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

m_e E

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: $x_0 = \dfrac{-eE_0}{m_e\omega^2 + im_e\gamma\omega}$

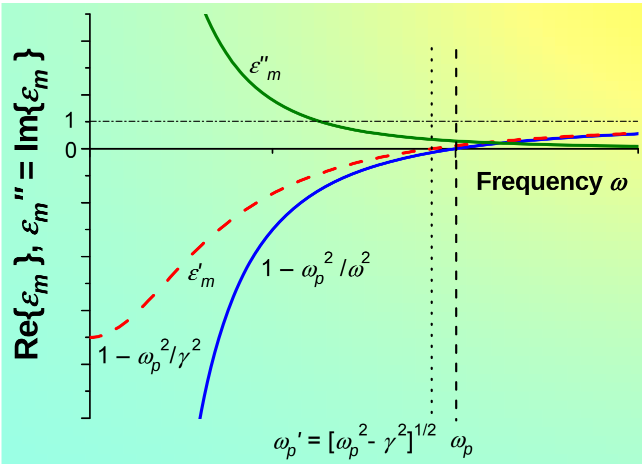
Polarizace: $P_0 = -n_e e x_0 = \dfrac{-e^2 n_e}{m_e\omega^2 + im_e\gamma\omega} E_0 = \varepsilon_0 \chi E_0$

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

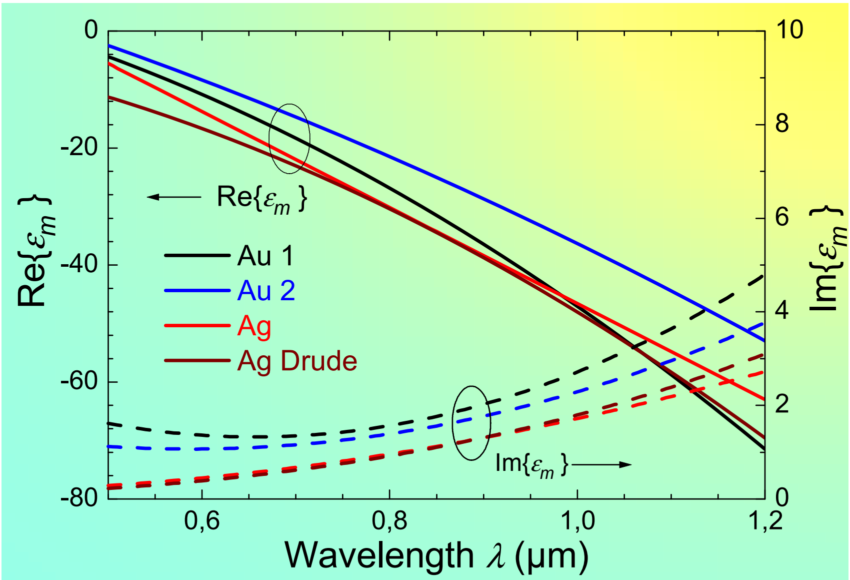
Plazmová frequence $\omega_p = e\sqrt{\dfrac{n_e}{m_e\varepsilon_0}}$

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)



Povrchová plazmová vlna

(povrchový plazmon-polariton, povrchový plazmon)

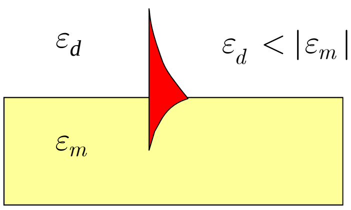
Vzájemně vázaná elektromagnetická a nábojová povrchová **vlna** localizovaná na rozhraní mezi dielectrikem a kovem

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**

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

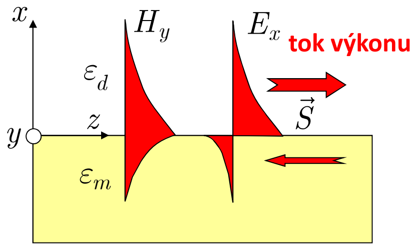


Rozložení pole povrchového plazmonu

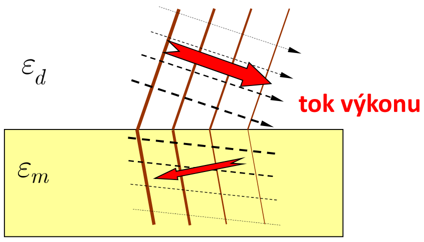
$$H_y(x,z) = H_0 e^{ik_0 N z} \begin{cases} e^{-k_0\sqrt{N^2-\varepsilon_d}\,x}, & x > 0 \\ e^{k_0\sqrt{N^2-\varepsilon_m}\,x}, & x < 0 \end{cases} \qquad 1\big/k_0\sqrt{N^2-\varepsilon_d} = 265\ \text{nm}, \quad 1\big/k_0\sqrt{N^2-\varepsilon_m} = 26\ \text{nm}$$

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

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



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



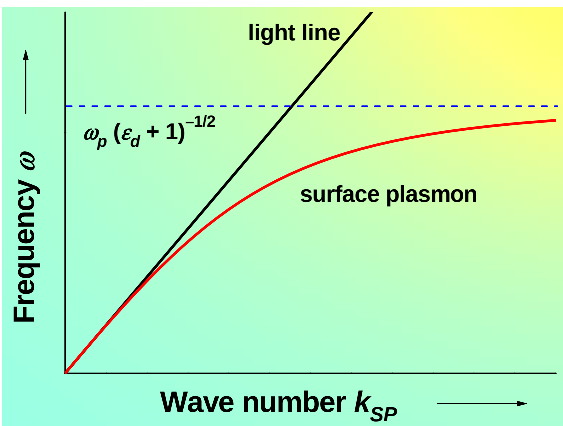
Disperzní vlastnosti povrchového plazmonu

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

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

"light line" ($\frac{\omega n_d}{c}$)

faktor < 1

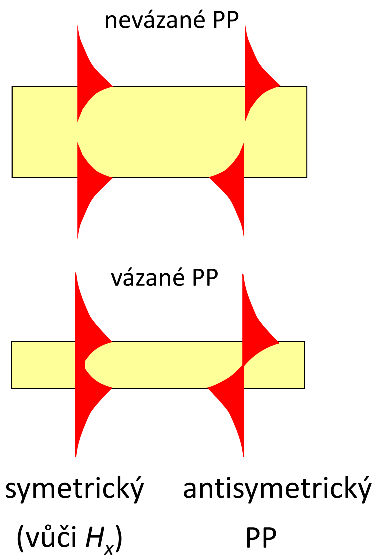


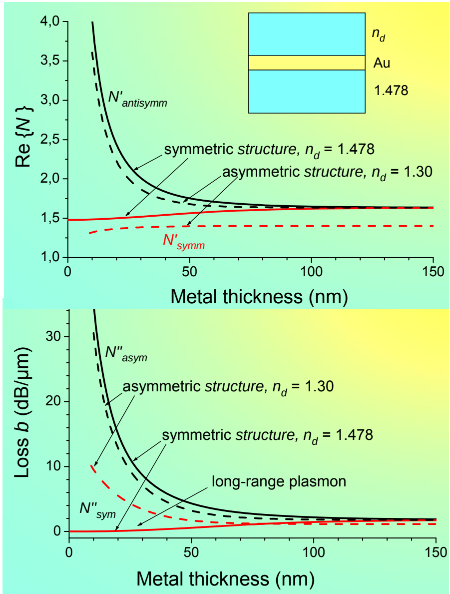
$\mathrm{Re}\{N_{SP}\} > n_d \;\Rightarrow$

PP je **pomalá vlna**

nemůže být excitována zářením z dielektrika

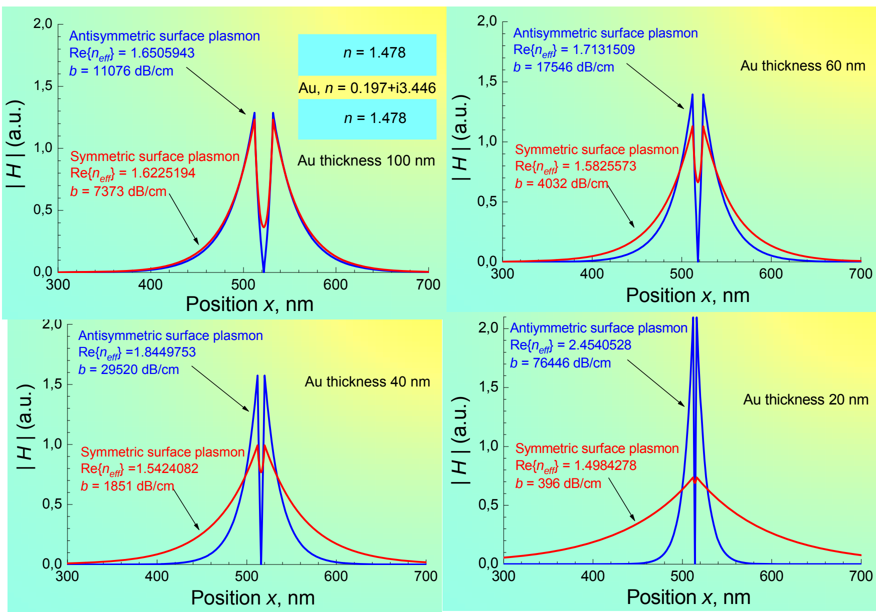
Povrchové plazmony na kovové vrstvě





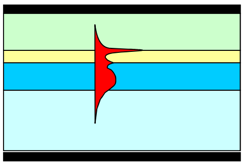
Rozložení polí PP na kovových vrstvách

Závislost na tloušťce kovové vrstvy

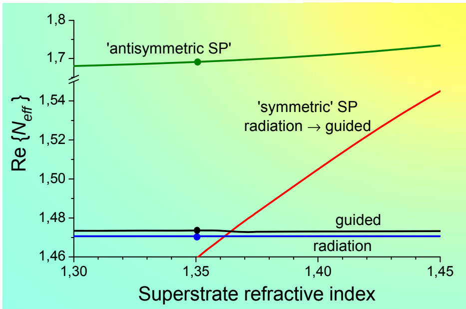


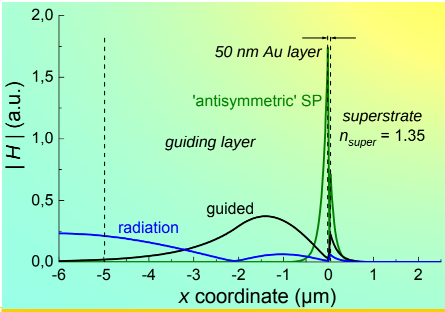
Vidy planárních vlnovodů s kovovou vrstvou

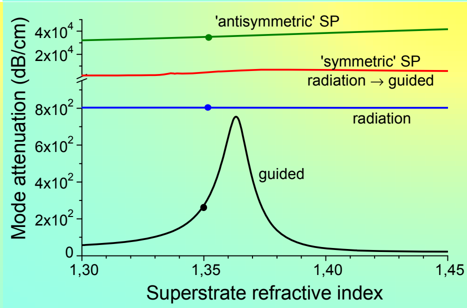
1.



$d_{Au} = 50$ nm

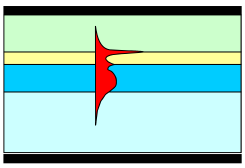




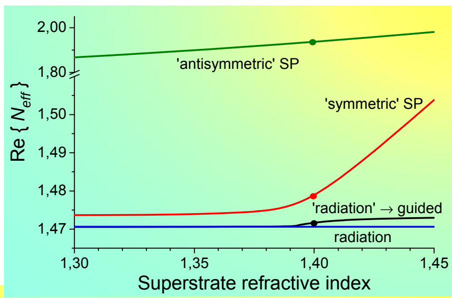


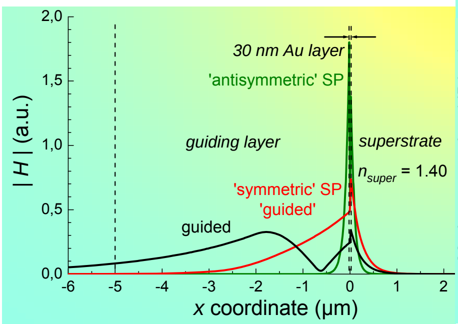
Vidy planárních vlnovodů s kovovou vrstvou

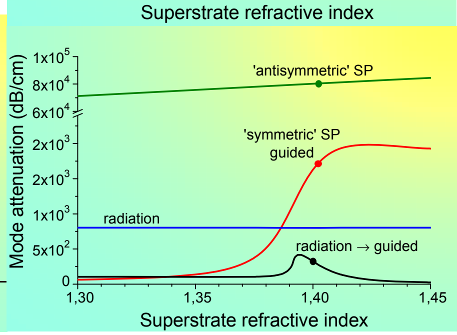
2.



