

Povrchové plazmony v integrované fotonice

úfe

Povrchové plazmony v integrované fotonice

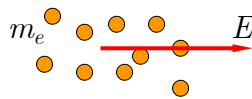
Typické aplikace:

1. vlnovodné polarizátory
2. SPR senzory
3. povrchové plazmony pro přenos informace („plazmonika“)

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

Polarizace: $P_0 = -n_e e x_0 = \frac{-e^2 n_e}{m_e \omega^2 + im_e \gamma \omega} E_0 = \epsilon_0 \chi E_0$

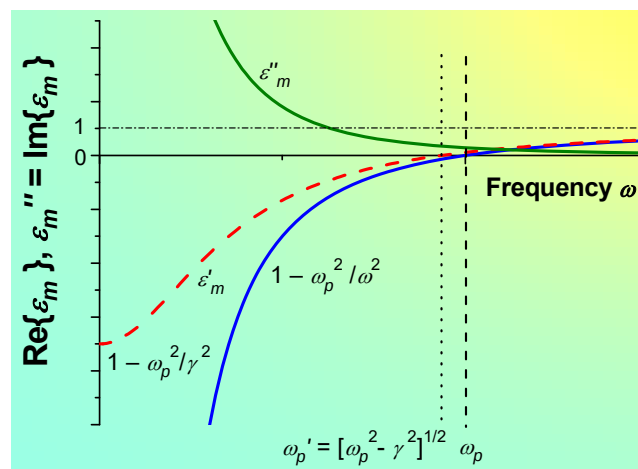
Permitivita: $\epsilon_m = 1 + \chi = 1 - \frac{e^2 n_e / (m_e \epsilon_0)}{\omega^2 + i\gamma \omega} = 1 - \frac{\omega_p^2}{\omega^2 + i\gamma \omega}$

Plazmová frekvence $\omega_p = e \sqrt{\frac{n_e}{m_e \epsilon_0}}$

life

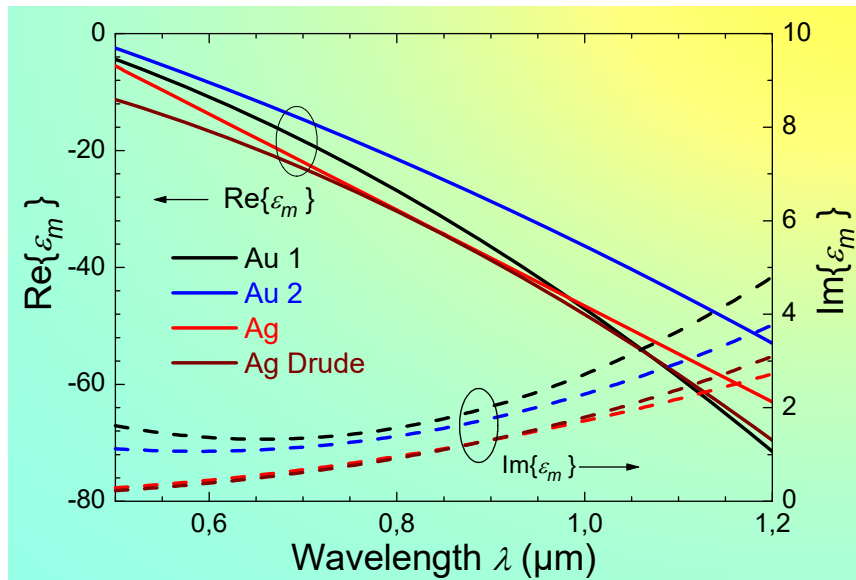
Disperze kovu (Drudeho model)

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



life

Disperze kovu (experimentální data)



Povrchová plazmová vlna

(povrchový plazmon-polariton, **povrchový plazmon**)

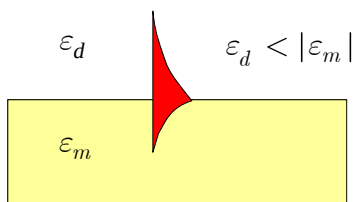
Vzájemně vázaná elektromagnetická a nábojová povrchová **vlna**
localizovaná na rozhraní mezi dielektrikem a kovem

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**

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



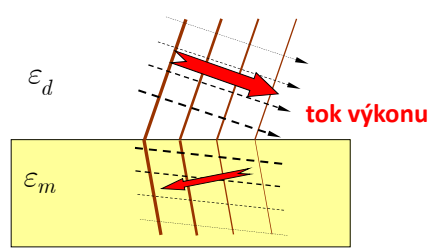
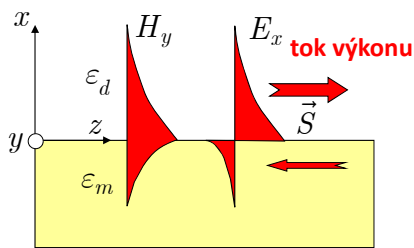
Rozložení pole povrchového plazmonu

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

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

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

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

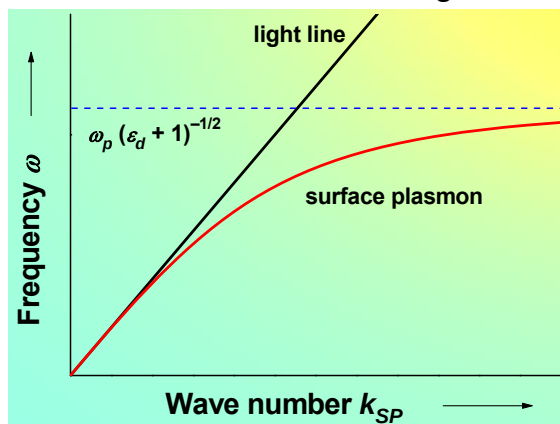


Disperzní vlastnosti povrchového plazmonu

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

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

"light line" $\rightarrow$ faktor < 1

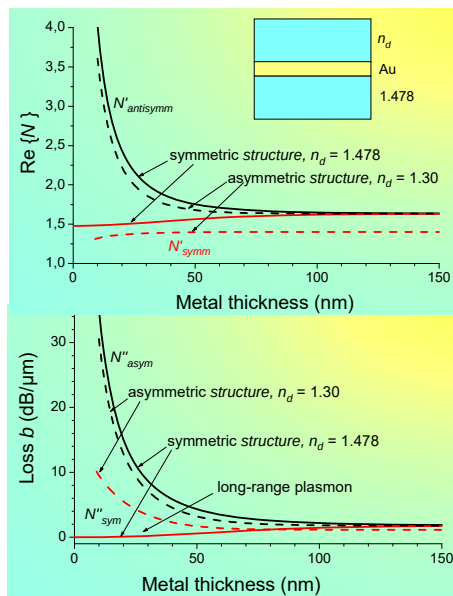
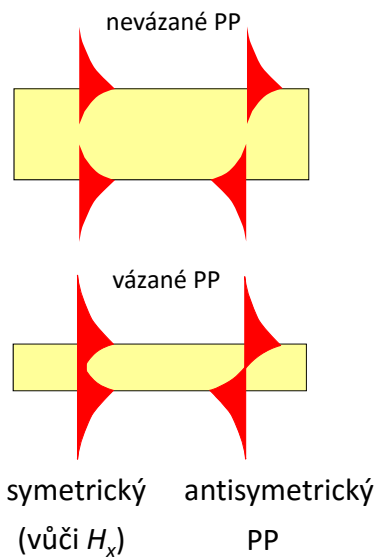


$\text{Re}\{N_{SP}\} > n_d \Rightarrow$

PP je **pomalá vlna**

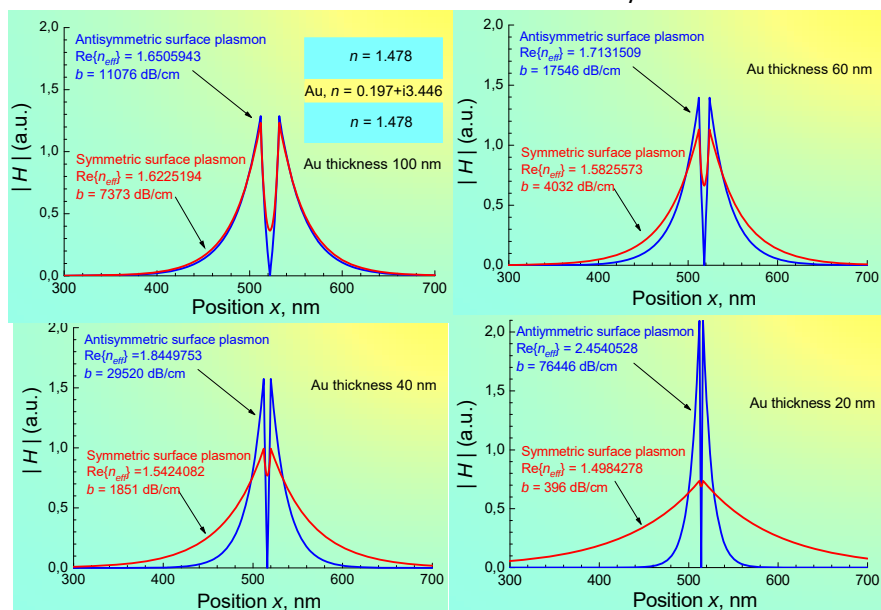
nemůže být excitována
zářením z dielektrika

Povrchové plazmony na kovové vrstvě



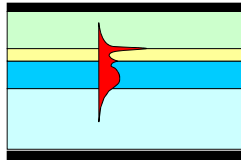
Rozložení polí PP na kovových vrstvách

Závislost na tloušťce kovové vrstvy

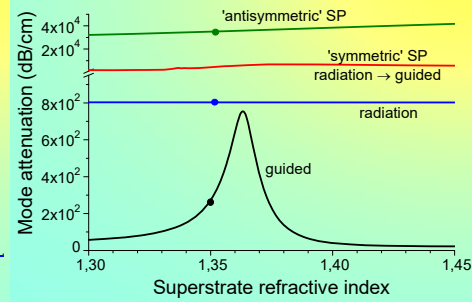
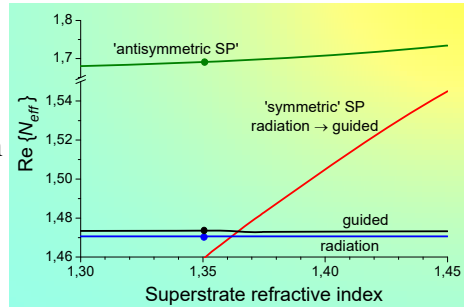
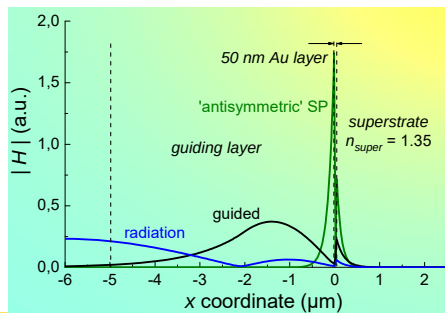


Vidy planárních vlnovodů s kovovou vrstvou

1.

