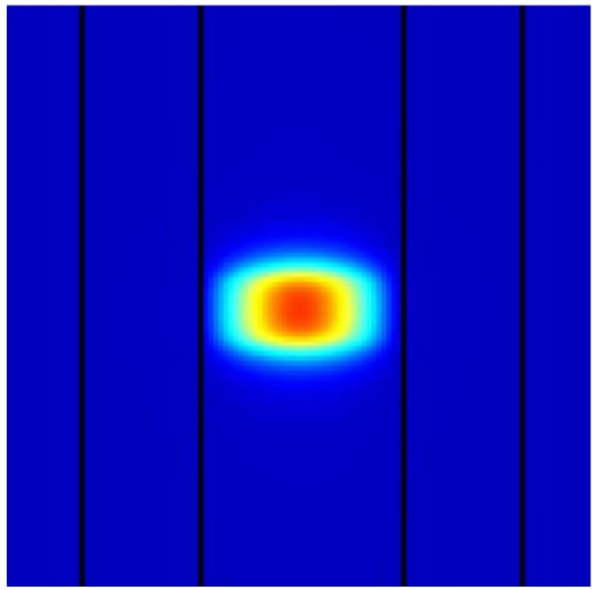
$S_{21} = -21$ dB

Koncept „plazmonového polovodičového laseru“

(M. Hill, ECIO 2007)







Rozměry aktivní oblasti laseru
26 × 26 × 82 nm