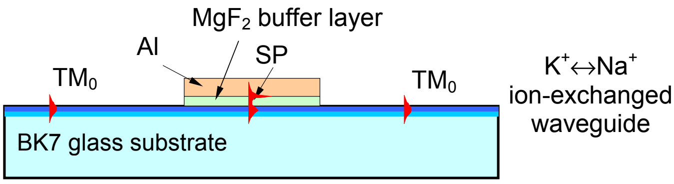
$d_{Au} = 30$ nm

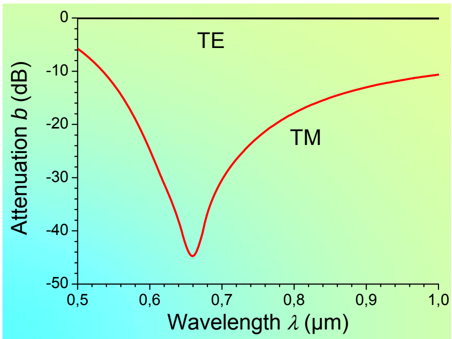


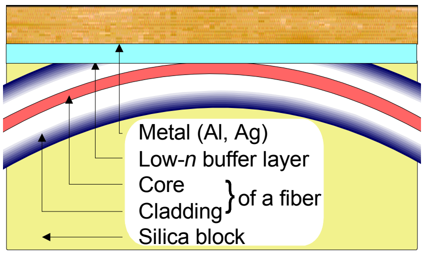




Vlnovodný polarizátor založený na rezonanční excitaci PP



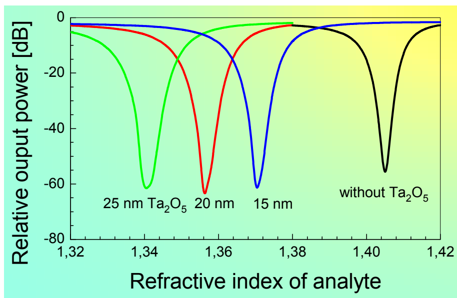


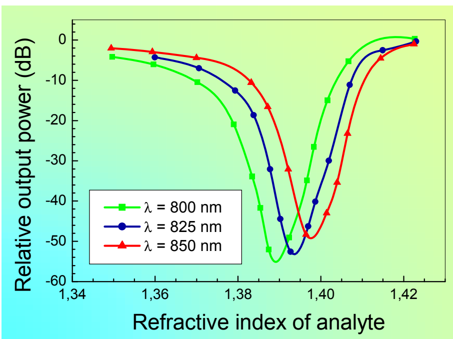


Průchod optického záření senzorem s PP

1. závislost na indexu lomu analytu (zkoumaného prostředí)

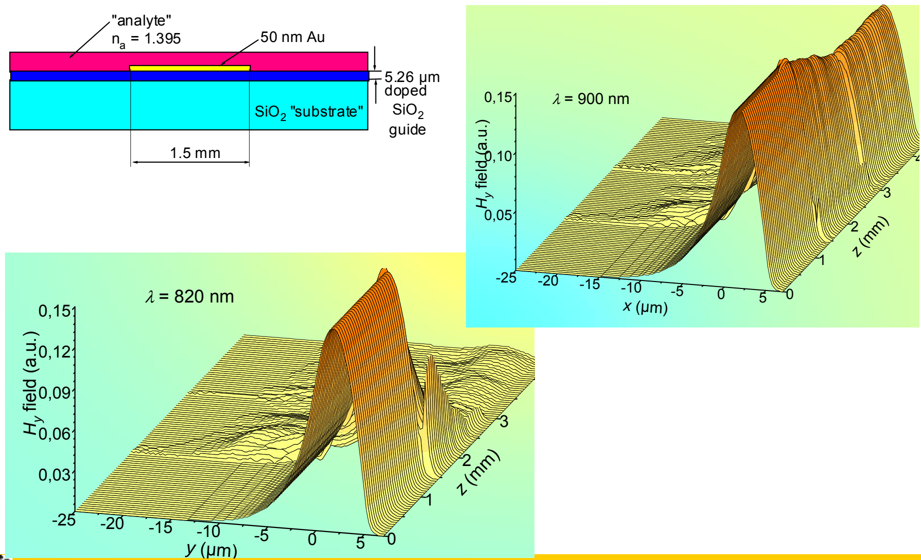
2D (planární) model



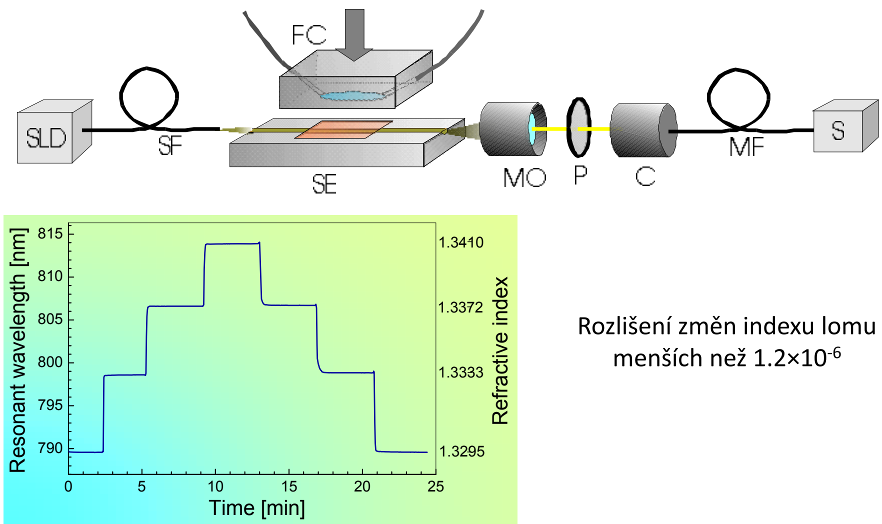


měření laditelným Ti:safírovým laserem

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

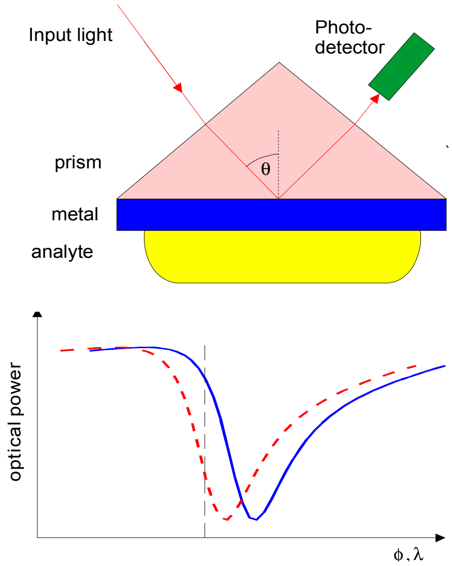


Experimentální uspořádání integrovaně-optického senzoru s PP

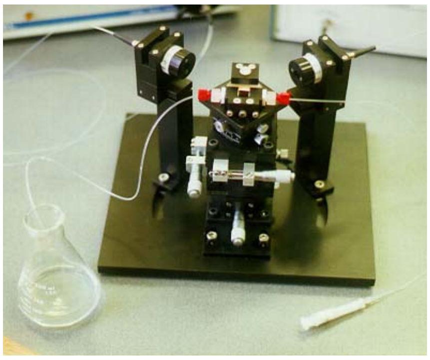


Rozlišení změn indexu lomu menších než 1.2×10^{-6}

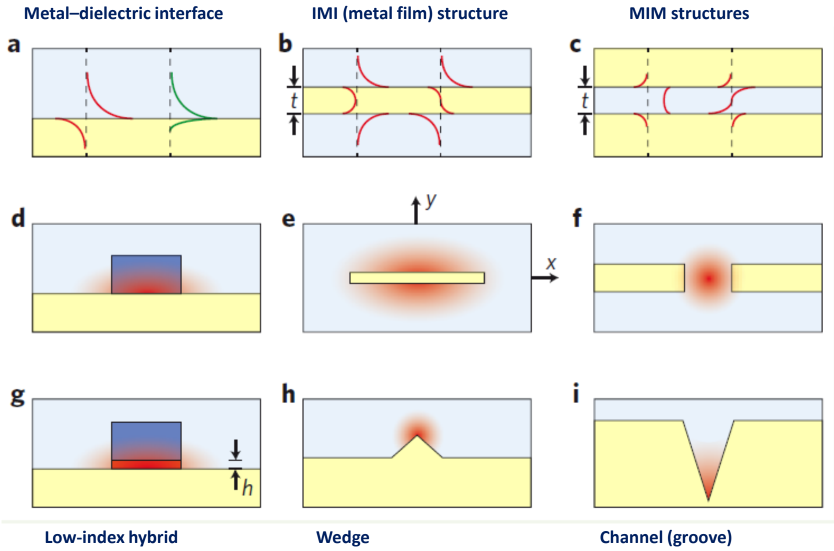
Objemové senzory s PP



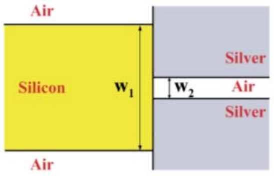
Rozlišení změn indexu lomu menších než 5×10^{-7}



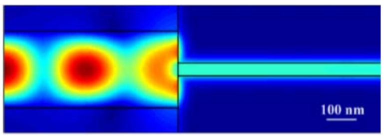
PLAZMONICKÉ VLNOVODY

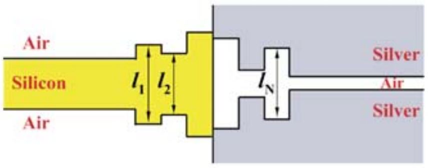


Přechod mezi vlnovodem SOI a plazmonovým vlnovodem

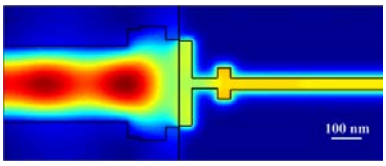


Účinnost vazby cca 64%





Účinnost vazby cca 90%



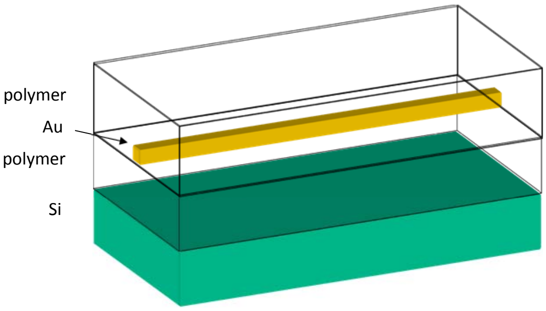
G. Veronis, S. Fan, OWTNM 2006, p. 12
(Stanford university)

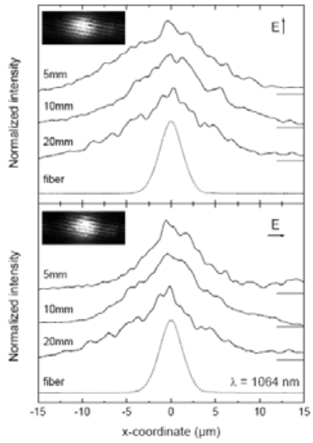
„Zlatý nanodrát“ jako vlnovod pro povrchové plazmony

(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)

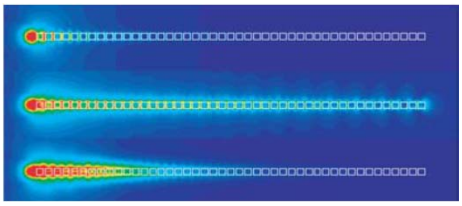
„Řetízek“ Au krychliček o straně 45 nm vzdálených od sebe 20 nm

Excitační vlnová délka

500 nm

429 nm

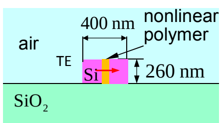
390 nm



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

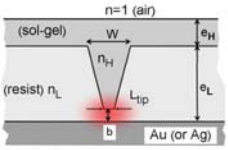
Nové typy plazmonických vlnovodů

SOI “slot waveguide”

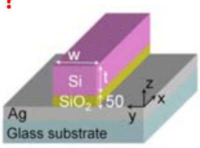


C. Koos & al., *Nat. Photonics* **3**(4), 16–219 (2009)

PIROW – plasmonic inverted rib optical waveguide

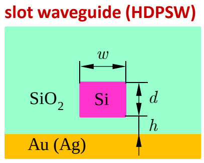


H. Benisty and M. Besbes, *J. Appl. Phys.* **108**(6), 063108 (2010).

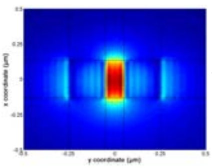


H.-S. Chu & al., *J. Opt. Soc. Am. B* **28**(12), 2895 (2011) (others, too)

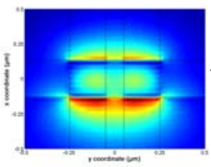
Hybrid dielectric-plasmonic slot waveguide (HDPSW)



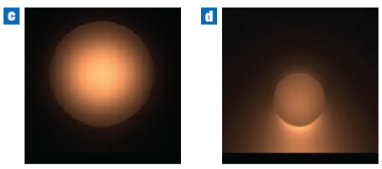
R. F. Oulton & al., *New J. Phys.* **10**, 105018 (2008)