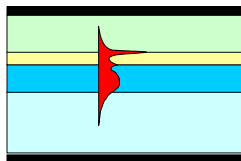


$$d_{Au} = 50 \text{ nm}$$

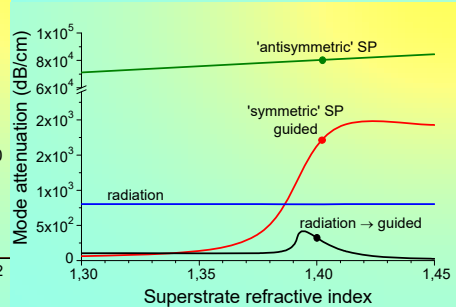
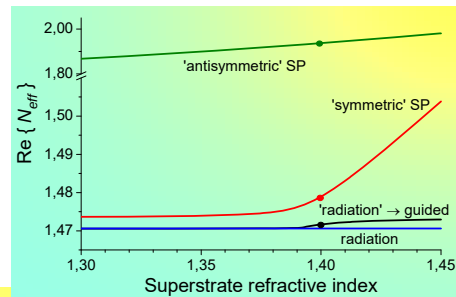
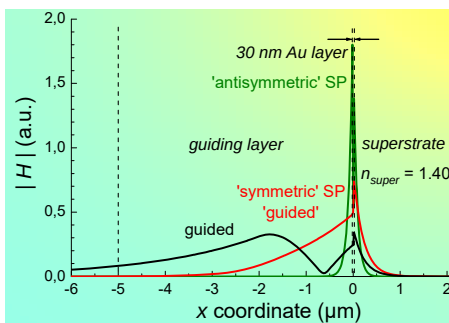


Vidy planárních vlnovodů s kovovou vrstvou

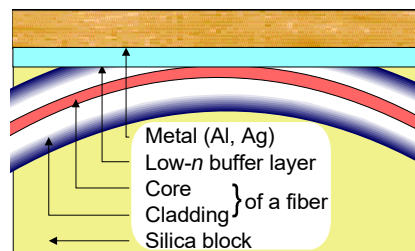
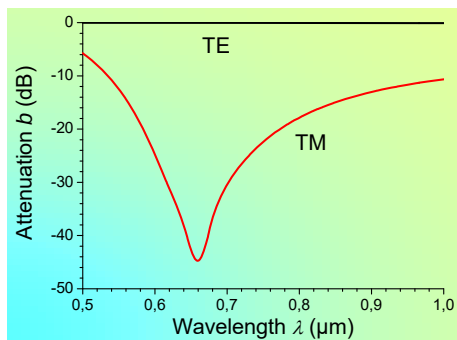
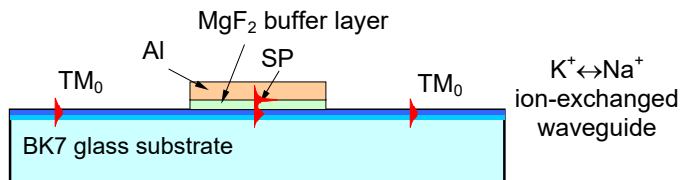
2.



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



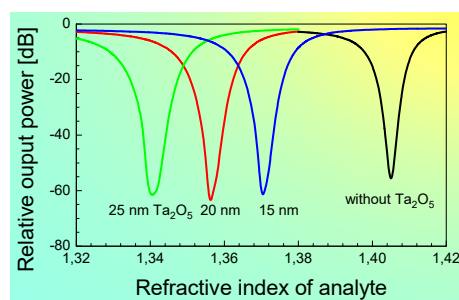
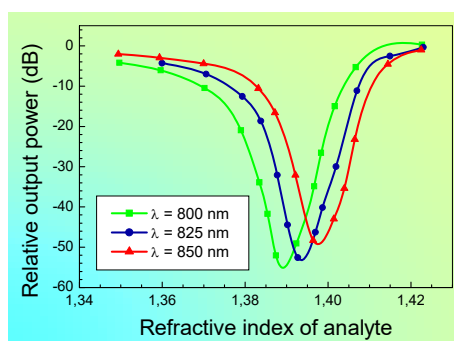
Vlnodný polarizátor založený na rezonanční excitaci PP



Průchod optického záření senzorem s PP

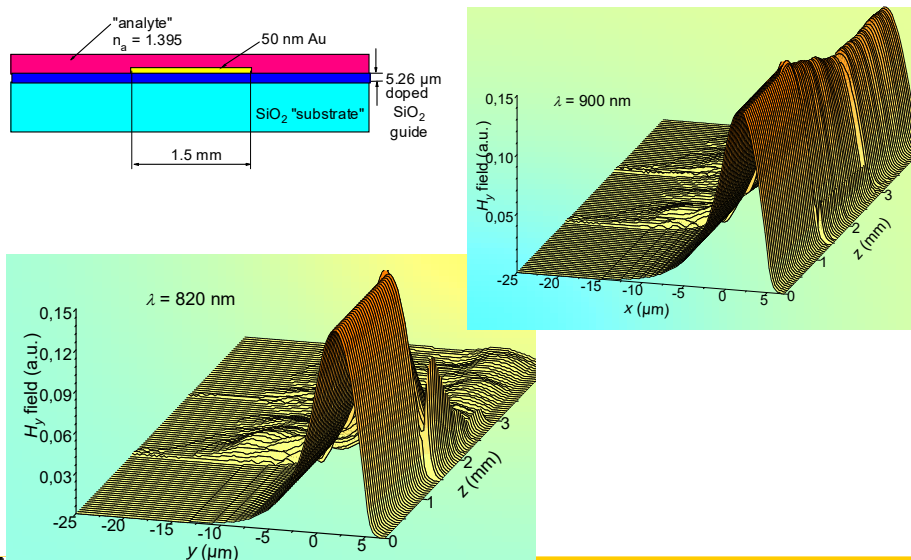
- závislost na indexu lomu analytu (zkoumaného prostředí)

2D (planární) model

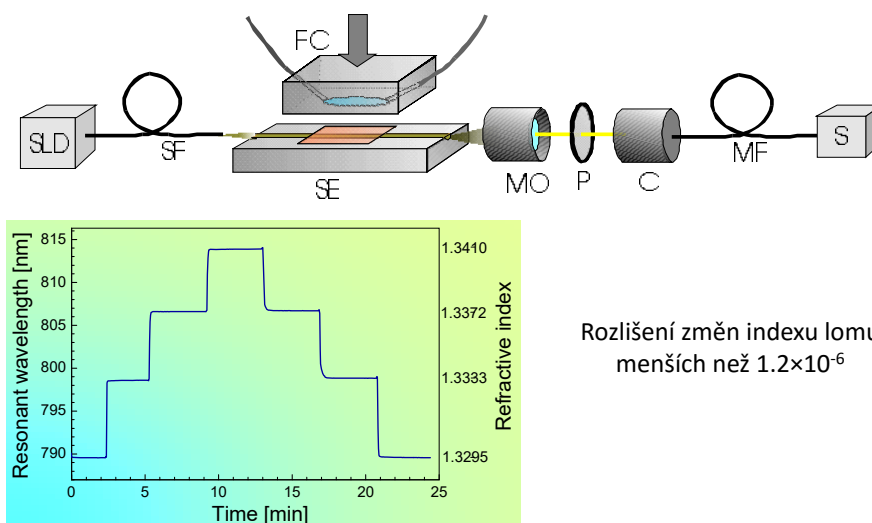


měření laditelným
Ti:safírovým laserem

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

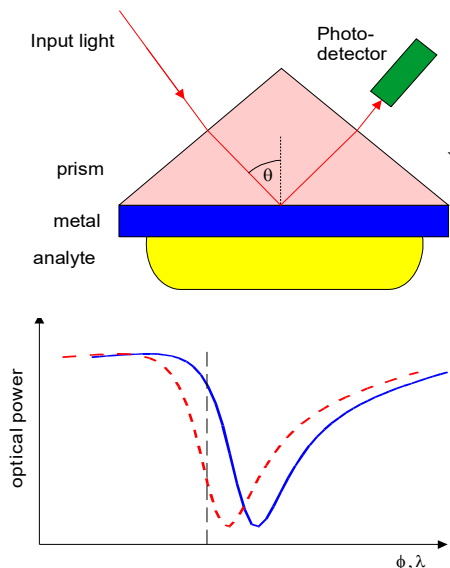


Experimentální uspořádání integrovaně-optického senzoru s PP

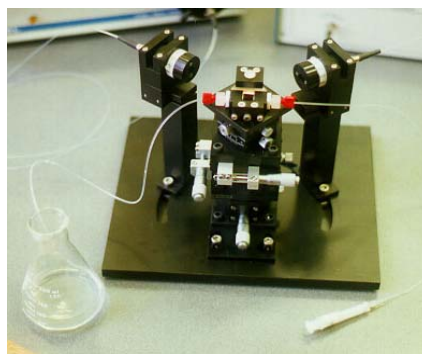


Rozlišení změn indexu lomu menších než 1.2×10^{-6}

Objemové senzory s PP

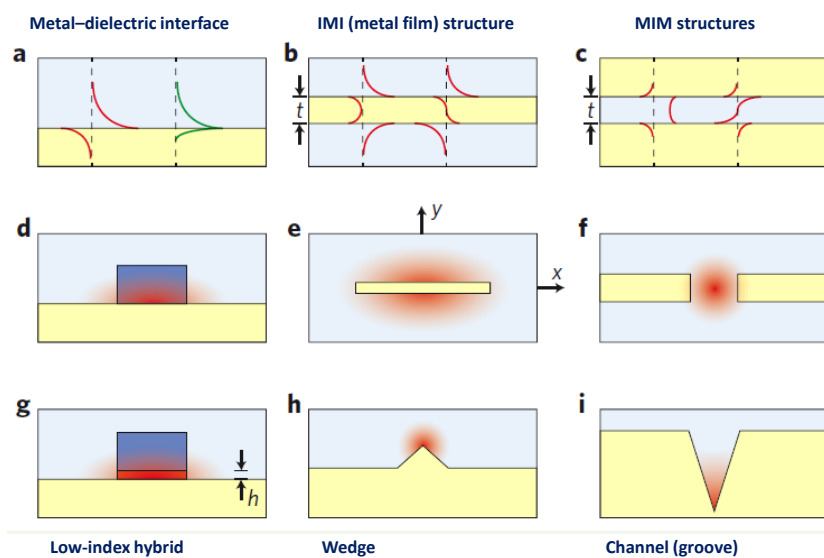


Rozlišení změn indexu lomu
menších než 5×10^{-7}



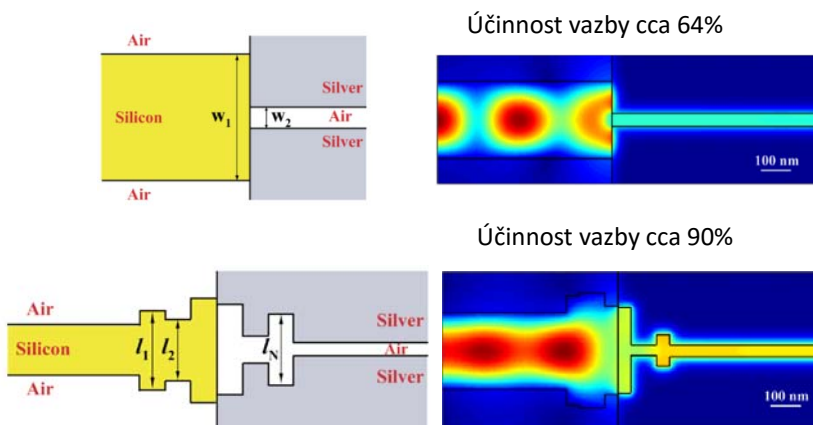
life

PLAZMONICKÉ VLNOVODY



life

Přechod mezi vlnovodem SOI a plazmonovým vlnovodem



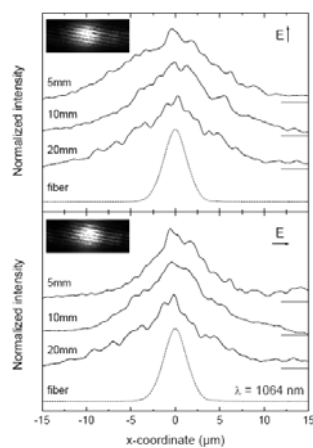
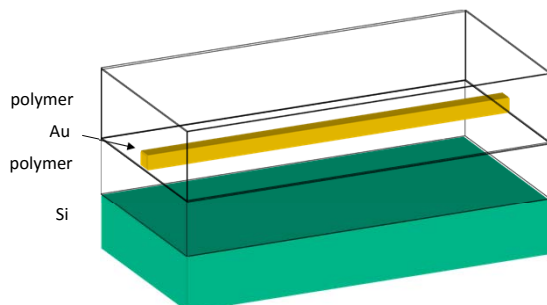
G. Veronis, S. Fan, OWTNM 2006, p. 12
(Stanford university)

„Zlatý nanodrát“ jako vlnovod pro povrchové plazmony

(T. Rosenzweig, 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)

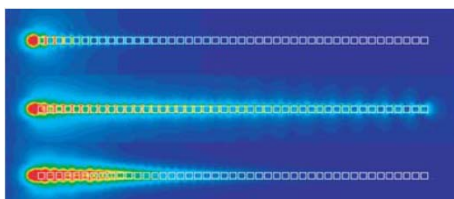
„Řetízek“ Au krychliček o straně 45 nm vzdálených od sebe 20 nm

Excitační vlnová délka

500 nm

429 nm

390 nm



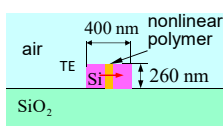
Na vlnové délce 429 je „překlenutelná vzdálenost“
pro pokles výkonu na $1/e^2$ celkem 2,2 mm
(útlum cca 40 dB/cm)

life

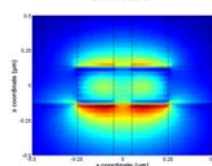
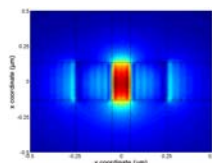
2

Nové typy plazmonických vlnovodů

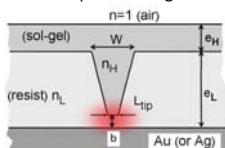
SOI “slot waveguide”



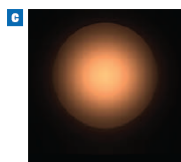
C. Koos & al., *Nat. Photonics* **3**(4), 16–219 (2009)



PIROW – plasmonic inverted
rib optical waveguide

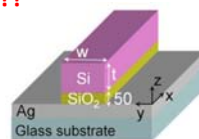


H. Benisty and M. Besbes,
J. Appl. Phys. **108**(6), 063108 (2010).



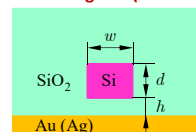
R. F. Oulton & al., *Nat. Photonics* **2**, 496 (2008);

??

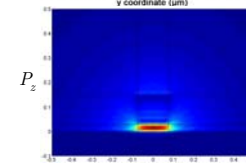
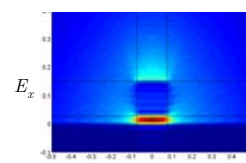


H.-S. Chu & al., *J. Opt. Soc. Am. B* **28**(12), 2895 (2011) (others, too)

Hybrid dielectric-plasmonic
slot waveguide (HDPSW)



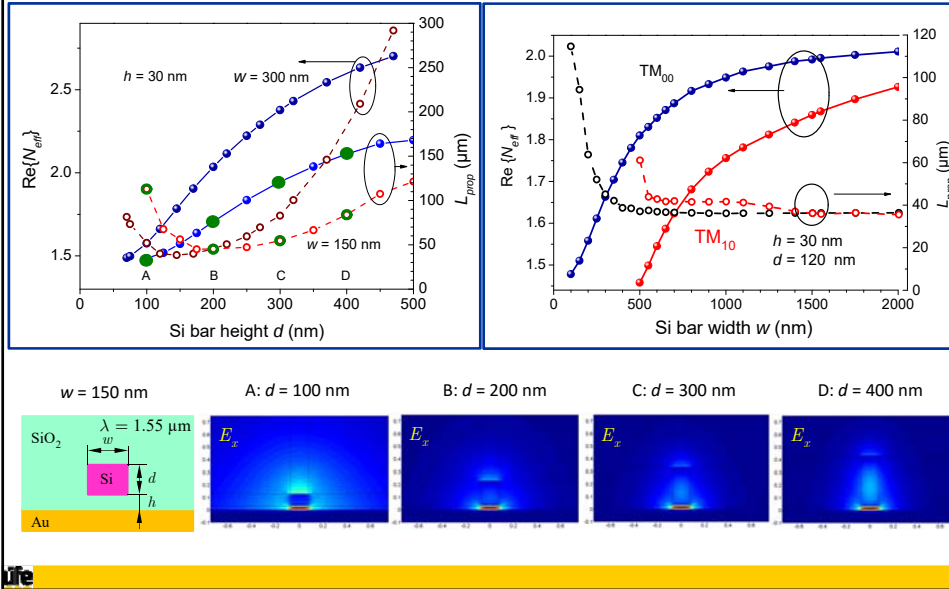
R. F. Oulton & al., *New J. Phys.* **10**, 105018 (2008)



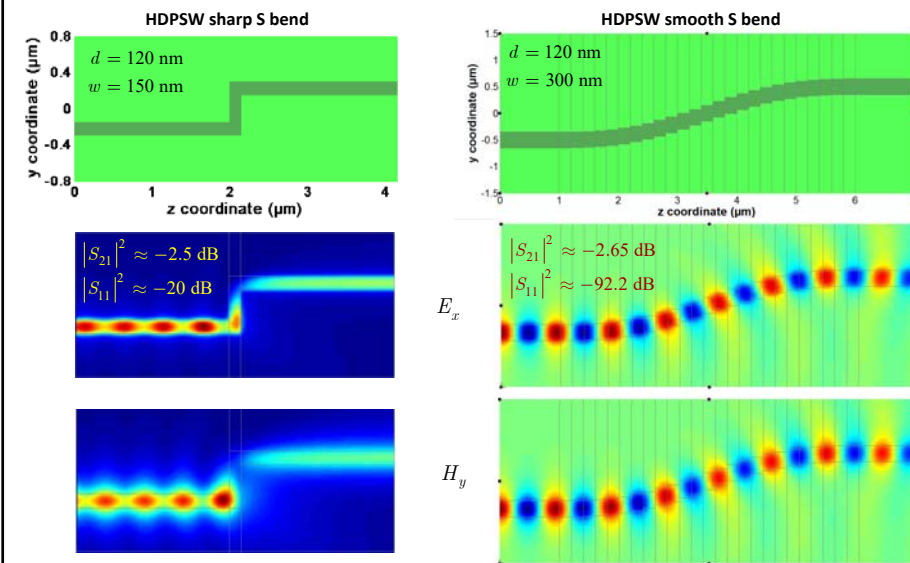
life

Hybrid dielectric-plasmonic slot waveguide

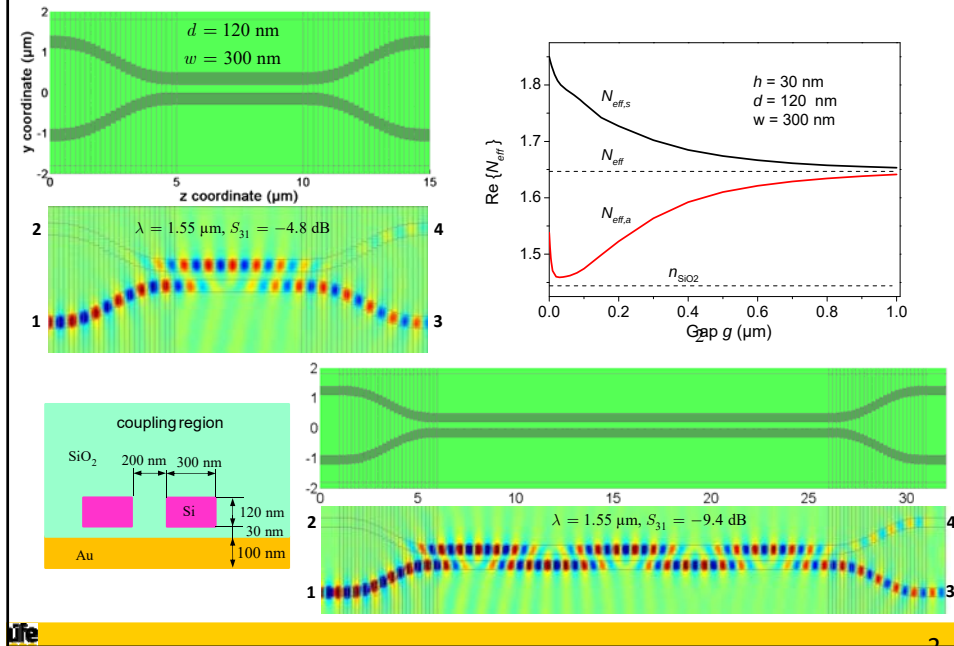
Influence of basic geometric parameters



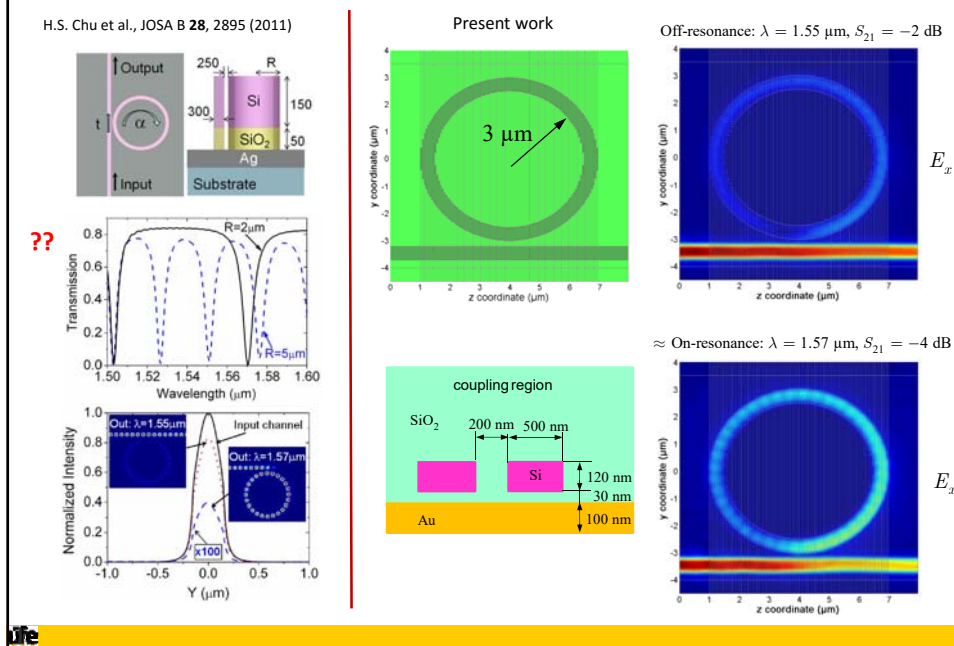
HDPSW DEVICES



DIRECTIONAL COUPLER

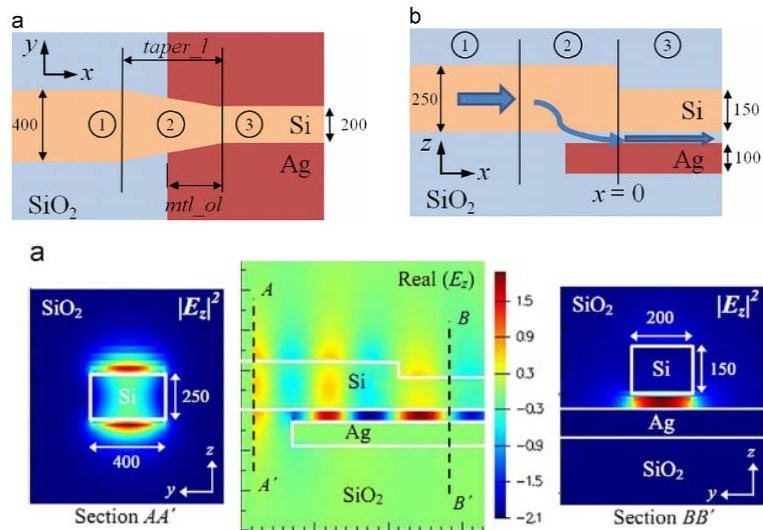


RING MICRORESONATOR

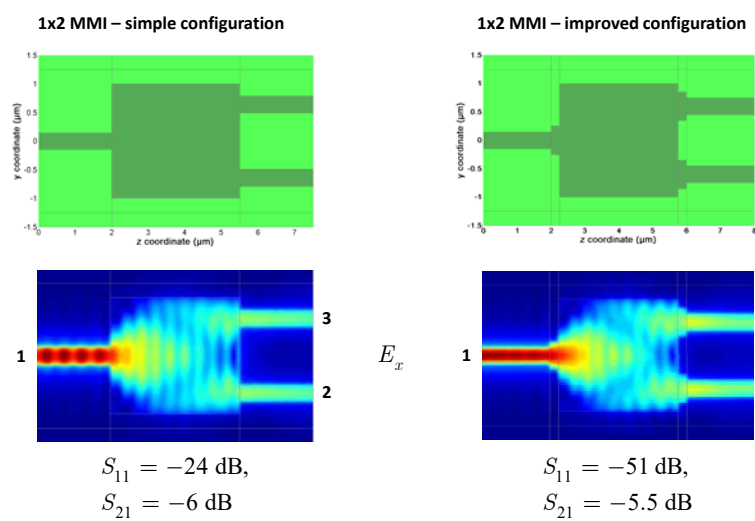


VAZBA MEZI SOI NANODRÁTEM A HDPSW

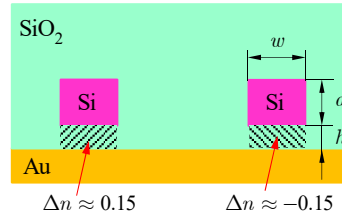
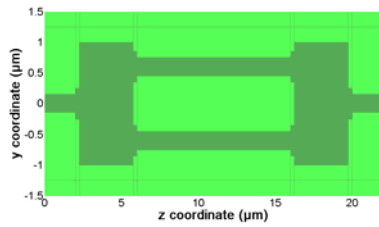
R. Mote et al., *Optics Communications* 285 (2012) 3709–3713