TE_{00} E_y



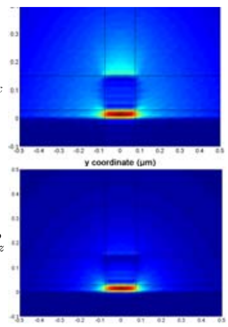
TM_{00} E_x



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

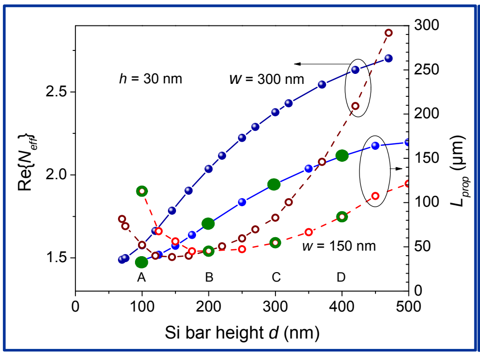
E_x

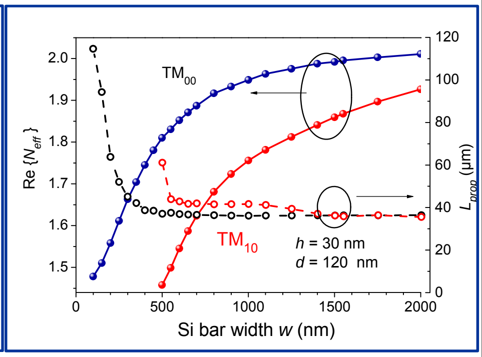
P_z

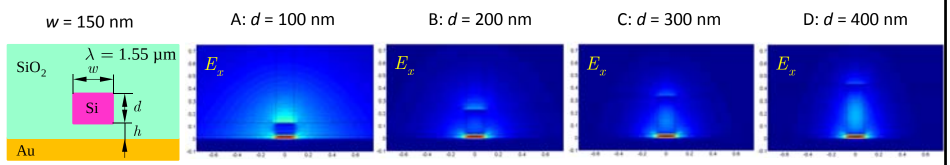


Hybrid dielectric-plasmonic slot waveguide

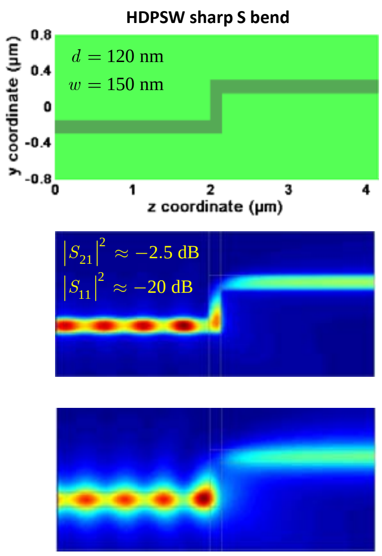
Influence of basic geometric parameters

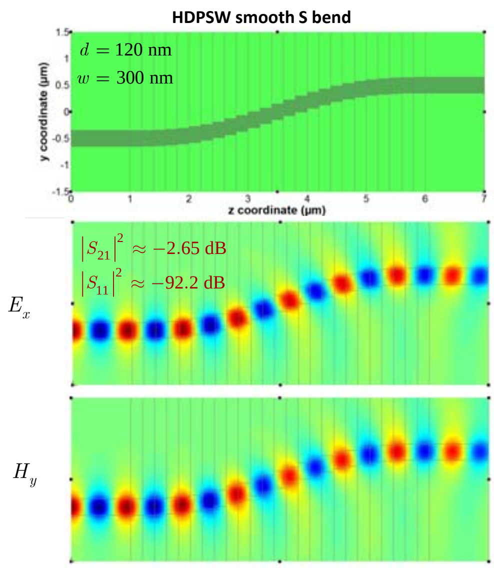


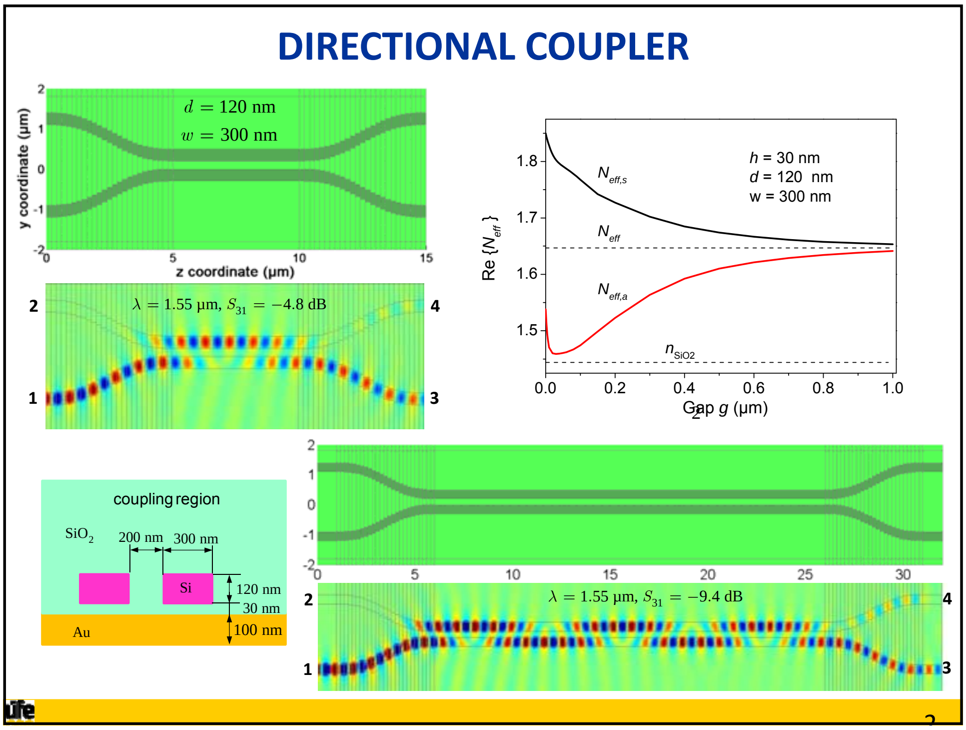


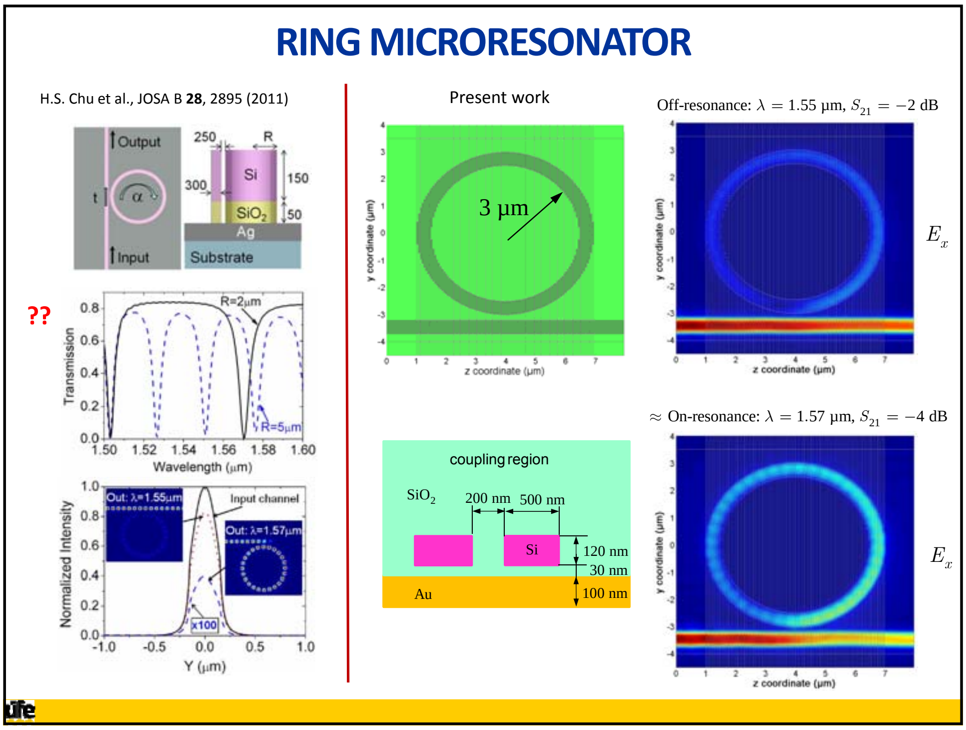


HDPSW DEVICES



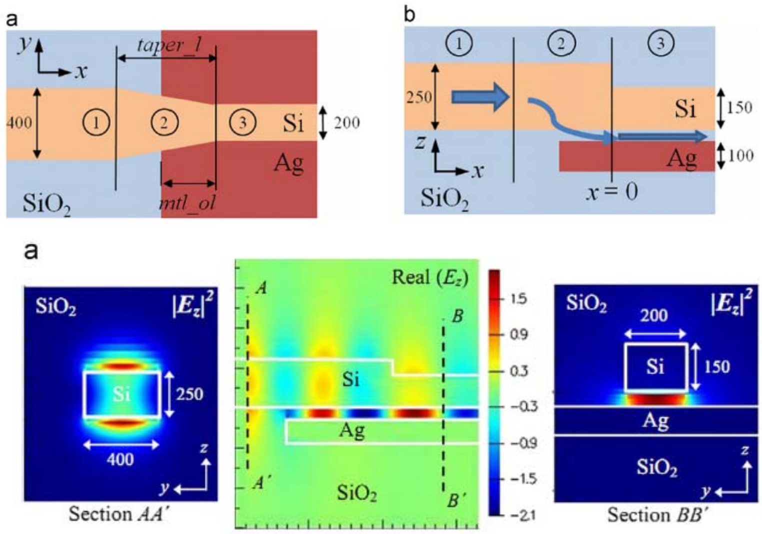



DIRECTIONAL COUPLER
d = 120 nm
w = 300 nm
y coordinate (μm)
z coordinate (μm)
λ = 1.55 μm, S31 = −4.8 dB
h = 30 nm
d = 120 nm
w = 300 nm
Neff,s
Neff
Neff,a
nSiO2
Re {Neff}
Gap g (μm)
coupling region
SiO2
200 nm
300 nm
Si
120 nm
30 nm
100 nm
Au
λ = 1.55 μm, S31 = −9.4 dB


RING MICRORESONATOR
H.S. Chu et al., JOSA B 28, 2895 (2011)
Output
Input
Si
SiO2
Ag
Substrate
??
R=2μm
R=5μm
Transmission
Wavelength (μm)
Normalized Intensity
Input channel
Y (μm)
Present work
3 μm
z coordinate (μm)
Off-resonance: λ = 1.55 μm, S21 = −2 dB
Ex
≈ On-resonance: λ = 1.57 μm, S21 = −4 dB
Ex
coupling region
SiO2
200 nm
500 nm
Si
120 nm
30 nm
100 nm
Au

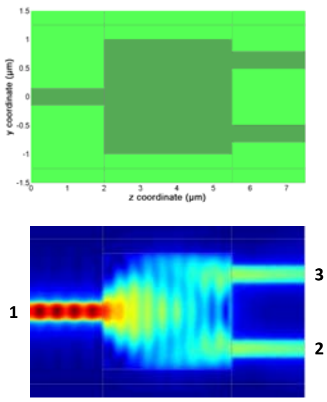
VAZBA MEZI SOI NANODRÁTEM A HDPSW

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



MULTIMODE INTERFERENCE COUPLER

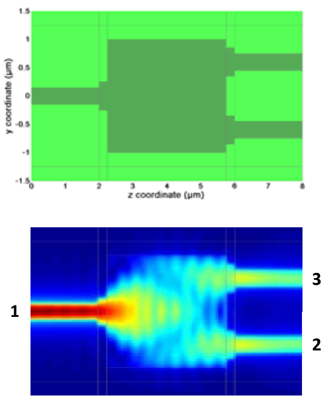
1x2 MMI – simple configuration



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

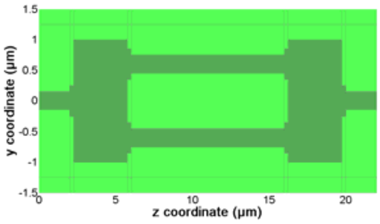
E_x

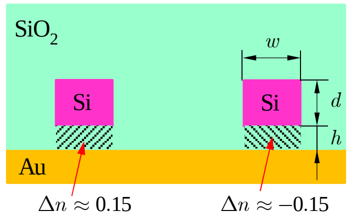
1x2 MMI – improved configuration



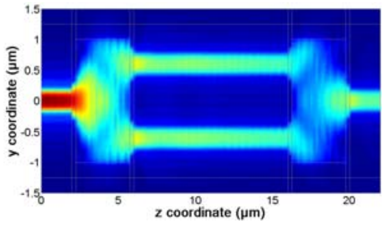
$S_{11} = -51$ dB,
$S_{21} = -5.5$ dB

MACH-ZEHNDER INTERFEROMETER



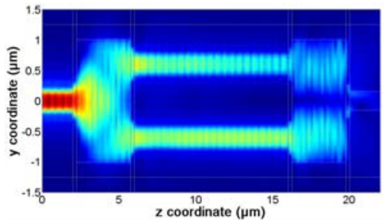


"On" state



$S_{11} = -37$ dB
$S_{21} = -6$ dB

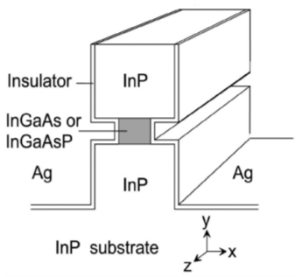
"Off" state

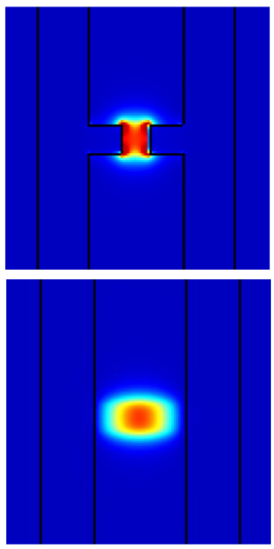


$S_{11} = -25$ dB
$S_{21} = -21$ dB

Koncept „plazmonového polovodičového laseru"

(M. Hill, ECIO 2007)





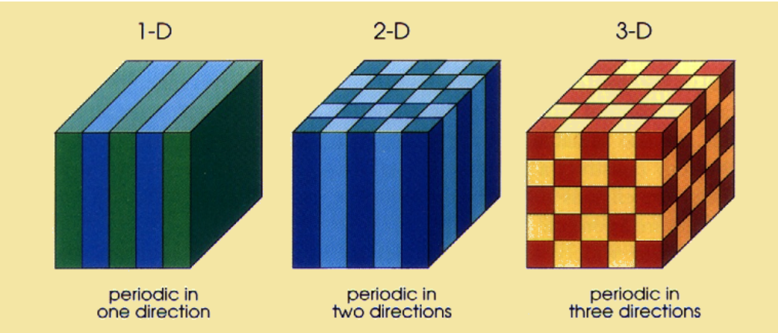
Rozměry aktivní oblasti laseru
26 × 26 × 82 nm

Fotonické krystaly

a integrovaná fotonika

Fotonické krystaly

1D, 2D nebo 3D periodické struktury s velkým kontrastem permitivity



E. Yablonovitch: „Inhibited spontaneous emission in solid-state physics and electronics“, *Phys. Rev. Lett.*, vol. 58, pp. 2059–2062, 1987

J. D. Joannopoulos *et al.*: *Photonic Crystals: molding the flow of light*, Princeton University Press 1995

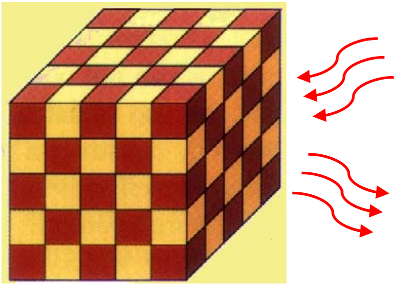
S. G. Johnson, J. D. Joannopoulos: *Photonic Crystals, The road from theory to practice,* Kluwer Academic Publishers 2003

J.-M. Lourtioz *et al.: Photonic Crystals : Towards Nanoscale Photonic Devices*, Springer 2005

…

Fotony se v periodickém dielektrickém prostředí pohybují „podobně“ jako **elektrony** v periodickém potenciálovém poli

Za jistých podmínek existuje **zakázaný pás energií fotonů.** Fotony s energií uvnitř zakázaného pásu se v periodickém prostředí nemohou šířit, záření se tudíž **totálně odráží zpět**



Z pohledu vlnové optiky jde o **braggovský odraz vlny od periodického prostředí**. Totální odraz je možno využít k vytvoření **optických vlnovodů ve fotonických krystalech**

Vytvořit trojrozměrné periodické prostředí je však technologicky obtížné.