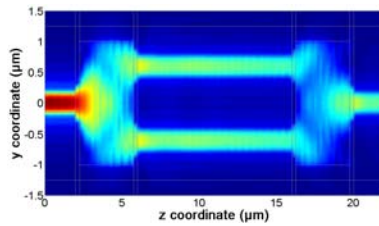
MULTIMODE INTERFERENCE COUPLER



MACH-ZEHNDER INTERFEROMETER



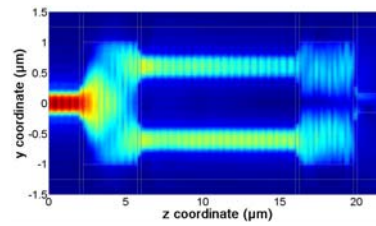
“On” state



$$S_{11} = -37 \text{ dB}$$

$$S_{21} = -6 \text{ dB}$$

“Off” state



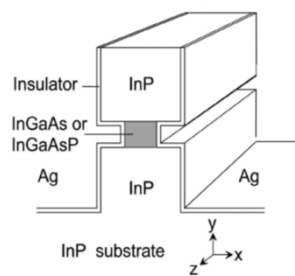
$$S_{11} = -25 \text{ dB}$$

$$S_{21} = -21 \text{ dB}$$

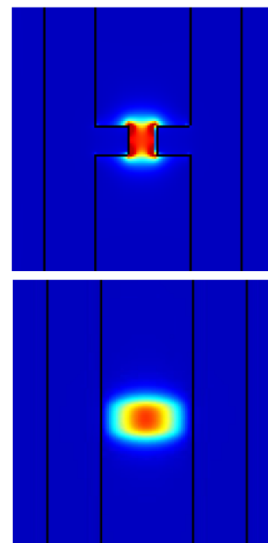
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Koncept „plazmonového polovodičového laseru“

(M. Hill, ECIO 2007)



Rozměry aktivní oblasti laseru
26 × 26 × 82 nm



life

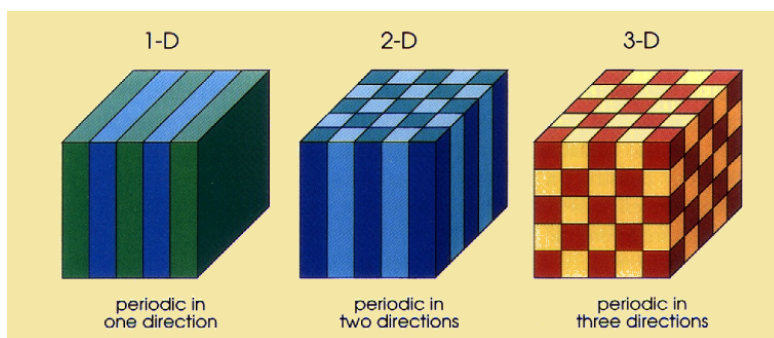
Fotonické krystaly

a integrovaná fotonika

life

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

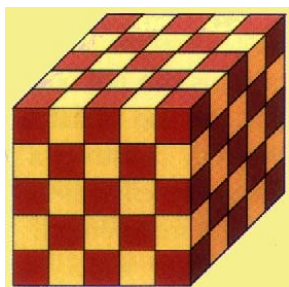
S. G. Johnson, J. D. Joannopoulos: *Photonic Crystals, The road from theory to practice*, Kluwer Academic Publishers 2003

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

life

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 vlnodů ve fotonických krystalech**

Vytvořit trojrozměrné periodické prostředí je však technologicky obtížné.

úfe

“Pohybové rovnice” pro elektrony a fotony v krystalech

Schrödingerova rovnice pro elektron v periodickém potenciálu:

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

periodický potenciál vlnová funkce energie fotonu $\psi(\mathbf{r}) = \sum_m u_m(\mathbf{r}) e^{im\mathbf{K}\cdot\mathbf{r}}$ (Floquetova)-Blochova vlna,

Aproximativní (jednočásticové) přiblížení

“Vlnová rovnice” pro fotony v periodické permitivitě

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

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

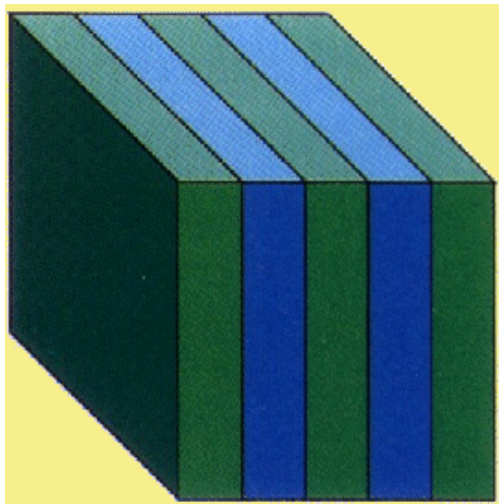
Přesná (“mnohočásticová”) teorie

Rovnice pro vlastní hodnoty energie fotonů a F-B funkce

Tento přístup je jednoduchý a průzračný, ale standardně nebere v úvahu *disperzi permitivity* $\varepsilon(\mathbf{r}, \omega)$

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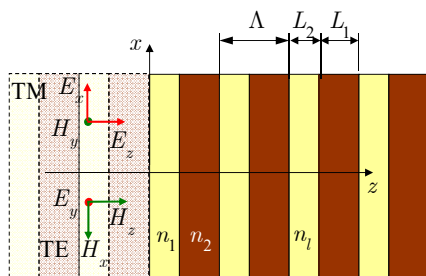
Periodická vrstevnatá struktura jako jednorozměrný fotonický krystal



úfe

Jednorozměrný fotonický krystal

Existence zakázaného pásu odvozená metodou přenosové matice
(fotonická analogie Kronigova - Penneyova modelu krystalu)



Normalizace souřadnic a vln. vektorů

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

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

$$\gamma^2 + N_l^2 = \varepsilon_l = \begin{cases} n_1^2 \\ n_2^2 \end{cases} \quad \begin{array}{l} \gamma - \text{příčná konst.} \\ \text{šíření } \textbf{stejná} \\ \text{konst. šíření} \end{array}$$

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

TE

TM

$$\begin{aligned} E_{y,l}(x, z) &= \sqrt{2k_0 Z_0 / N_l} p_l(\zeta) e^{i\gamma \xi}, & H_{y,l}(x, z) &= \sqrt{2k_0 Y_0 \varepsilon_l / N_l} p_l(\zeta) e^{i\gamma \xi}, & Z_0 &= \sqrt{\frac{\mu_0}{\varepsilon_0}}, \\ H_{x,l}(x, z) &= -\sqrt{2k_0 Y_0 N_l} q_l(\zeta) e^{i\gamma \xi}, & E_{x,l}(x, z) &= \sqrt{2k_0 Z_0 N_l / \varepsilon_l} q_l(\zeta) e^{i\gamma \xi}, & Y_0 &= \sqrt{\frac{\varepsilon_0}{\mu_0}}, \\ H_{z,l}(x, z) &= \sqrt{2k_0 Y_0 / N_l} \gamma p_l(\zeta) e^{i\gamma \xi}, & E_{z,l}(x, z) &= -\sqrt{2k_0 Y_0 / (\varepsilon_l N_l)} \gamma p_l(\zeta) e^{i\gamma \xi}, \end{aligned}$$

úfe

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 $l \rightarrow l+1$ a $l+1 \rightarrow l$ je popsán maticemi

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

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

Přenosová matice jedné celé periody je ${}^L \mathbf{A} = {}^{12} \mathbf{A} \cdot {}^21 \mathbf{A} \cdot {}^1 \mathbf{A} \cdot {}^0 \mathbf{A}$.

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

$${}^L \mathbf{A} \cdot \begin{pmatrix} p_1^F \\ q_1^F \end{pmatrix} = s \begin{pmatrix} p_1^F \\ q_1^F \end{pmatrix}, \quad s = \exp(i\varphi^F), \quad \varphi^F = k^F \Lambda, \quad k^F \text{ je konstanta šíření F-B vidu.}$$

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

Proto stačí určit k^F v intervalu $-K/2 < k^F \leq K/2 \Rightarrow \text{první Brillouinova zóna.}$

úfe

Vlastní hodnoty a fotonický zakázaný pás

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

matice ${}^L \mathbf{A}$ 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 $|s| = 1$, t.j., pokud

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

Normovaná konstanta šíření je pak

$$k^{F'} = \frac{k^F}{K/2} = \frac{1}{\pi} \arccos \left[\cos \left(\frac{\omega}{c} N_1 L_1 \right) \cos \left(\frac{\omega}{c} N_2 L_2 \right) - \frac{1}{2} \left(\rho^2 + \frac{1}{\rho^2} \right) \sin \left(\frac{\omega}{c} N_1 L_1 \right) \sin \left(\frac{\omega}{c} N_2 L_2 \right) \right].$$

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

k^F je komplexní, a vlna se nemůže šířit podél nekonečně dlouhého krystalu.

Tak vzniká **fotonický zakázaný pás**.

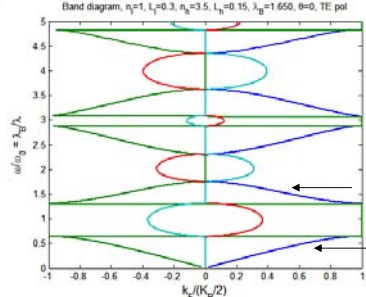
úfe

Pásová struktura jednorozměrného krystalu

$$n_1 = 1$$

$$n_2 = 3.5$$

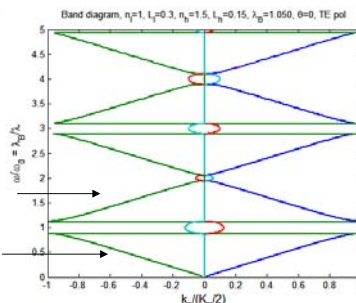
$$\theta = 0^\circ$$



$$n_1 = 1$$

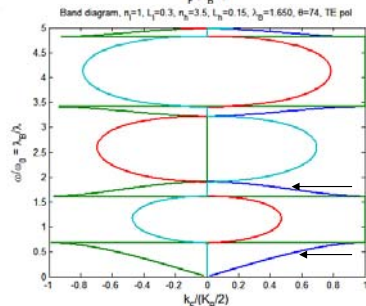
$$n_2 = 1.5$$

$$\theta = 0^\circ$$



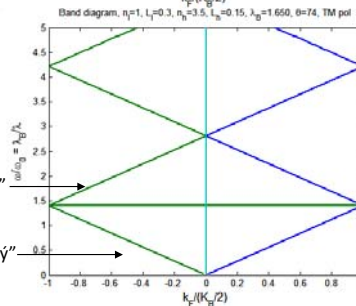
$$\text{TE}$$

$$\theta = 74^\circ$$



$$\text{TM}$$

$$\theta = 74^\circ$$



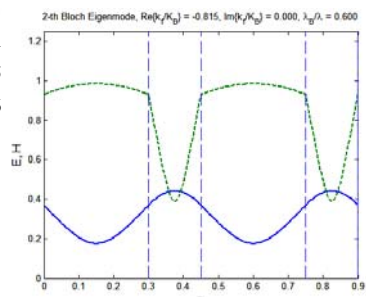
Elektromagnetické Floquetovy – Blochovy vlny

$$n_1 = 1$$

$$n_2 = 3.5$$

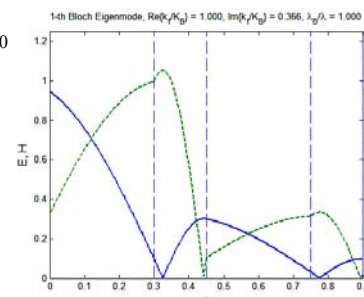
$$\lambda_B / \lambda = 0.6$$

“dielektr.”
pás



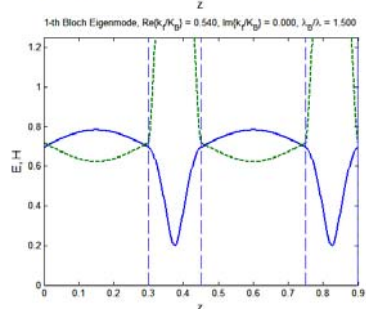
$$\lambda_B / \lambda = 1.0$$

uvnitř
zakázaného
pásu

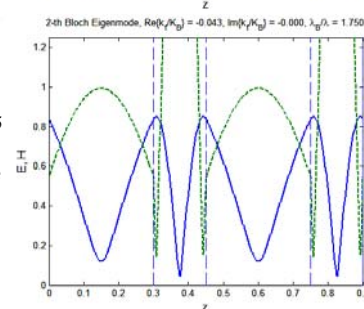


$$\lambda_B / \lambda = 1.5$$

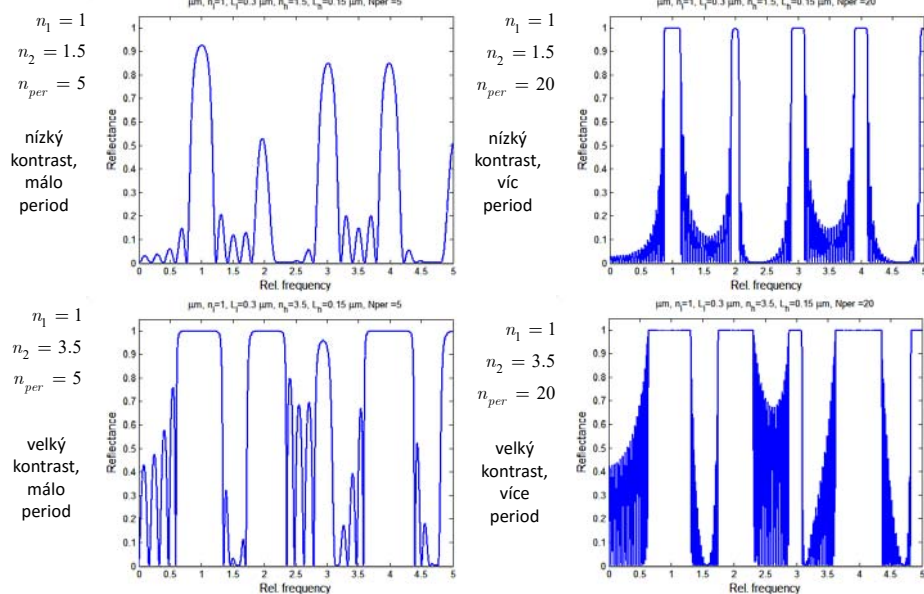
“vzduch.”
pás



$\lambda_B / \lambda = 1.75$
blízko okraje
Brillouinovy
zóny

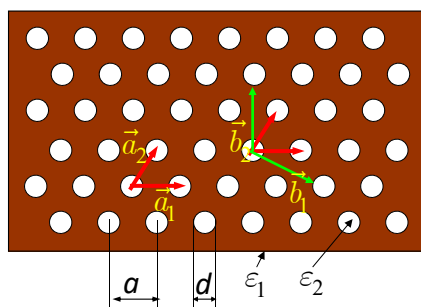


Spektrální reflektance



Fotonické krystaly odpovídají často spíše „nanokrystalům“

Dvozměrné „fotonické krystaly“



Elementární vektory prostorové mřížky

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

Elementární vektory reciproké mřížky

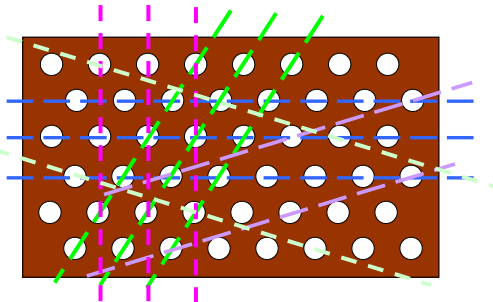
$$\vec{b}_1 = \left(\frac{1}{a}, \frac{1}{a\sqrt{3}}\right), \quad \vec{b}_2 = \left(0, \frac{2}{a\sqrt{3}}\right)$$

Periodické uspořádání otvorů;
Blochův – Floquetův teorém

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

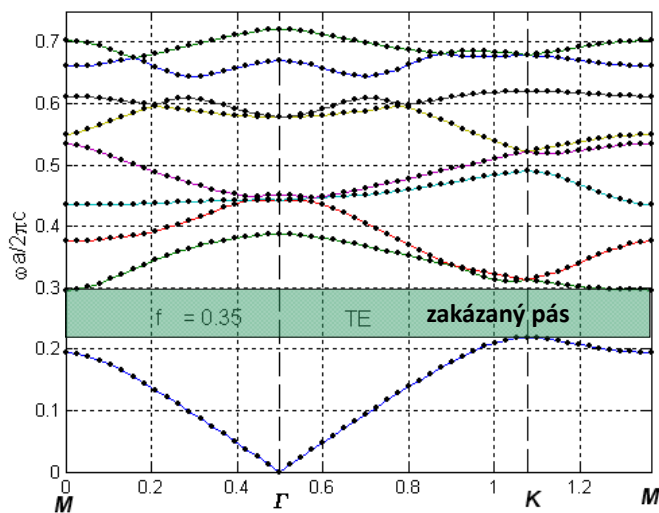
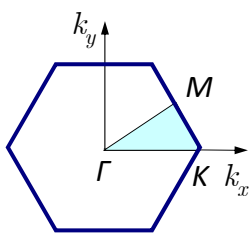
$$u_{\vec{k}}(\vec{r}_{\parallel}) = u_{\vec{k}}(\vec{r}_{\parallel} + \vec{a}_1) = u_{\vec{k}}(\vec{r}_{\parallel} + \vec{a}_2)$$

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



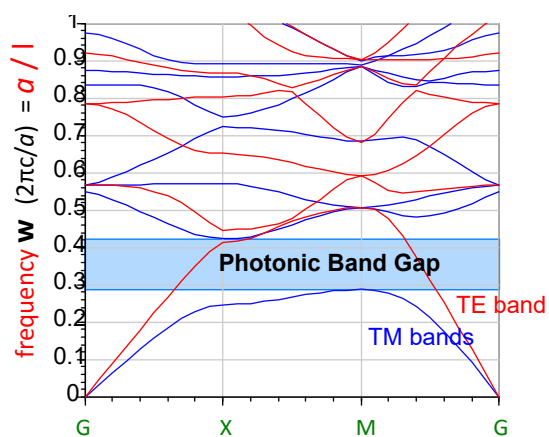
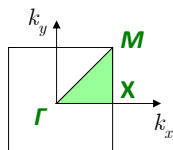
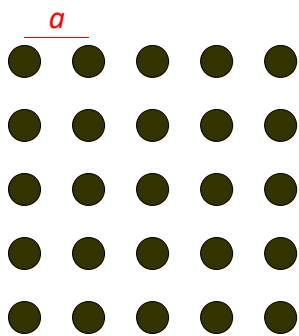
Pásový diagram energií fotonů 2D krystalu s trojúhelníkovou mřížkou

první
Brillouinova
zóna
prostoru
vlnových vektorů



life

Pásový diagram energií fotonů 2D krystalu se čtvercovou mřížkou

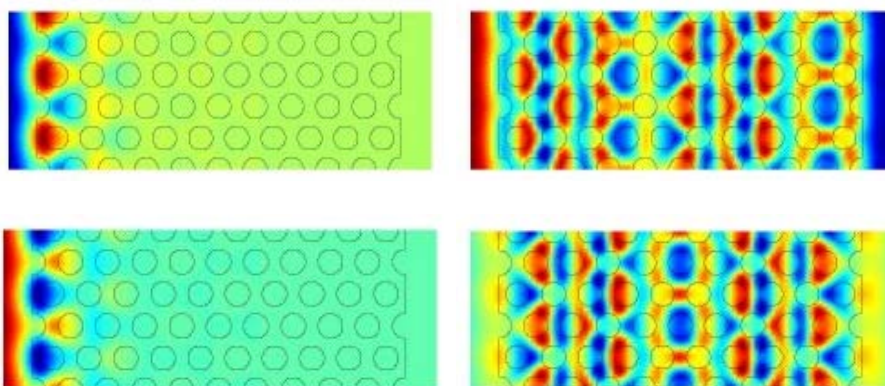


life

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

Uvnitř zakázaného pásu

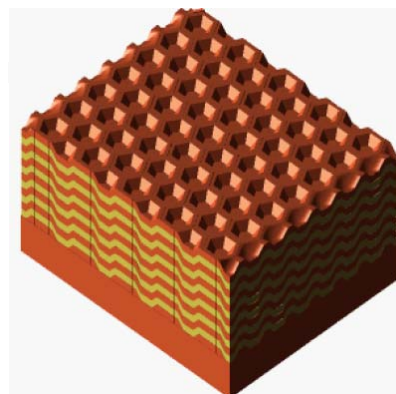
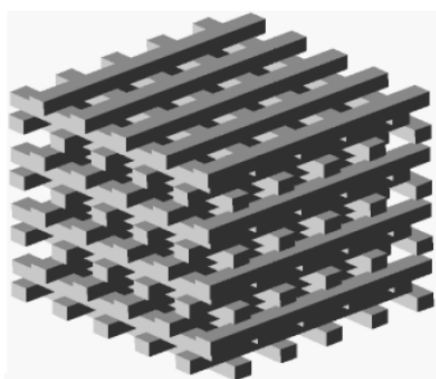
Vně zakázaného pásu



(Ing. Jiří Petráček, Dr., VUT Brno)

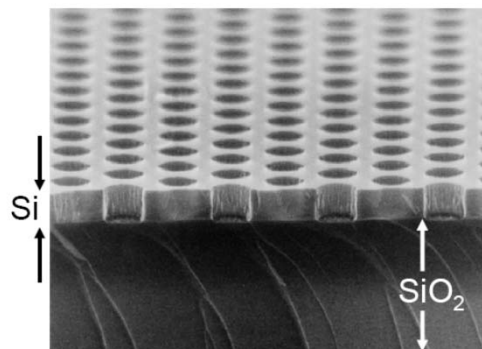
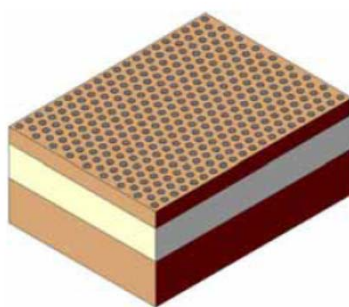
úfe

Trojrozměrné fotonické krystaly



úfe

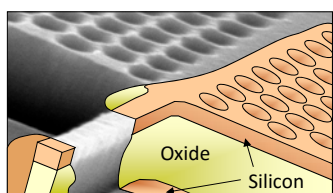
„2.5-dimenzionální“ fotonické krystaly



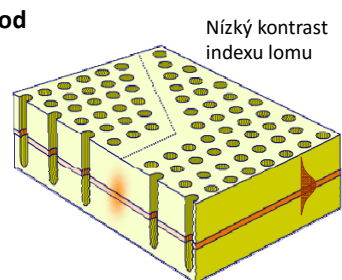
úfe

Fotonické krystaly a vlnovody

1. 2D fotonický krystal + vertikální vlnovod

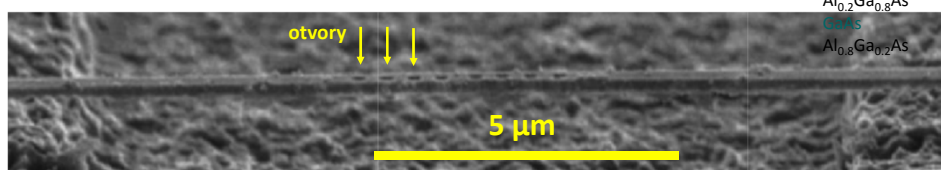


Vysoký
kontrast
indexu
lomu



Nízký kontrast
indexu lomu

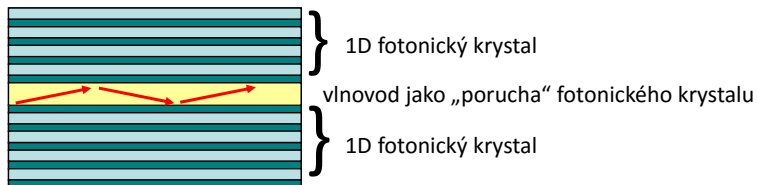
2. Čárový 2D dielektrický vlnovod s 1D „fotonickým krystalem“



$\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$
 GaAs
 $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$