“Pohybové rovnice” pro elektrony a fotony v krystalech

Schrödingerova rovnice pro elektron v periodickém potenciálu:

$$\left[-\frac{\hbar^2}{2m_e^*}\Delta + V(\mathbf{r})\right]\psi(\mathbf{r}) = E\psi(\mathbf{r})$$

$$V(\mathbf{r}+\mathbf{a}) = V(\mathbf{r}) \qquad K = \frac{2\pi}{|\mathbf{a}|}$$

$$\psi(\mathbf{r}) = \sum_m u_m(\mathbf{r})\, e^{im\mathbf{K}\cdot\mathbf{r}}$$

periodický potenciál — vlnová funkce — energie fotonu — (Floquetova)-Blochova vlna,

Aproximativní (jednočásticové) přiblížení

“Vlnová rovnice” pro fotony v periodické permitivitě

$$\nabla\times\mathbf{E} = i\omega\mu_0\mathbf{H}, \qquad \nabla\times\mathbf{H} = -i\omega\varepsilon_0\varepsilon(\mathbf{r})\mathbf{E},$$

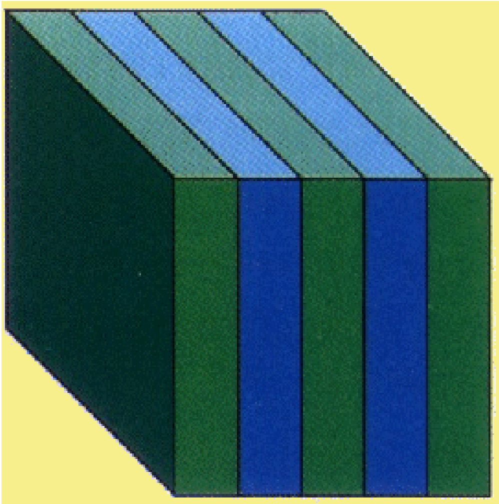
$$\nabla\times\left(\frac{1}{\varepsilon(\mathbf{r})}\nabla\times\mathbf{H}(\mathbf{r})\right) = \left(\frac{\omega}{c}\right)^2\mathbf{H}(\mathbf{r})$$

Přesná (“mnohočásticová”) teorie

Rovnice pro vlastní hodnoty energie fotonů a F-B funkce

Tento přístup je jednoduchý a průzračný,
ale standardně nebere v úvahu *disperzi permitivity e*(**r**,*w*)

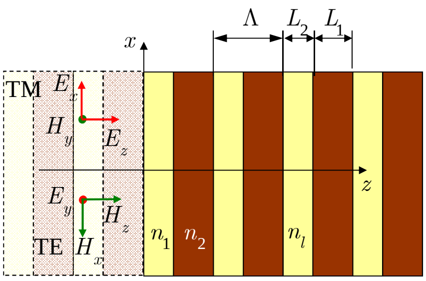
Periodická vrstevnatá struktura jako jednorozměrný fotonický krystal



Jednorozměrný fotonický krystal

Existence zakázaného pásu odvozená metodou přenosové matice

(fotonická analogie Kronigova - Penneyova modelu krystalu)



Normalizace souřadnic a vln. vektorů

$$\xi = k_0 x,\quad \zeta = k_0 z,\quad k_0 = 2\pi / \lambda$$

$$\mathbf{k}_l = k_0\left(\gamma \mathbf{x}^0 + N_l \mathbf{z}^0\right),\quad l = 1,2,\ldots,L$$

$$\gamma^2 + N_l^2 = \varepsilon_l = \begin{cases} n_1^2 \\ n_2^2 \end{cases}$$

konst. šíření

γ – příčná konst. šíření ***stejná***

Elektromagnetické pole je popsáno komplexními amplitudami $p_l(\zeta), q_l(\zeta)$

TE

$$E_{y,l}(x,z) = \sqrt{2k_0 Z_0 / N_l}\, p_l(\zeta) e^{i\gamma\xi},$$

$$H_{x,l}(x,z) = -\sqrt{2k_0 Y_0 N_l}\, q_l(\zeta) e^{i\gamma\xi},$$

$$H_{z,l}(x,z) = \sqrt{2k_0 Y_0 / N_l}\, \gamma p_l(\zeta) e^{i\gamma\xi},$$

TM

$$H_{y,l}(x,z) = \sqrt{2k_0 Y_0 \varepsilon_l / N_l}\, p_l(\zeta) e^{i\gamma\xi},$$

$$E_{x,l}(x,z) = \sqrt{2k_0 Z_0 N_l / \varepsilon_l}\, q_l(\zeta) e^{i\gamma\xi},$$

$$E_{z,l}(x,z) = -\sqrt{2k_0 Y_0 / (\varepsilon_l N_l)}\, \gamma\, p_l(\zeta) e^{i\gamma\xi},$$

$$Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}},\quad Y_0 = \sqrt{\frac{\varepsilon_0}{\mu_0}}$$

Elektromagnetické Floquetovy – Blochovy vidy

Průchod l-tou vrstvou je popsán přenosovou maticí $\mathbf{A}_l$

$$\begin{pmatrix} p_l(\zeta+\Delta\zeta) \\ q_l(\zeta+\Delta\zeta) \end{pmatrix} = \mathbf{A}_l \cdot \begin{pmatrix} p_l(\zeta) \\ q_l(\zeta) \end{pmatrix}, \quad \mathbf{A}_l = \begin{pmatrix} \cos N_l\Delta\zeta & i\sin N_l\Delta\zeta \\ i\sin N_l\Delta\zeta & \cos N_l\Delta\zeta \end{pmatrix},$$

průchod rozhraním $l \to l+1$ a $l+1 \to l$ je popsán maticemi

$${}^{l+1,l}\mathbf{A} = \begin{pmatrix} \rho & 0 \\ 0 & 1/\rho \end{pmatrix}, \qquad \rho = \sqrt{N_{l+1}/N_l} \qquad \text{pro TE polarizaci a}$$

$${}^{l,l+1}\mathbf{A} = \begin{pmatrix} 1/\rho & 0 \\ 0 & \rho \end{pmatrix} \qquad \rho = \sqrt{N_{l+1}\varepsilon_l / N_l\varepsilon_{l+1}} \qquad \text{pro TM polarizaci.}$$

Přenosová matice jedné celé periody je $\quad {}^{\Lambda}\mathbf{A} = {}^{12}\mathbf{A} \cdot \mathbf{A}_2 \cdot {}^{21}\mathbf{A} \cdot \mathbf{A}_1$.

Floquetův-Blochův „vid“ (vlna) je definován pomocí vlastní funkce matice $\quad {}^{\Lambda}\mathbf{A}$,

$${}^{\Lambda}\mathbf{A} \cdot \begin{pmatrix} p_1^F \\ q_1^F \end{pmatrix} = s \begin{pmatrix} p_1^F \\ q_1^F \end{pmatrix}, \quad s = \exp\left(i\varphi^F\right), \quad \varphi^F = k^F\Lambda,$$

k^F je konstanta šíření F-B vidu.

k^F je určen až na aditivní konstantu $\quad K = 2\pi/\Lambda: \quad \exp(ik^F\Lambda) = \exp\left[i\left(k^F + K\right)\Lambda\right]$

Proto stačí určit k^F v intervalu $\quad -K/2 < k^F \le K/2 \quad \Rightarrow$ *první Brillouinova zóna.*

Vlastní hodnoty a fotonický zakázaný pás

Označme $\quad \Lambda = L_1 + L_2, \quad \varphi_1 = k_0 N_1 L_1, \quad \varphi_2 = k_0 N_2 L_2,$

matice $\ {}^{\Lambda}\mathbf{A}\ $ má pak vlastní čísla

$$s = \cos\varphi_1\cos\varphi_2 - \frac{1}{2}\left(\rho^2 + \frac{1}{\rho^2}\right)\sin\varphi_1\sin\varphi_2 \pm \sqrt{\left[\cos\varphi_1\cos\varphi_2 - \frac{1}{2}\left(\rho^2 + \frac{1}{\rho^2}\right)\sin\varphi_1\sin\varphi_2\right]^2 - 1}\ .$$

FB vid se „šíří“ , jen pokud $\quad |s| = 1, \quad$ *t.j.*, pokud

$$\left|\cos\varphi_1\cos\varphi_2 - \frac{1}{2}\left(\rho^2 + \frac{1}{\rho^2}\right)\sin\varphi_1\sin\varphi_2\right| \le 1.$$

Normovaná konstanta šíření je pak

$$k^{F\prime} = \frac{k^F}{K/2} = \frac{1}{\pi}\arccos\left[\cos\left(\frac{\omega}{c}N_1L_1\right)\cos\left(\frac{\omega}{c}N_2L_2\right) - \frac{1}{2}\left(\rho^2 + \frac{1}{\rho^2}\right)\sin\left(\frac{\omega}{c}N_1L_1\right)\sin\left(\frac{\omega}{c}N_2L_2\right)\right].$$

Pokud $\quad \left|\cos\varphi_1\cos\varphi_2 - \frac{1}{2}\left(\rho^2 + \frac{1}{\rho^2}\right)\sin\varphi_1\sin\varphi_2\right| > 1,$

k^F je komplexní, a vlna se nemůže šířit podél nekonečně dlouhého krystalu.
Tak vzniká **fotonický zakázaný pás.**

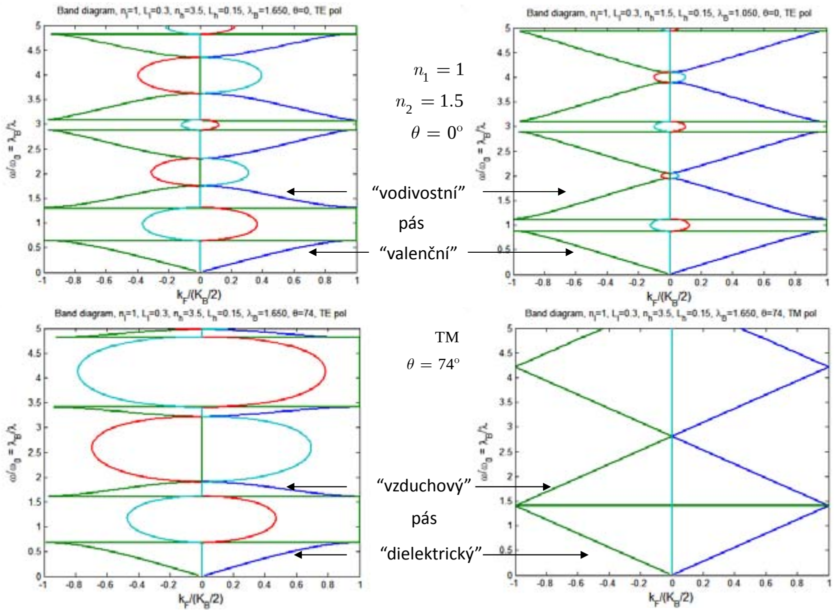
Pásová struktura jednorozměrného krystalu

$n_1 = 1$
$n_2 = 3.5$
$\theta = 0^{\circ}$

$n_1 = 1$
$n_2 = 1.5$
$\theta = 0^{\circ}$

TE
$\theta = 74^{\circ}$

TM
$\theta = 74^{\circ}$



Elektromagnetické Floquetovy – Blochovy vidy

$n_1 = 1$
$n_2 = 3.5$
$\lambda_B / \lambda = 0.6$

“dielektr.”
pás

$\lambda_B / \lambda = 1.0$

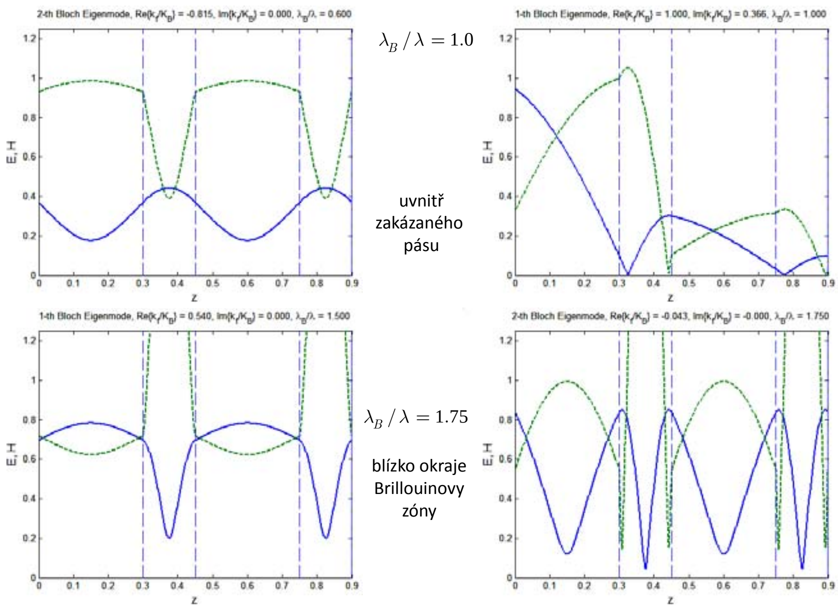
uvnitř zakázaného pásu

$\lambda_B / \lambda = 1.5$

“vzduch.”
pás

$\lambda_B / \lambda = 1.75$

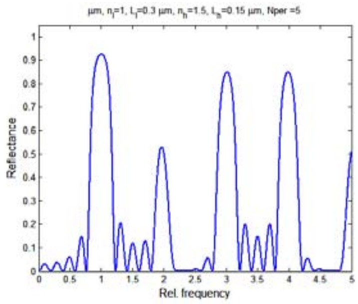
blízko okraje Brillouinovy zóny



Spektrální reflektance

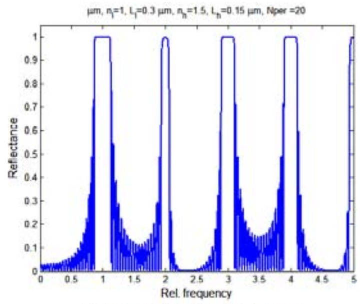
$n_1 = 1$
$n_2 = 1.5$
$n_{per} = 5$

nízký kontrast, málo period



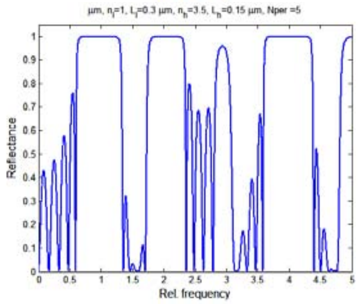
$n_1 = 1$
$n_2 = 1.5$
$n_{per} = 20$

nízký kontrast, víc period



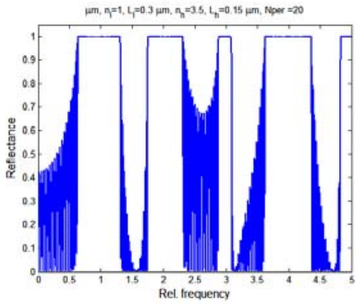
$n_1 = 1$
$n_2 = 3.5$
$n_{per} = 5$

velký kontrast, málo period



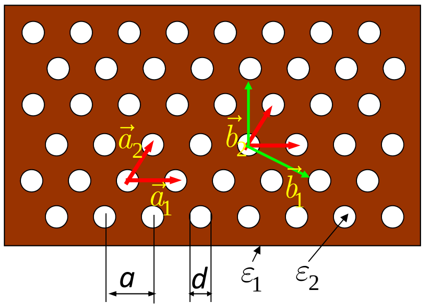
$n_1 = 1$
$n_2 = 3.5$
$n_{per} = 20$

velký kontrast, více period



Fotonické krystaly odpovídají často spíše „nanokrystalům“

Dvojrozměrné „fotonické krystaly“



Periodické uspořádání otvorů;
Blochův – Floquetův teorém

$$\left.\begin{matrix} E_z \\ H_z \end{matrix}\right\} = u_{\vec{k}}\left(\vec{r}_{\|}\right) e^{i\vec{k}\cdot\vec{r}_{\|}} e^{i\vec{G}\cdot\vec{r}_{\|}},$$

$$u_{\vec{k}}\left(\vec{r}_{\|}\right) = u_{\vec{k}}\left(\vec{r}_{\|} + \vec{a}_1\right) = u_{\vec{k}}\left(\vec{r}_{\|} + \vec{a}_2\right)$$