úfe

Vlnovody v 1D fotonickém krystalu



Princip znám od 80. let jako „braggovský vlnovod“
(antiresonant reflecting optical waveguide, **ARROW**)

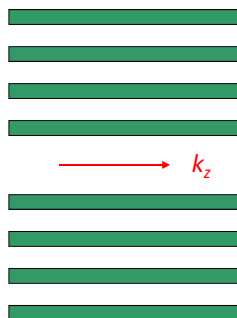
Rozdíly ARROW vlnovodu vůči konvenčnímu vlnovodu:

1. pro příslušný 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

úfe

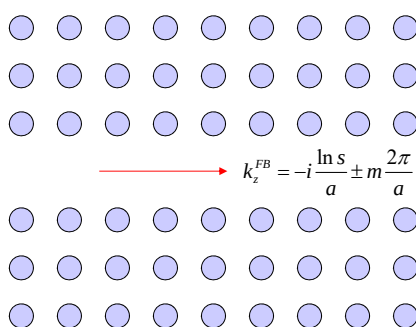
Vlnovod ve fotonickém krystalu

Braggovský vlnovod
(ARROW waveguide)



Anti-Reflecting Resonant
Optical Waveguide

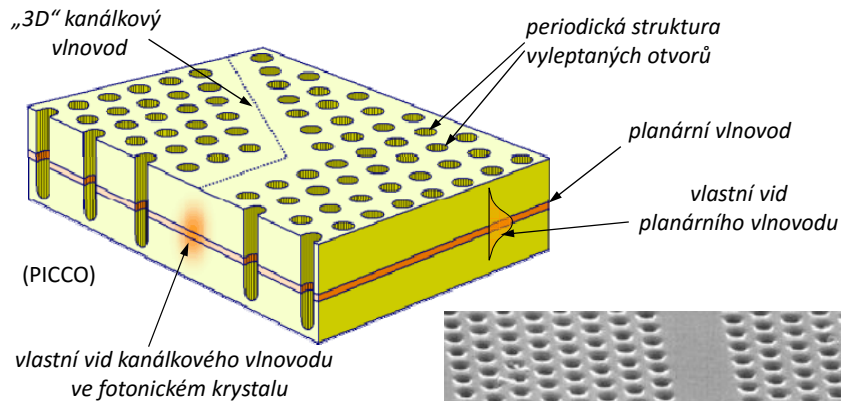
„Čárový defekt“ jako **vlnovod**
1D periodicitu



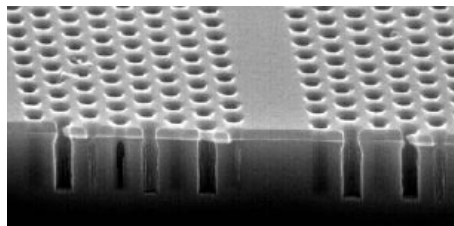
$k_z^{FB} a = \varphi \pm 2m\pi$...fázový posun při šíření
o jednu periodu

úfe

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

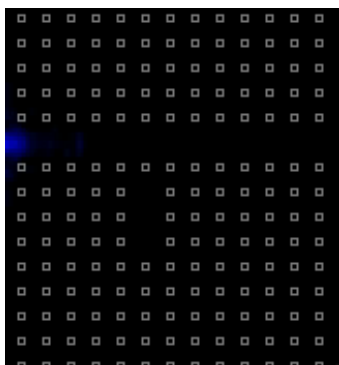


Zásadní problém:
ztráty vyzářováním
z roviny vlnovodu

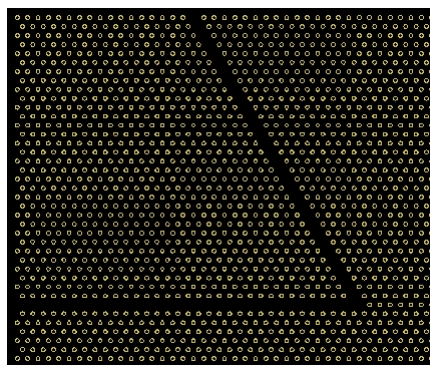


úfe

Numerické modelování šíření vln ve fotonických krystalech



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

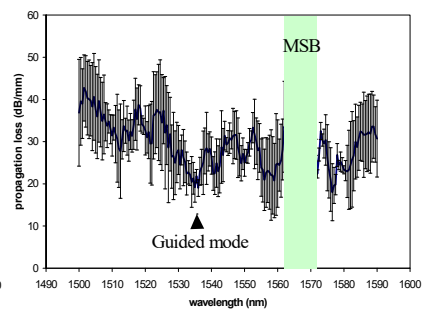
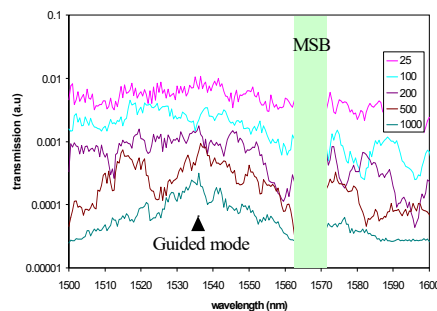
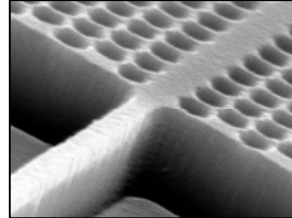


Šíření femtosekundového impulzu
vlnovodným ohybem ve fotonickém
krystalu (**F. Lederer et al.**,
Friedrich-Schiller-Universität Jena, D)

úfe

Vlnovody ve fotonických krystalech v SOI

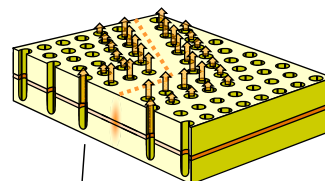
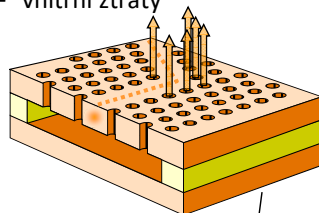
- Příprava:
 - „hluboká“ UV litografie a leptání
- vlnovod W1
 - perioda 500nm, $\varnothing$ 337nm
 - Mini-stop band
 - Nejnižší ztráty: 20 ± 3 dB/mm (lichý vid!)



life

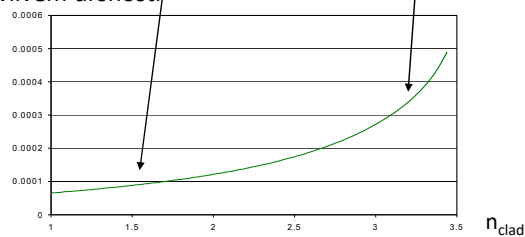
Ztráty vyzářováním z roviny krystalu

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



– ztráty vlivem drsnosti

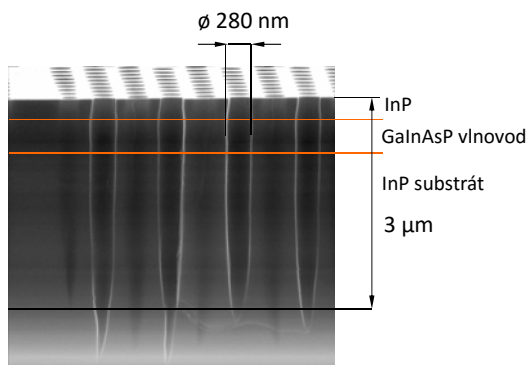
– ztráty vlivem drsnosti



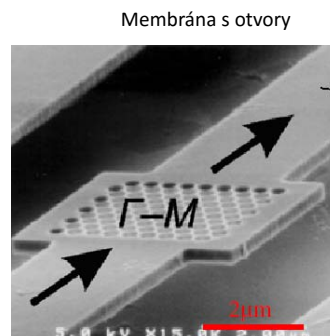
life

Potlačení ztrát vyžarováním do substrátu

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



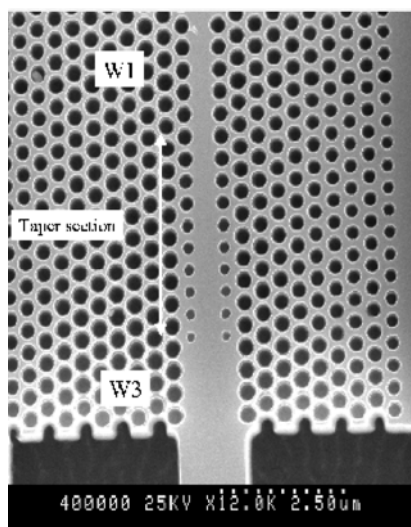
2. Úplné odstranění substrátu
(technologicky náročné)



úfe

Vazba s vlnovodem ve fotonickém krystalu

CNRS – LPN, Anne Talneau, Ph. Lalanne

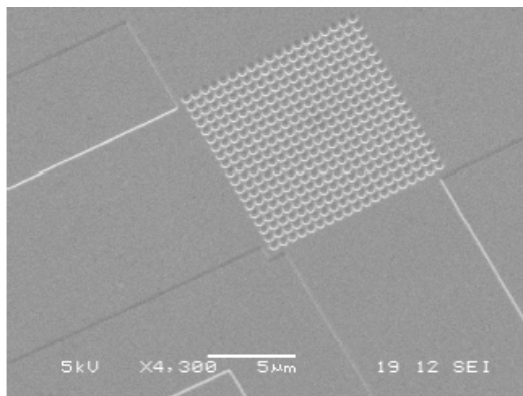
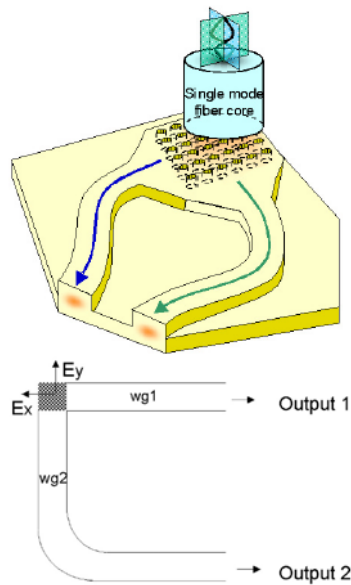


CNRS French patent
(2001)

úfe

Vlnovodné aplikace: polarizačně nezávislý mřížkový vazební člen

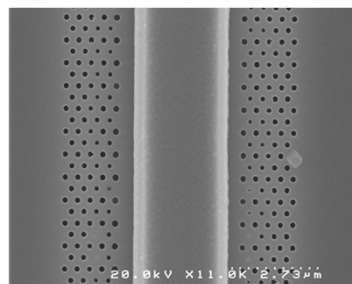
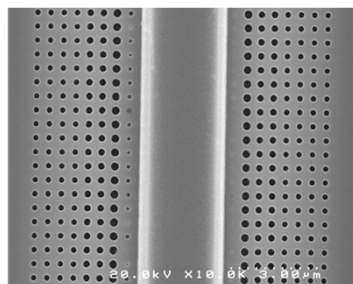
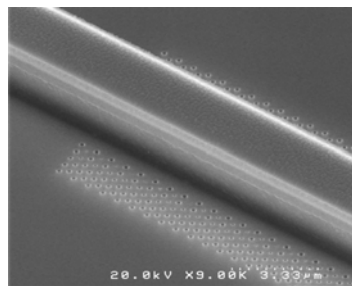
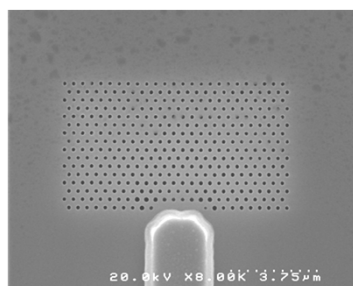
Ghent University, *Picco*



life

2D fotonické krystaly jako zrcadla polovodičových laserů

(Alcatel, 2002-3)



life

**Vlnovodné struktury se ztrátami a ziskem
jako analogie kvantově-mechanických struktur
s (porušenou) symetrií parita-čas**

life

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

**Eigenmode equation for TE modes
of a planar waveguide**

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

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

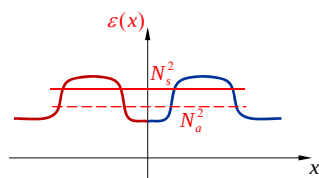
effective refractive index

N^2

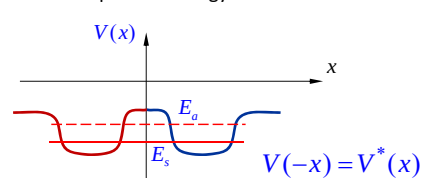
$\Leftrightarrow$

$-E$

particle energy



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

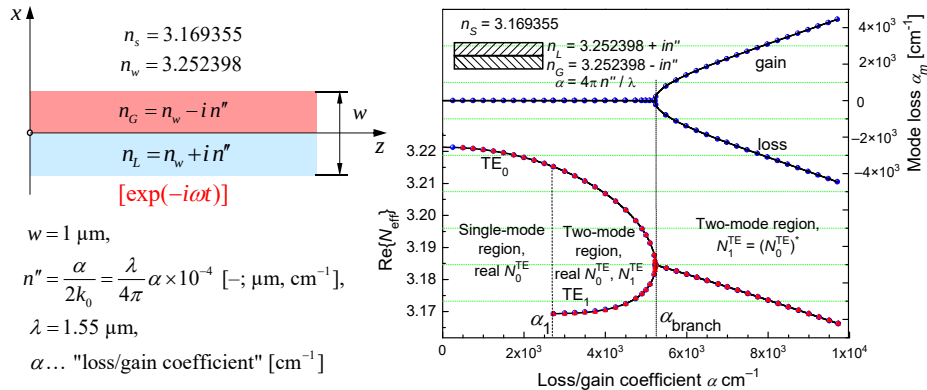


“ $\mathcal{PT}$ symmetry”: **complex potential(!)**,

life

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)



1. H.-P. Nolting, G. Sztéfka, 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)

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

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

"Exceptional" point: $\frac{dN}{d\alpha} \rightarrow \infty$.

Since $\Phi(N, \alpha) = 0$, $\frac{\partial \Phi}{\partial N} \frac{\partial N}{\partial \alpha} + \frac{\partial \Phi}{\partial \alpha} = 0 \Rightarrow \frac{\partial N}{\partial \alpha} = -\frac{\partial \Phi}{\partial \alpha} / \frac{\partial \Phi}{\partial N} \rightarrow \infty \Rightarrow \frac{\partial \Phi}{\partial N} = 0$.

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

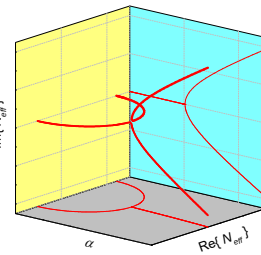
$$\Phi(N_B, \alpha_B) = 0, \quad \Phi'_N = \frac{d\Phi(N_B, \alpha_B)}{dN} = 0$$

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

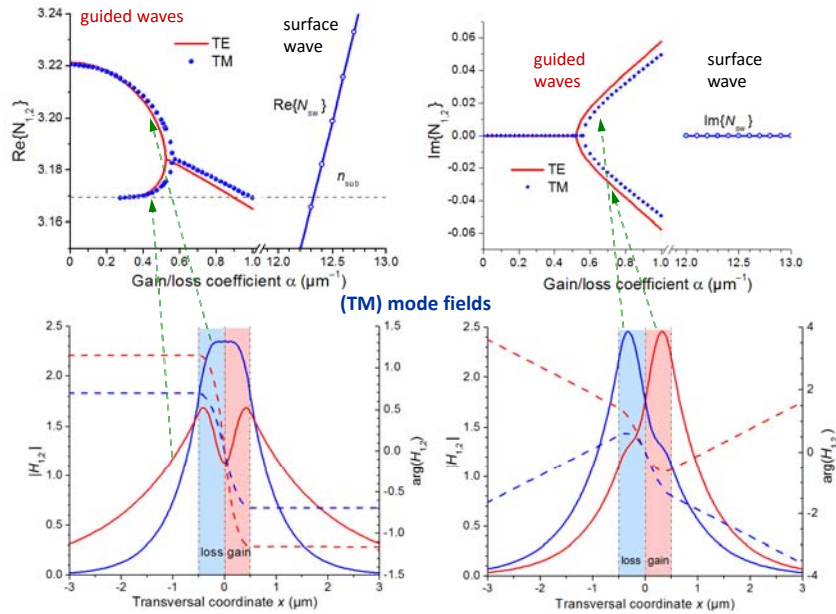
$$\Phi(N, \alpha) \approx \Phi'_\alpha (\alpha - \alpha_B) + \frac{1}{2} \Phi''_N (N - N_B)^2 = 0$$

from which it follows

$$N \approx N_B \pm iC \sqrt{(\alpha - \alpha_B)}, \quad C = \sqrt{\frac{2\Phi'_\alpha}{\Phi''_N}}$$

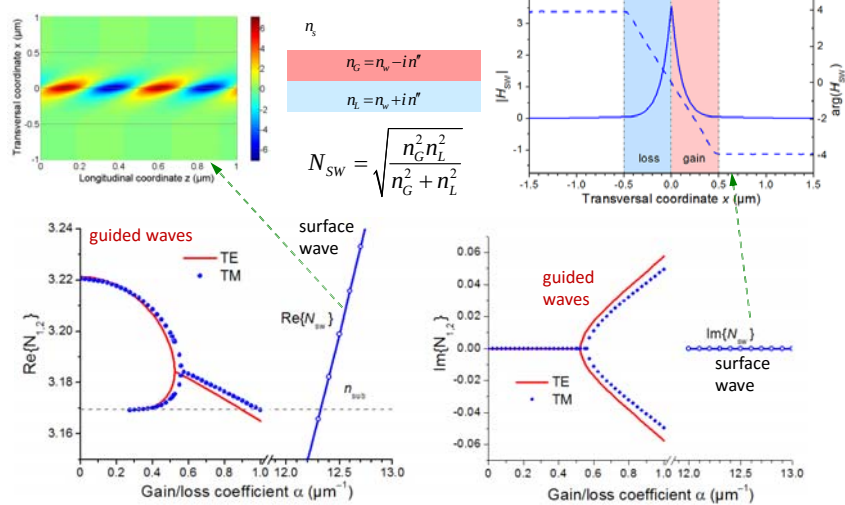


2D ANALYSIS (PLANAR WAVEGUIDES)



WAVEGUIDE STRUCTURE WITH LOSS/GAIN: SURFACE WAVE

Non-attenuated TM surface wave



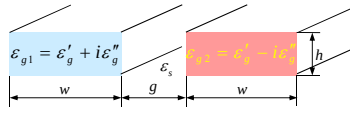
J. Čtyroký et al., "Waveguide structures with antisymmetric gain/loss profile," *Optics Express*, vol. 18, pp. 21585-21593, 2010.

COUPLED WAVEGUIDES WITH LOSS/GAIN

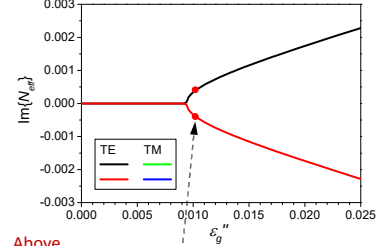
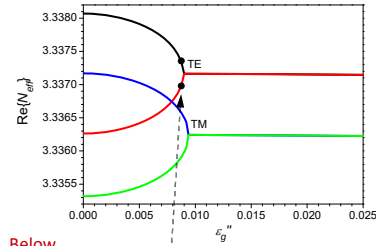
Balanced loss/gain

switching:

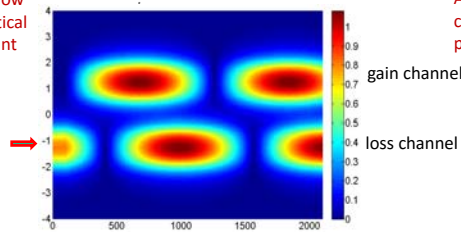
$$\mathcal{E}(-x, y) = \mathcal{E}^*(x, y)$$



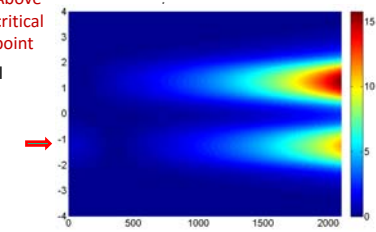
$$\begin{aligned} \epsilon_s &= 10.89, \quad \epsilon'_g = 11.56 \\ w &= 1.5 \mu\text{m}, \quad h = 0.75 \mu\text{m}, \\ g &= 1 \mu\text{m}, \quad \lambda = 1.55 \mu\text{m}. \end{aligned}$$



Below critical point



Above critical point



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

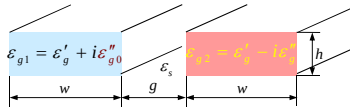
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COUPLED WAVEGUIDES WITH LOSS/GAIN

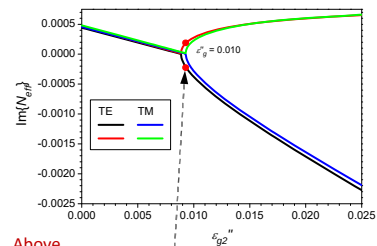
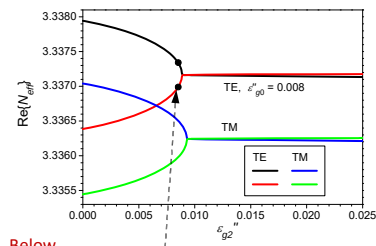
Fixed loss/variable gain

switching:

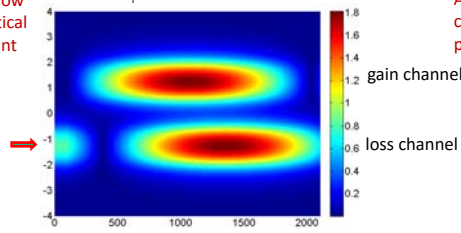
$$\mathcal{E}(-x, y) \neq \mathcal{E}^*(x, y)$$



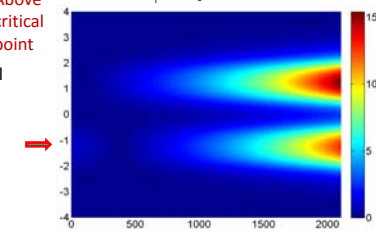
$$\begin{aligned} \epsilon_s &= 10.89, \quad \epsilon'_g = 11.56 \\ w &= 1.5 \mu\text{m}, \quad h = 0.75 \mu\text{m}, \\ g &= 1 \mu\text{m}, \quad \lambda = 1.55 \mu\text{m}. \end{aligned}$$



Below critical point



Above critical point

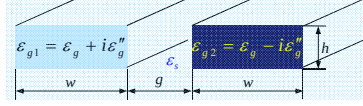


life

COUPLED WAVEGUIDES WITH LOSS/GAIN

Balanced loss/gain with reduced gain:

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



$$\begin{aligned} \epsilon_s &= 10.89 + i\epsilon_s'', \quad \epsilon_g = 11.56 + i\epsilon_g'' \\ w &= 1.5 \mu\text{m}, \quad h = 0.75 \mu\text{m}, \\ g &= 1 \mu\text{m}, \quad \lambda = 1.55 \mu\text{m}. \end{aligned}$$

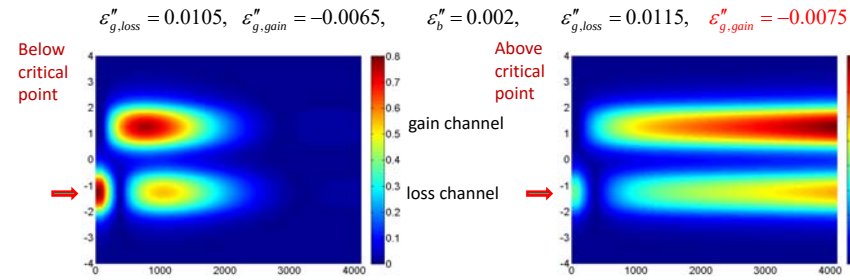
Rigorous equation for transversal field components: $\Delta_{\perp} \mathbf{e}_{\perp} + \nabla_{\perp} [\nabla_{\perp} (\ln \epsilon) \cdot \mathbf{e}_{\perp}] + k_0^2 (\epsilon - N^2) \mathbf{e}_{\perp} = 0$,

Small uniform permittivity modification: $\epsilon_1(x, y) = \epsilon(x, y) + i\epsilon_b''$, $|\epsilon_b''| \ll |\epsilon|$