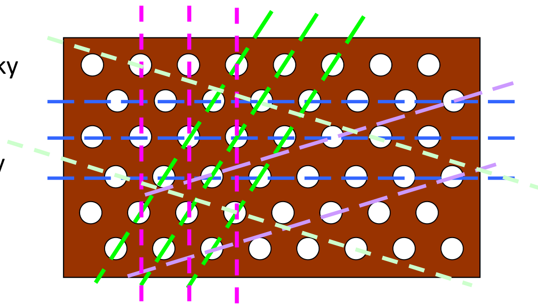
$$\vec{G} = m\vec{b}_1 + n\vec{b}_2;\ m,\ n \text{ celé}$$

Elementární vektory prostorové mřížky

$$\vec{a}_1 = (a, 0); \qquad \vec{a}_2 = (a/2, \sqrt{3}a/2)$$

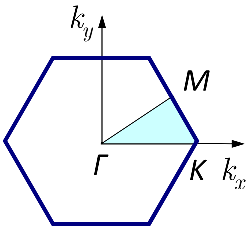
Elementární vektory reciproké mřížky

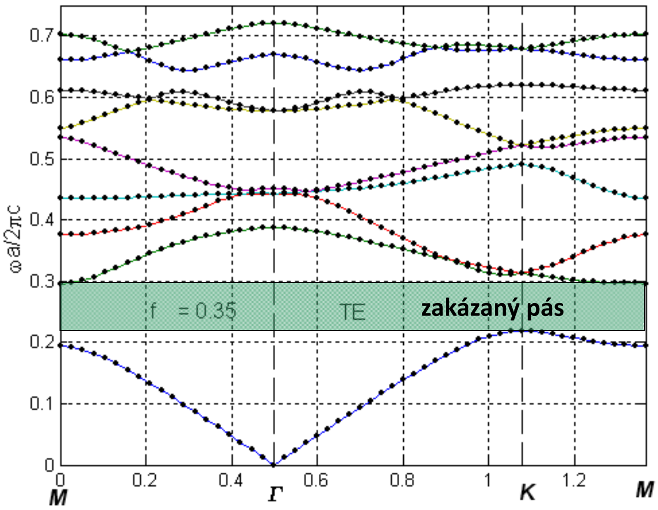
$$\vec{b}_1 = \left(\frac{1}{a}, \frac{1}{a\sqrt{3}}\right), \qquad \vec{b}_2 = \left(0, \frac{2}{a\sqrt{3}}\right)$$



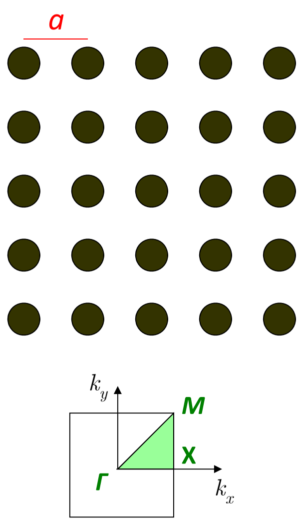
Pásový diagram energií fotonů 2D krystalu s trojúhelníkovou mřížkou

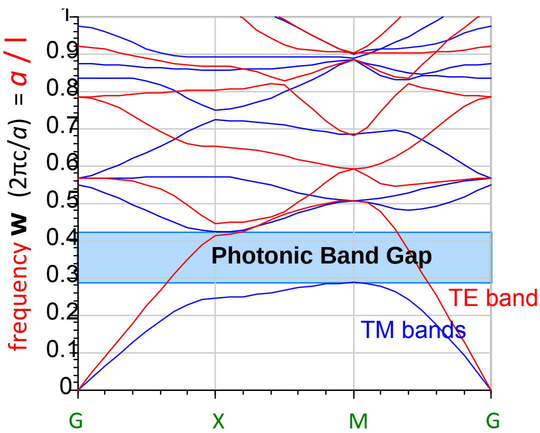
první Brillouinova zóna prostoru vlnových vektorů





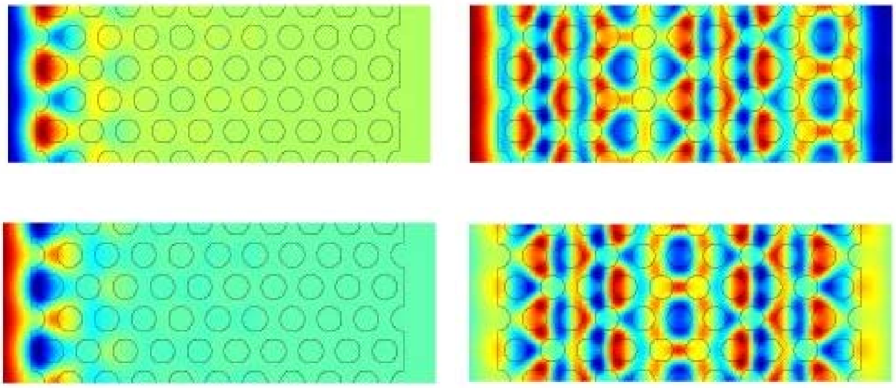
Pásový diagram energií fotonů 2D krystalu se čtvercovou mřížkou





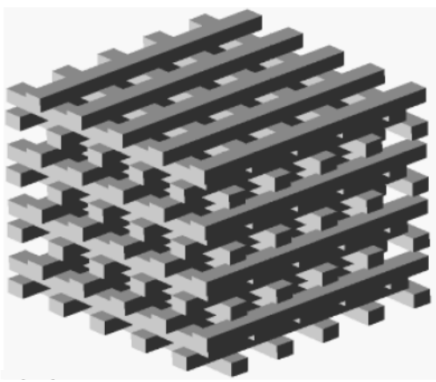
Odraz rovinné vlny od 2D fotonického krystalu s trojúhelníkovou mřížkou otvorů v InP

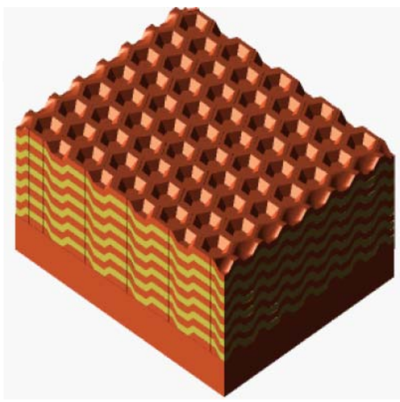
Uvnitř zakázaného pásu | Vně zakázaného pásu



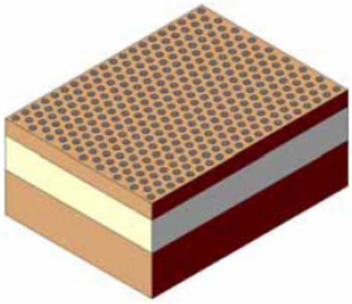
(Ing. Jiří Petráček, Dr., VUT Brno)

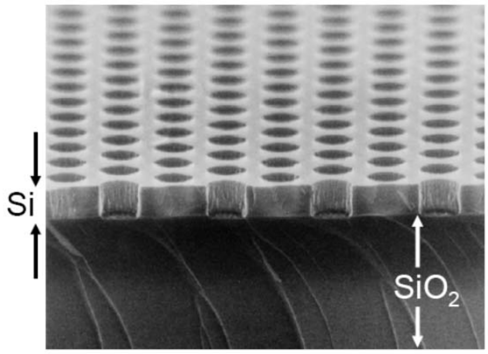
Trojrozměrné fotonické krystaly





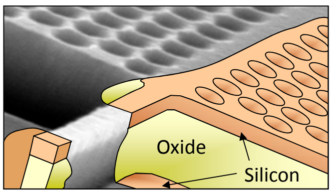
„2.5-dimenzionální“ fotonické krystaly





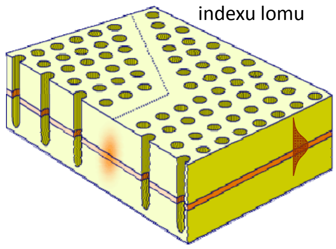
Fotonické krystaly a vlnovody

1. **2D fotonický krystal + vertikální vlnovod**

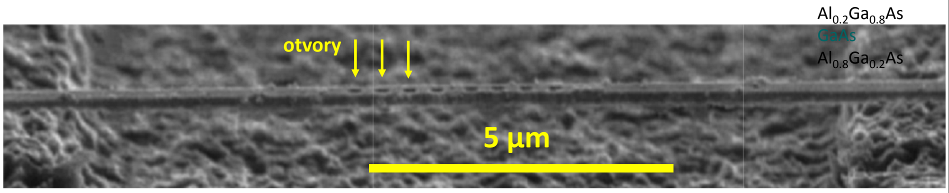


Vysoký kontrast indexu lomu

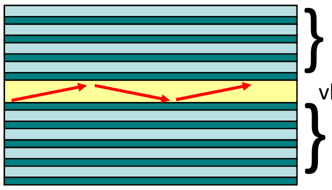
Nízký kontrast indexu lomu



2. **Čárový 2D dielektrický vlnovod s 1D „fotonickým krystalem“**



Vlnovody v 1D fotonickém krystalu



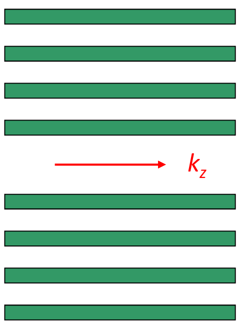
Princip znám od 80. let jako „braggovský vlnovod“
(**a**ntiresonant **r**eflecting **o**ptical **w**aveguide, ***ARROW***)

Rozdíly ARROW vlnovodu vůči konvenčnímu vlnovodu:

1. pro přílušný úhel dopadu vlny musí existovat **zakázaný pás**
2. počet period musí být dostatečný, jinak vzniká **útlum vytékáním** („tunelováním“); v krystalu konečných rozměrů existují **pouze vytékající vidy** s komplexní konstantou šíření

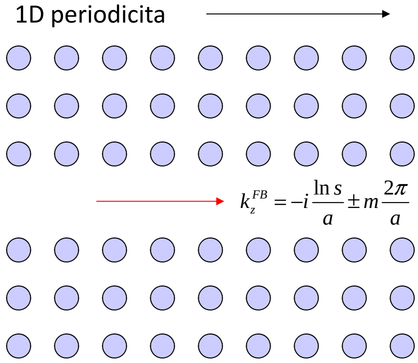
Vlnovod ve fotonickém krystalu

Braggovský vlnovod
(ARROW waveguide)



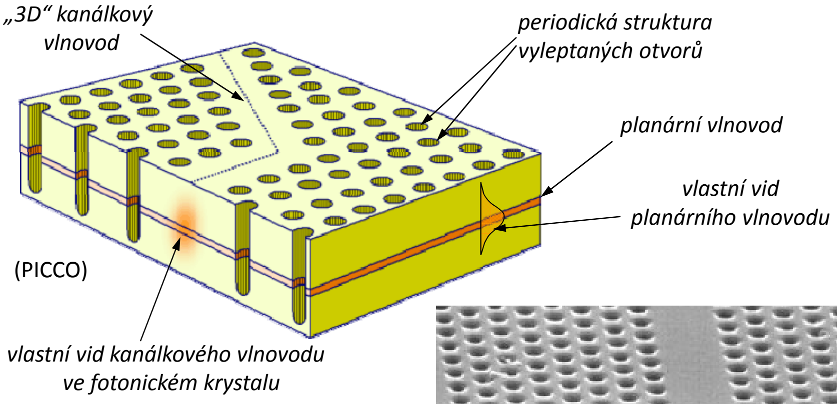
Anti-Reflecting Resonant
Optical Waveguide

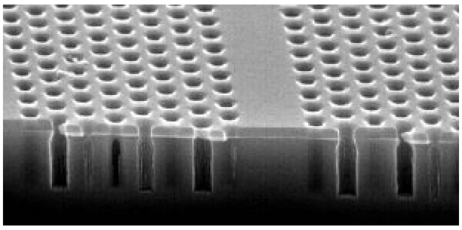
„Čárový defekt“ jako **vlnovod**



$k_z^{FB} a = \varphi \pm 2m\pi$ …fázový posun při šíření o jednu periodu

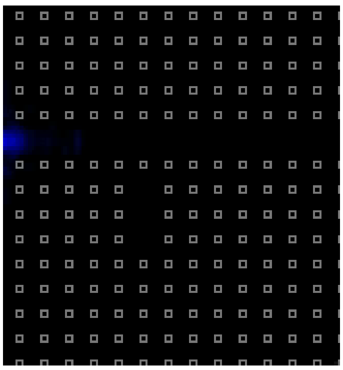
Realizace 2D fotonických krystalů: 2D krystal v planárním vlnovodu



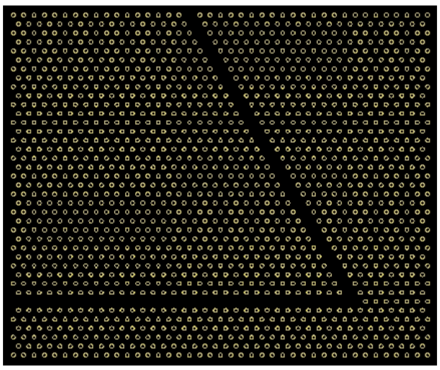


Zásadní problém:
ztráty vyzařováním
z roviny vlnovodu

Numerické modelování šíření vln ve fotonických krystalech



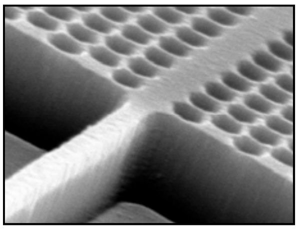
Buzení mikrodutiny
ve fotonickém krystalu
femtosekundovým impulsem
(FDTD, Uni Twente, NL)

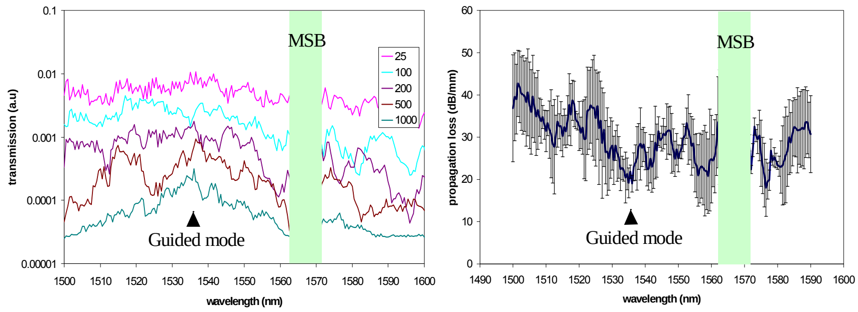


Šíření femtosekundového impulzu
vlnovodným ohybem ve fotonickém
krystalu (**F. Lederer et al.,**
Friedrich-Schiller-Universität Jena, D)

Vlnovody ve fotonických krystalech v SOI

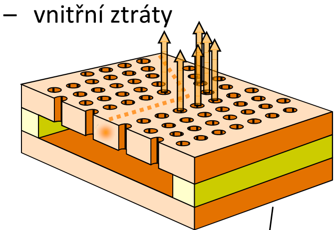
- Příprava:
  - „hluboká“ UV litografie a leptání
- vlnovod W1
  - perioda 500nm, Ø 337nm
  - Mini-stop band
  - Nejnižší ztráty: 20 ± 3 dB/mm (lichý vid!)

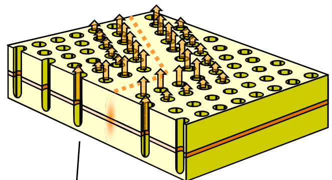


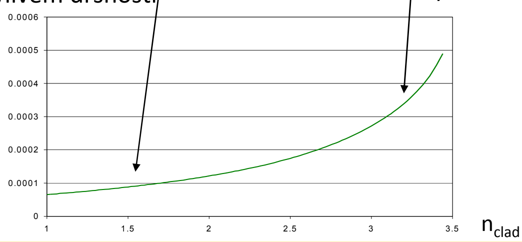


Ztráty vyzařováním z roviny krystalu

- Vysoký „vertikální“ kontrast indexu lomu
  - vnitřní ztráty
  - ztráty vlivem drsnosti
- Malý „vertikální“ kontrast indexu lomu
  - vnitřní ztráty
  - ztráty vlivem drsnosti

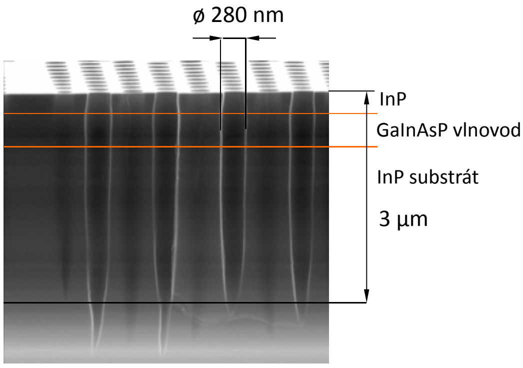






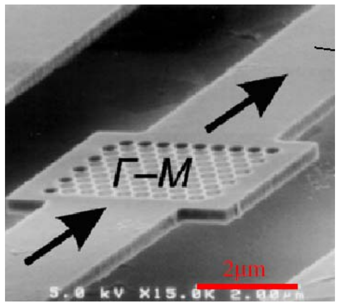
Potlačení ztrát vyzařováním do substrátu

1. Leptání hlubokých otvorů: záření „nevnímá“ substrát (kromě vlnovodu ??)



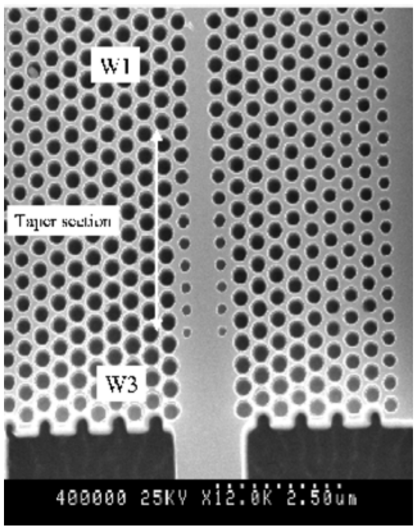
2. Úplné odstranění substrátu (technologicky náročné)

Membrána s otvory



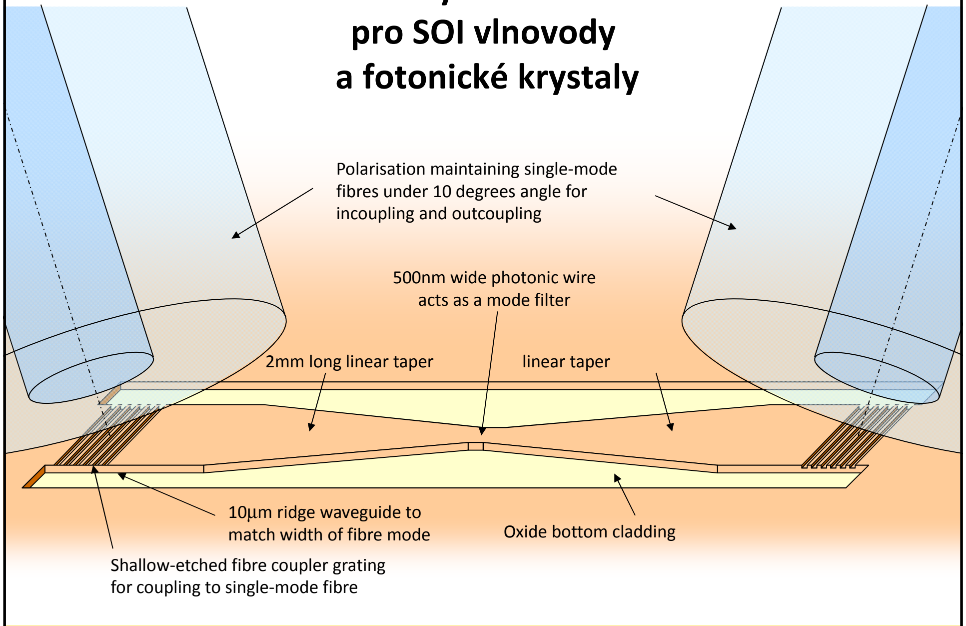
Vazba s vlnovodem ve fotonickém krystalu

CNRS – LPN, Anne Talneau, Ph. Lalanne



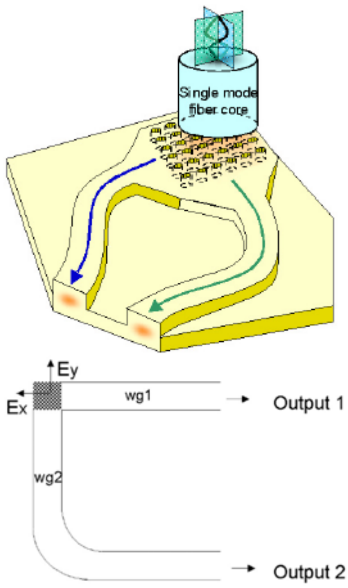
CNRS French patent (2001)

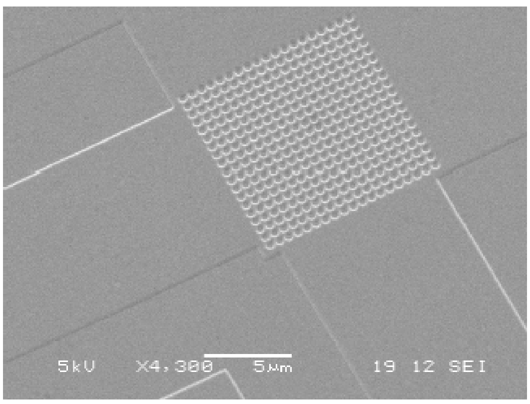
Mřížkový vazební člen pro SOI vlnovody a fotonické krystaly



Vlnovodné aplikace: polarizačně nezávislý mřížkový vazební člen

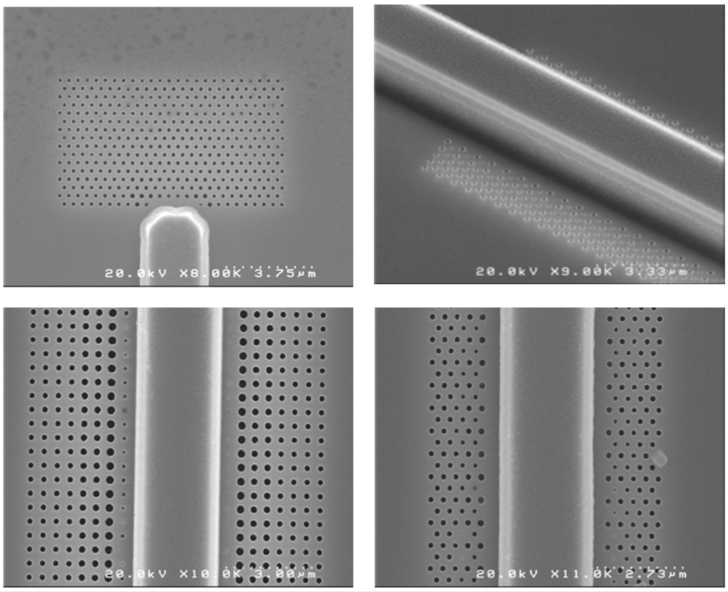
Ghent University,





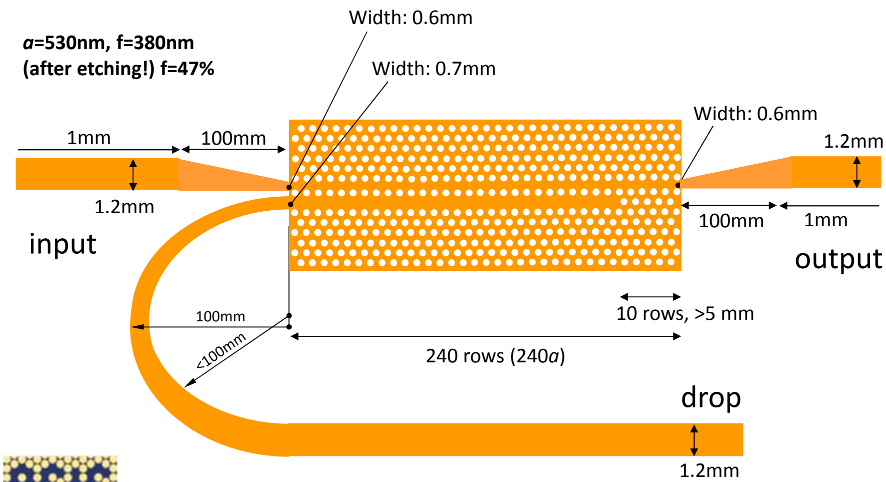
2D fotonické krystaly jako zrcadla polovodičových laserů

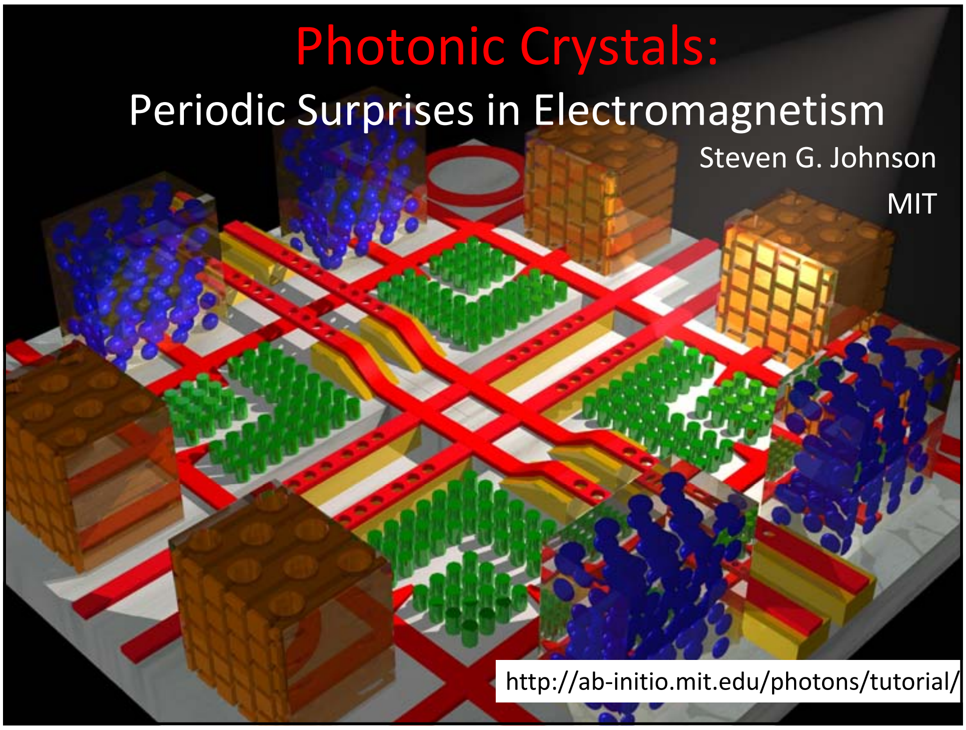
(Alcatel, 2002-3)



PC Add-Drop Layout

KTH Stockholm, Min Qiu





Vlnovodné struktury se ztrátami a ziskem

jako analogie kvantově-mechanických struktur

s (porušenou) symetrií parita-čas

FORMAL ANALOGY BETWEEN A PHOTONIC WAVEGUIDE AND A POTENTIAL WELL IN QUANTUM MECHANICS

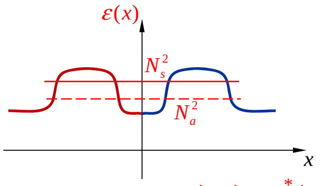
Eigenmode equation for TE modes of a planar waveguide

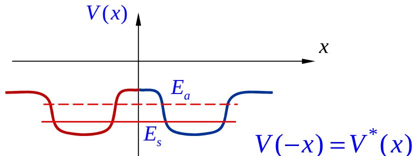
$$\frac{1}{k_0^2}\frac{d^2E(x)}{dx^2}+\varepsilon(x)E(x)=N^2E(x)$$

Schrödinger equation for a particle in a 1D potential well

$$-\frac{\hbar^2}{2m}\frac{d^2\psi(x)}{dx^2}+V(x)\psi(x)=E\psi(x)$$

mode field distribution	$E(x)$	$\Leftrightarrow$	$\psi(x)$	wave function
wave number	k_0	$\Leftrightarrow$	$\frac{\sqrt{2m}}{\hbar}$	mass; Planck constant
relative permittivity profile	$\varepsilon(x)$	$\Leftrightarrow$	$-V(x)$	potential
effective refractive index	N^2	$\Leftrightarrow$	$-E$	particle energy





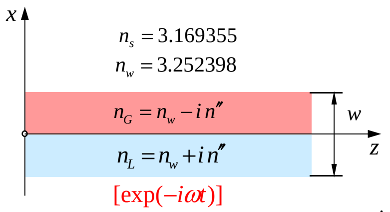
$V(-x)=V^*(x)$

Loss/gain structure: $\varepsilon(-x)=\varepsilon^*(x)$

"$\mathcal{PT}$ symmetry": ***complex potential****(!)*,

WAVEGUIDE STRUCTURE WITH LOSS/GAIN: HISTORICAL REMARKS

≈ 1995: COST 240 Action: Loss/gain waveguide modelling task by **H. P. Nolting (HHI)** (aimed at benchmarking of BPM methods)

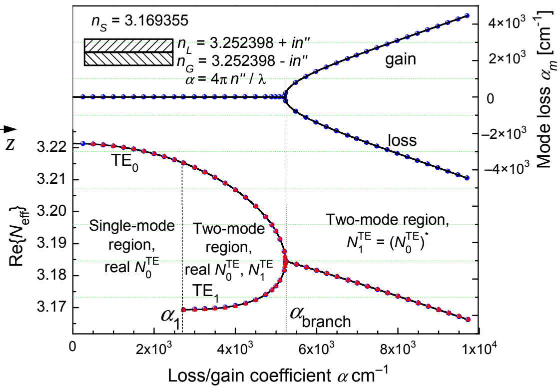


$w=1\ \mu\text{m}$,

$n''=\frac{\alpha}{2k_0}=\frac{\lambda}{4\pi}\alpha\times10^{-4}$ [–; μm, cm^{-1}],

$\lambda=1.55\ \mu\text{m}$,

α… "loss/gain coefficient" [cm^{-1}]



1. H.-P. Nolting, G. Sztefka, J. Čtyroký, "Wave Propagation in a Waveguide with a Balance of Gain and Loss," Integrated Photonics Research '96, Boston, USA, 1996, pp. 76-79.
2. G. Guekos, *Ed.*, Photonic Devices for telecommunications: how to model and measure. Berlin: Springer, 1998, pp. 76-78.

DISPERSION EQUATION (TE modes)

$$\Phi(N,\alpha)=\gamma_G\left[\gamma_S\cos(k_0\gamma_G w)-\gamma_G\sin(k_0\gamma_G w)\right]\left[\gamma_S\sin(k_0\gamma_L w)+\gamma_L\cos(k_0\gamma_L w)\right]+$$
$$+\gamma_L\left[\gamma_S\cos(k_0\gamma_L w)-\gamma_L\sin(k_0\gamma_L w)\right]\left[\gamma_S\sin(k_0\gamma_G w)+\gamma_G\cos(k_0\gamma_G w)\right]=0$$

$$\gamma_S=\sqrt{N^2-n_s^2},\quad \gamma_L=\sqrt{n_L^2-N^2},\quad \gamma_G=\sqrt{n_G^2-N^2},\quad k_0=\frac{2\pi}{\lambda}$$

“Exceptional” point: $\dfrac{dN}{d\alpha}\to\infty.$

Since $\Phi(N,\alpha)\equiv 0,\quad \dfrac{\partial\Phi}{\partial N}\dfrac{\partial N}{\partial\alpha}+\dfrac{\partial\Phi}{\partial\alpha}=0 \quad\Rightarrow\quad \dfrac{\partial N}{\partial\alpha}=-\dfrac{\partial\Phi}{\partial\alpha}\Big/\dfrac{\partial\Phi}{\partial N}\to\infty \quad\Rightarrow\quad \dfrac{\partial\Phi}{\partial N}=0.$

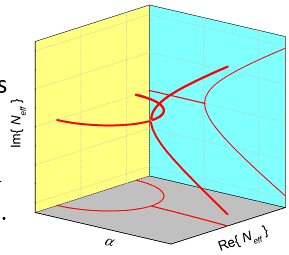
Exceptional point is given by the simultaneous solution of the following two equations:

$$\Phi(N_B,\alpha_B)=0,\qquad \Phi'_N=\frac{d\Phi(N_B,\alpha_B)}{dN}=0$$

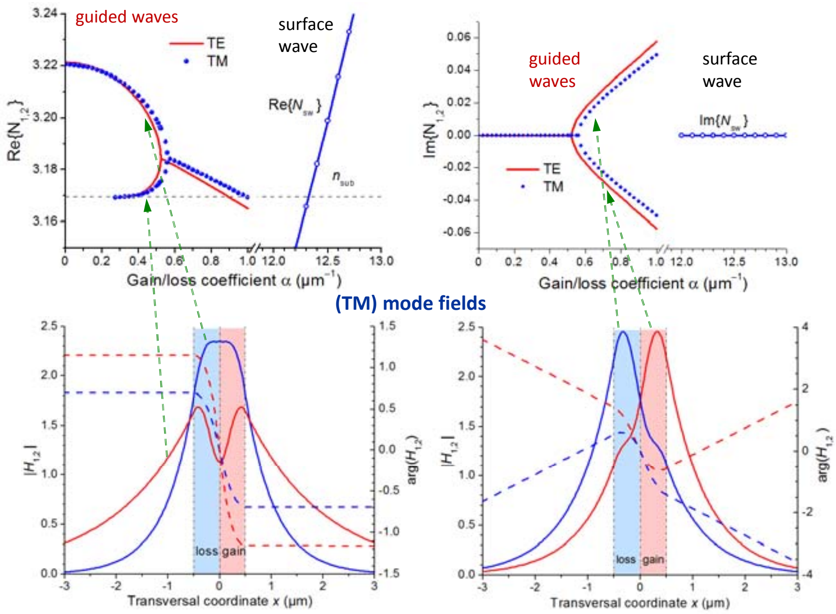
Taylor expansion of $\Phi(N,\alpha)$ in the vicinity of N_B,α_B sounds

$$\Phi(N,\alpha)\approx\Phi'_a(\alpha-\alpha_B)+\frac{1}{2}\Phi''_N\left(N-N_B\right)^2\overset{!}{=}0$$

from which it follows $\quad N\approx N_B\pm iC\sqrt{(\alpha-\alpha_B)},\quad C=\sqrt{\dfrac{2\Phi'_\alpha}{\Phi''_N}}.$

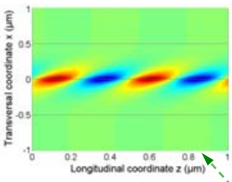


2D ANALYSIS (PLANAR WAVEGUIDES)



WAVEGUIDE STRUCTURE WITH LOSS/GAIN: SURFACE WAVE

Non-attenuated TM surface wave

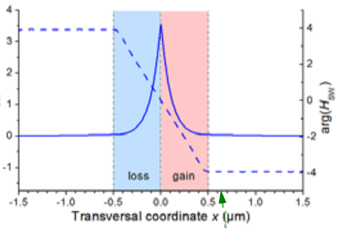


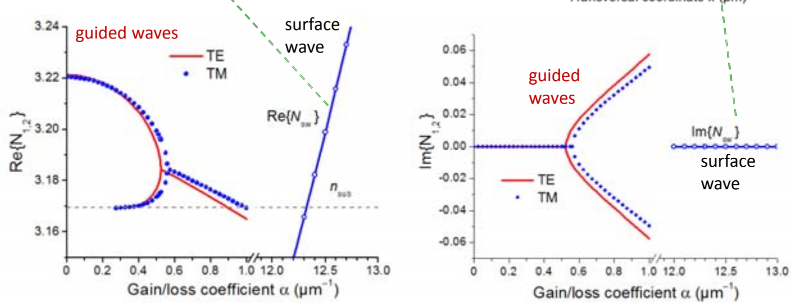
n_s

$n_G = n_w - in''$

$n_L = n_w + in''$

$$N_{SW} = \sqrt{\frac{n_G^2 n_L^2}{n_G^2 + n_L^2}}$$



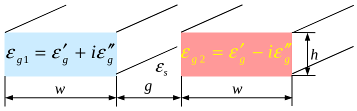


J. Čtyroký *et al.*, "Waveguide structures with antisymmetric gain/loss profile," *Optics Express*, vol. 18, pp. 21585-21593, 2010.

COUPLED WAVEGUIDES WITH LOSS/GAIN

Balanced loss/gain switching:

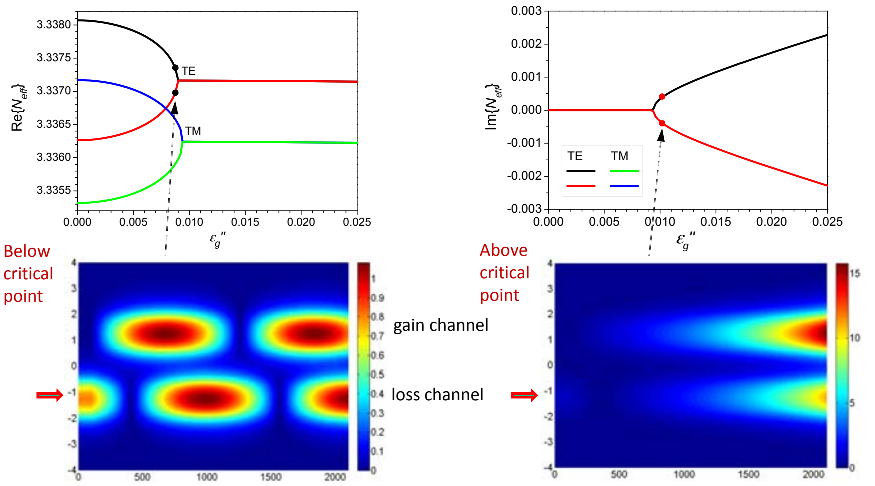
$\varepsilon(-x, y) = \varepsilon^*(x, y)$



$\varepsilon_s = 10.89, \quad \varepsilon'_g = 11.56$

$w = 1.5$ µm, $h = 0.75$ µm,

$g = 1$ µm, $\lambda = 1.55$ µm.

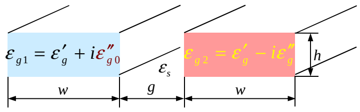


C. E. Rüter *et al.* "Observation of parity–time symmetry in optics," *Nature Physics*, vol. 6, pp. 192-195, 2010.

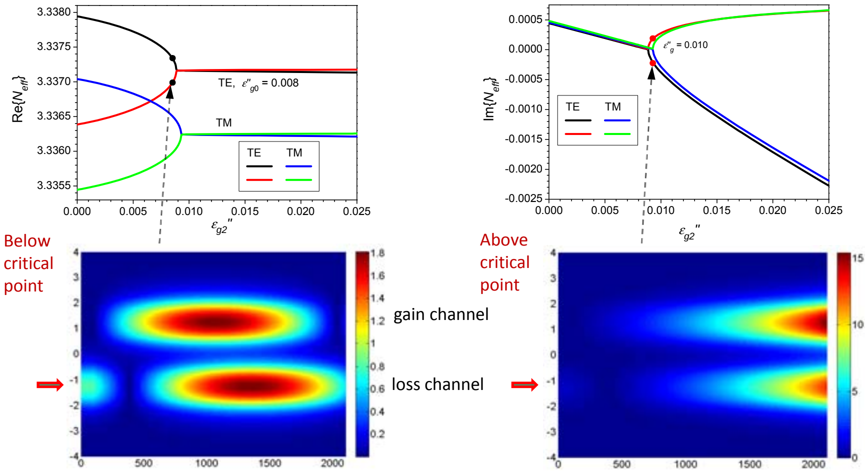
COUPLED WAVEGUIDES WITH LOSS/GAIN

Fixed loss/variable gain switching:

$\varepsilon(-x,y) \neq \varepsilon^*(x,y)$



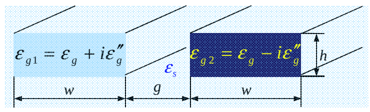
$\varepsilon_s = 10.89,\ \ \varepsilon_g' = 11.56$
$w = 1.5\ \mu\text{m},\ \ h = 0.75\ \mu\text{m},$
$g = 1\ \mu\text{m},\ \ \lambda = 1.55\ \mu\text{m}.$



COUPLED WAVEGUIDES WITH LOSS/GAIN

Balanced loss/gain with reduced gain:

$\mathbf{E}(x,y,z) = \mathbf{e}(x,y)\exp(ik_0 N z)$



$\varepsilon_s = 10.89 + i\varepsilon_b'',\ \ \varepsilon_g = 11.56 + i\varepsilon_b''$
$w = 1.5\ \mu\text{m},\ \ h = 0.75\ \mu\text{m},$
$g = 1\ \mu\text{m},\ \ \lambda = 1.55\ \mu\text{m}.$

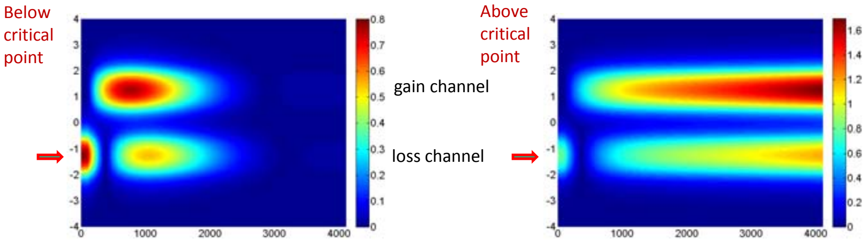
Rigorous equation for transversal field components: $\Delta_\perp \mathbf{e}_\perp + \nabla_\perp\left[\nabla_\perp(\ln\varepsilon)\cdot\mathbf{e}_\perp\right] + k_0^2(\varepsilon - N^2)\mathbf{e}_\perp = \mathbf{0},$

Small uniform permittivity modification: $\varepsilon_1(x,y) = \varepsilon(x,y) + i\varepsilon_b'',\ \ |\varepsilon_b| \ll |\varepsilon|$

$$\Delta_\perp \mathbf{e}_\perp + \nabla_\perp\left[\nabla_\perp\left(\ln\varepsilon + \frac{i\varepsilon_b''}{\varepsilon}\right)\cdot\mathbf{e}_\perp\right] + k_0^2\left[\varepsilon + i\varepsilon_b'' - (N^2 + i\varepsilon_b'')\right]\mathbf{e}_\perp = \mathbf{0};\quad \varepsilon \to \varepsilon + i\varepsilon_b'' \ \Rightarrow\ \boxed{N^2 \to N^2 + i\varepsilon_b''}$$

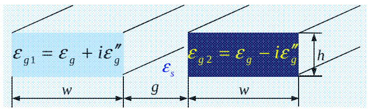
Uniform background loss can be used **to reduce the required gain**: $\varepsilon_{branch}'' = \pm 0.009$

$\varepsilon_{g,loss}'' = 0.0105,\ \ \varepsilon_{g,gain}'' = -0.0065,\ \ \ \varepsilon_b'' = 0.002,\ \ \ \varepsilon_{g,loss}'' = 0.0115,\ \ \varepsilon_{g,gain}'' = -0.0075$



COUPLED WAVEGUIDES WITH LOSS/GAIN

Un/balanced loss/gain:



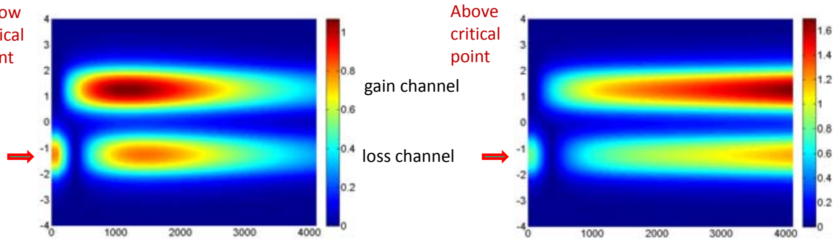
$\varepsilon_s = 10.89 + i\varepsilon_b''$, $\varepsilon_g = 11.56 + i\varepsilon_b''$
$w = 1.5$ μm, $h = 0.75$ μm,
$g = 1$ μm, $\lambda = 1.55$ μm.

Structure with background loss, $\varepsilon_b'' = 0.002$

Output ***power increase*** (from both waveguides) by ***increasing loss*** of the lossy channel:

Lower loss, "subcritical" regime | Higher loss, "supercritical" regime

$\varepsilon_{g,loss}'' = 0.0105$, $\varepsilon_{g,gain}'' = -0.0075$, $\varepsilon_b'' = 0.002$, $\varepsilon_{g,loss}'' = 0.0115$, $\varepsilon_{g,gain}'' = -0.0075$



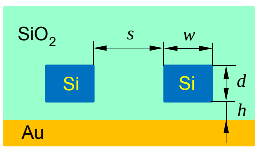
A. Guo *et al.*, "Observation of PT-Symmetry Breaking in Complex Optical Potentials," *Physical Review Letters, vol. 103, no. 9, pp. 093902-1-4, 2009.*

PLASMONIC LOSS/GAIN STRUCTURES

A hypothetic "canonic" (balanced) plasmonic loss/gain structure:

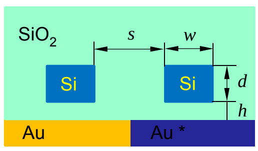
Hybrid dielectric-plasmonic slot waveguide directional coupler *with "tunable metal"*

"Passive" structure:

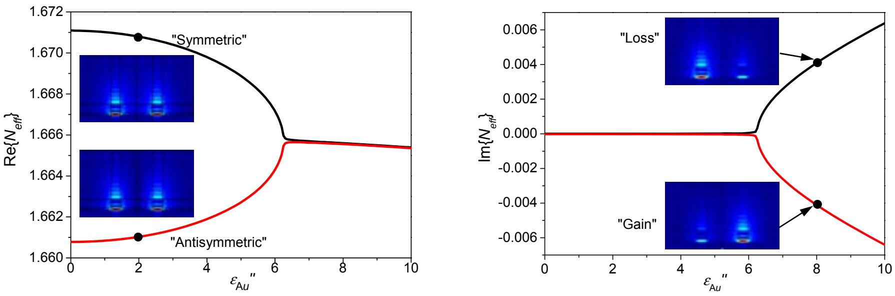


$\varepsilon(-x, y) = \varepsilon^*(x, y)$
$w = 300$ nm,
$d = 120$ nm,
$h = 30$ nm,
$s = 1000$ nm,
$\lambda = 1.55$ μm

Au with tunable loss / Au* with tunable gain



$\varepsilon_{Au^*} = \varepsilon_{Au}^*$

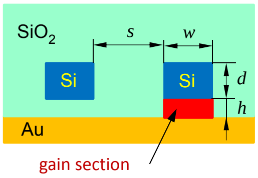


H. Benisty *et al.*, "Implementation of PT symmetric devices using plasmonics: principle and applications," *Optics Express*, vol. 19, pp. 18004-18019, 2011.

PLASMONIC LOSS/GAIN STRUCTURES

A more realistic model of an ***unbalanced*** plasmonic loss/gain structure:

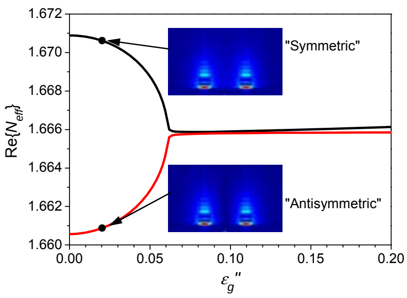
Hybrid dielectric-plasmonic slot waveguide directional coupler with gain section

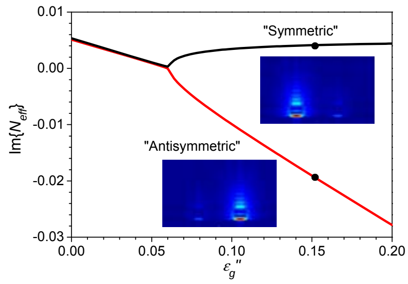


$w = 300$ nm,
$d = 120$ nm,
$h = 30$ nm,
$s = 1000$ nm

$$\varepsilon(-x, y) \neq \varepsilon^*(x, y)$$

Only gain (ε_g'') in the gain section is now tuned: $\varepsilon_{gain} = \varepsilon_{SiO_2} - i\varepsilon_g''$



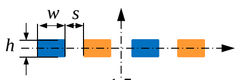


MORE COMPLEX GAIN-LOSS STRUCTURES

Linear arrays of coupled waveguides with loss and gain

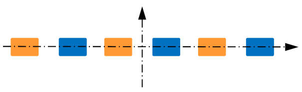
$$\varepsilon(-x, y) = \varepsilon^*(x, y)$$

4 coupled channel waveguides



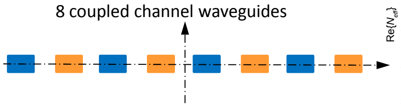
$w = 1.5$ μm,
$h = 0.75$ μm,
$s = 1$ μm

6 coupled channel waveguides

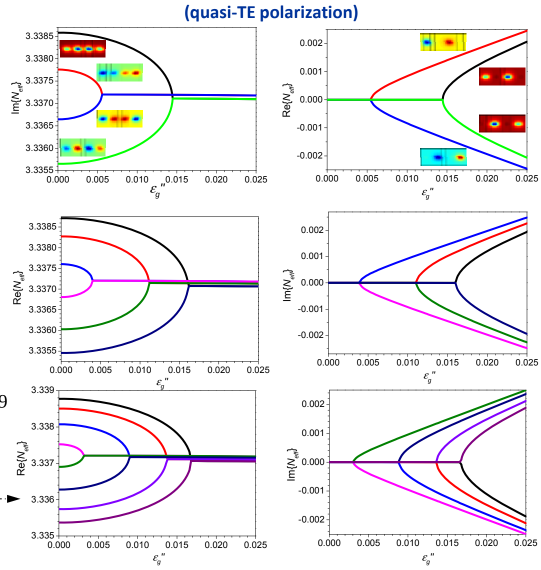


$\varepsilon_{g1} = 11.56 + i\varepsilon_g''$, $\varepsilon_{g2} = 11.56 - i\varepsilon_g''$, $\varepsilon_s = 10.89$

8 coupled channel waveguides



(quasi-TE polarization)

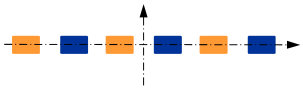


LINEAR ARRAY WITH UNBALANCED LOSS/GAIN

Coupled waveguides with ***fixed loss*** and ***variable gain***

$$\varepsilon(-x,y) \neq \varepsilon^*(x,y)$$

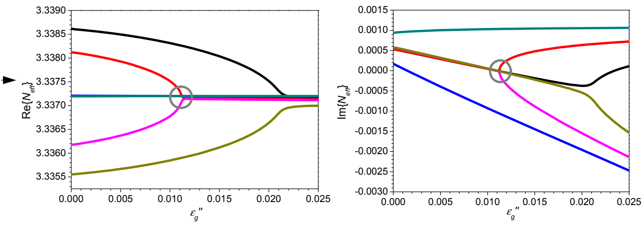
6 coupled channel waveguides



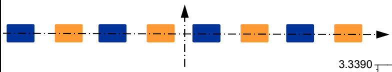
$\varepsilon_{g1} = 11.56 + 0.011i,$

$\varepsilon_{g2} = 11.56 - i\varepsilon_g'',$

$\varepsilon_s = 10.89$



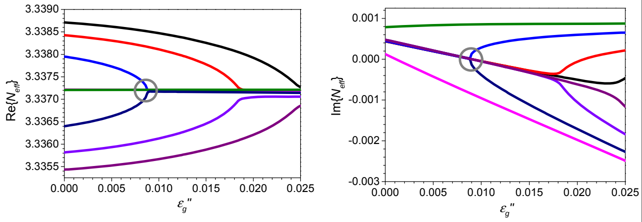
8 coupled channel waveguides



$\varepsilon_{g1} = 11.56 + 0.009i,$

$\varepsilon_{g2} = 11.56 - i\varepsilon_g'',$

$\varepsilon_s = 10.89$



"Switching" by pure gain modulation is feasible also in loss/gain waveguide arrays

MORE COMPLEX GAIN-LOSS STRUCTURES

"Circular" arrays of coupled waveguides with loss and gain

4 waveguides

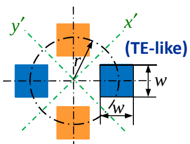
$w = 1\ \mu m$

$r = 1.5w$

$\varepsilon_{g1} = 11.56 + i\varepsilon_g'',$

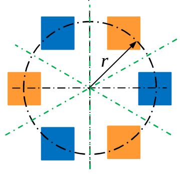
$\varepsilon_{g2} = 11.56 - i\varepsilon_g'',$

$\varepsilon_s = 10.89$



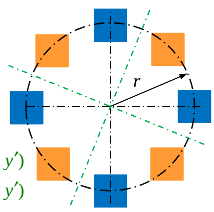
6 waveguides

$r = 2w$



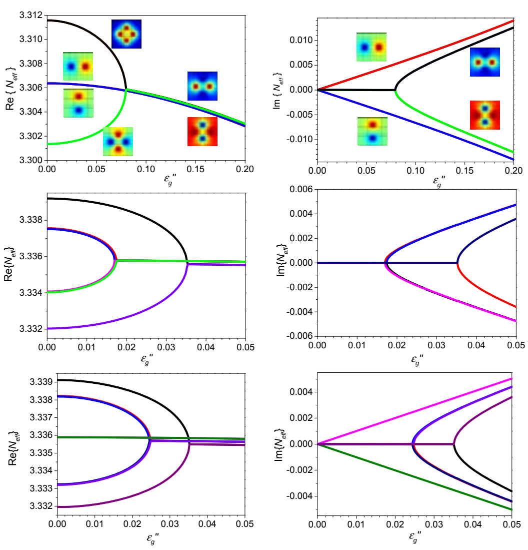
8 waveguides

$r = 2.55w$



$\varepsilon(-x',y') = \varepsilon^*(x',y')$

$\varepsilon(x',-y') = \varepsilon^*(x',y')$



CIRCULAR ARRAYS WITH UNBALANCED LOSS/GAIN

Coupled waveguides with ***fixed loss*** and ***variable gain***

6 waveguides

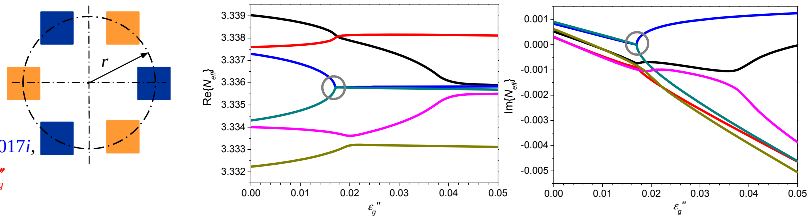
$w = 1\ \mu m$

$r = 2w$

$\varepsilon_S = 10.89$

$\varepsilon_{g1} = 11.56 + 0.017i,$

$\varepsilon_{g2} = 11.56 - i\varepsilon_g''$

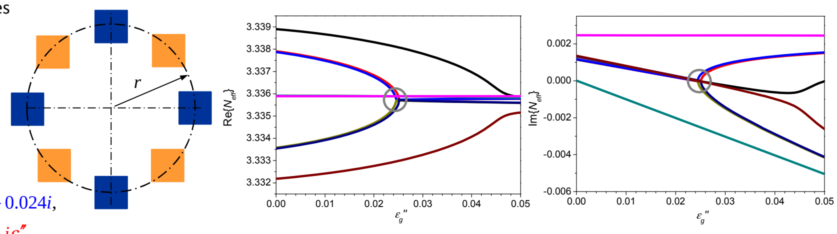


8 waveguides

$r = 2.55w$

$\varepsilon_{g1} = 11.56 + 0.024i,$

$\varepsilon_{g2} = 11.56 - i\varepsilon_g''$



"Switching" by pure gain modulation is feasible also in loss/gain waveguide arrays

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11. …and many others…
12. …