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

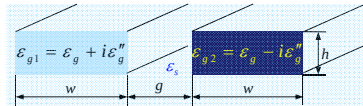
Uniform background loss can be used to reduce the required gain:

$$\epsilon_{\text{branch}}'' = \pm 0.009$$



COUPLED WAVEGUIDES WITH LOSS/GAIN

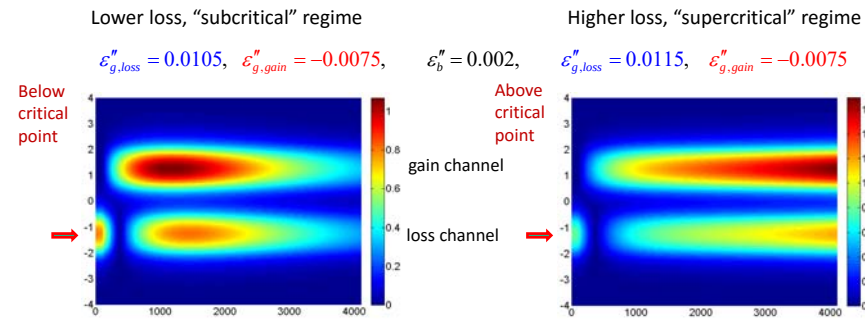
Un/balanced loss/gain:



$$\begin{aligned} \epsilon_s &= 10.89 + i\epsilon_s'', \quad \epsilon_g = 11.56 + i\epsilon_g'' \\ w &= 1.5 \mu\text{m}, \quad h = 0.75 \mu\text{m}, \\ g &= 1 \mu\text{m}, \quad \lambda = 1.55 \mu\text{m}. \end{aligned}$$

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

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

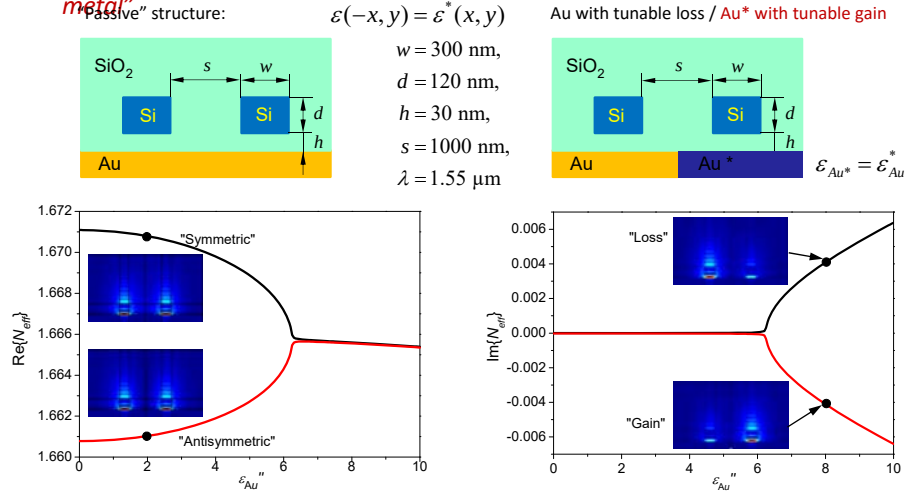


A. Guo et al., "Observation of PT-Symmetry Breaking in Complex Optical Potentials," *Physical Review Letters*, vol. 103, no. 9, pp. 093902-1-4, 2009.

PLASMONIC LOSS/GAIN STRUCTURES

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

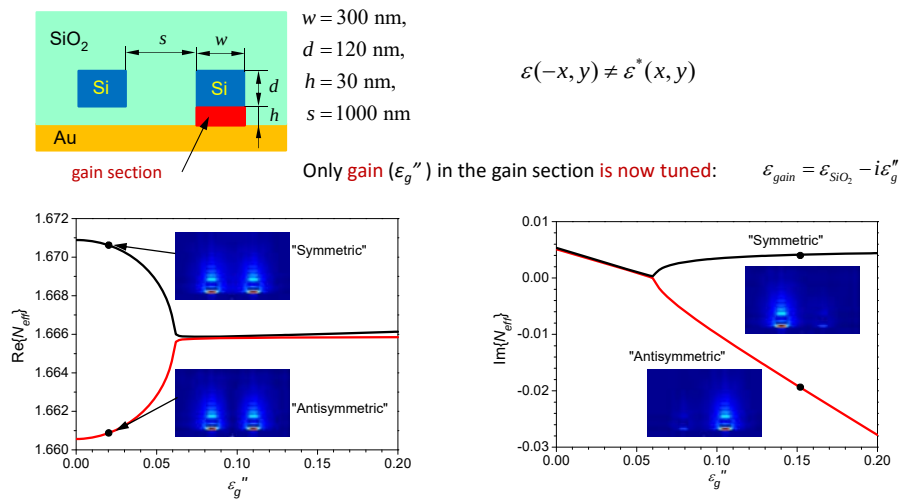
Hybrid dielectric-plasmonic slot waveguide directional coupler *with "tunable metal"*



PLASMONIC LOSS/GAIN STRUCTURES

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

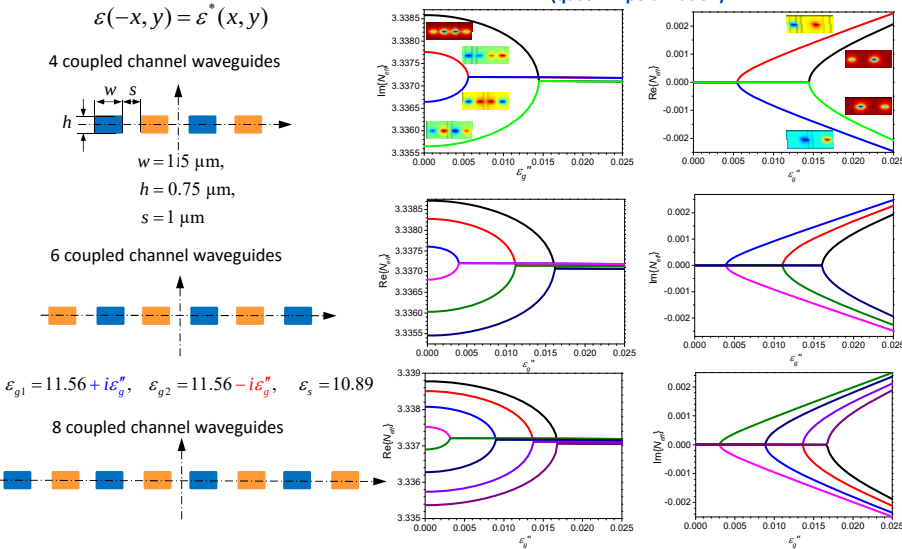
Hybrid dielectric-plasmonic slot waveguide directional coupler *with gain section*



MORE COMPLEX GAIN-LOSS STRUCTURES

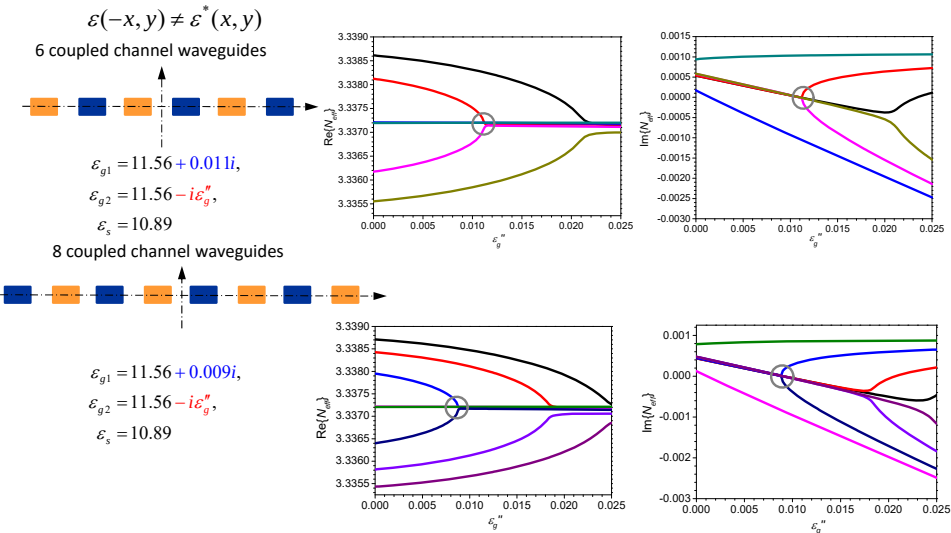
Linear arrays of coupled waveguides with loss and gain

(quasi-TE polarization)



LINEAR ARRAY WITH UNBALANCED LOSS/GAIN

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



"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

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

$$r = 1.5w$$

$$\epsilon_{g1} = 11.56 + i\epsilon_g''$$

$$\epsilon_{g2} = 11.56 - i\epsilon_g''$$

$$\epsilon_s = 10.89$$

6 waveguides

$$r = 2w$$

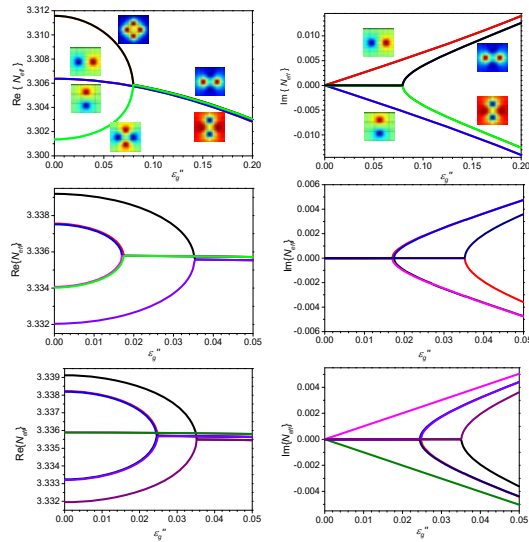
8 waveguides

$$r = 2.55w$$

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

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

(TE-like)



life

CIRCULAR ARRAYS WITH UNBALANCED LOSS/GAIN

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

6 waveguides

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

$$r = 2w$$

$$\epsilon_s = 10.89$$

$$\epsilon_{g1} = 11.56 + 0.017i$$

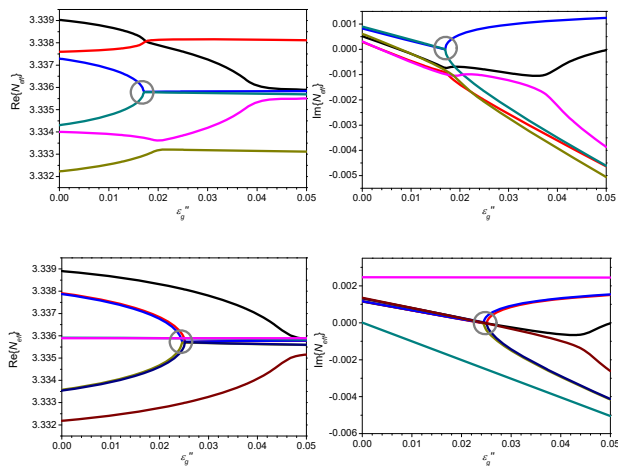
$$\epsilon_{g2} = 11.56 - i\epsilon_g''$$

8 waveguides

$$r = 2.55w$$

$$\epsilon_{g1} = 11.56 + 0.024i$$

$$\epsilon_{g2} = 11.56 - i\epsilon_g''$$



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

life

SOME RELEVANT REFERENCES

1. J. Zenneck, "Über die Fortpflanzung ebener elektromagnetischer Wellen längs einer ebenen Leiterfläche und ihre Beziehung zur drahtlosen Telegraphie," *Annalen der Physik*, vol. 328, pp. 846-866, 1907.
2. H.-P. Nolting, G. Sztefka, M. Grawert, and J. Čtyroký, "Wave Propagation in a Waveguide with a Balance of Gain and Loss," in *Integrated Photonics Research '96*, Boston, USA, 1996, pp. 76-79.
3. G. Guekos, Ed., *Photonic Devices for telecommunications: how to model and measure*. Berlin: Springer, 1998.
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5. K. G. Makris, R. El-Ganainy, and D. N. Christodoulides, "Beam Dynamics in PT Symmetric Optical Lattices," *Physical Review Letters*, vol. 100, pp. 103904(1)-103904(4), 2008.
6. J. Čtyroký, V. Kuzmiak, and S. Eyderman, "Waveguide structures with antisymmetric gain/loss profile," *Optics Express*, vol. 18, pp. 21585-21593, 2010.
7. C. E. Rüter, K. G. Makris, R. El-Ganainy, D. N. Christodoulides, M. Segev, and D. Kip, "Observation of parity-time symmetry in optics," *Nature Physics*, vol. 6, pp. 192-195, 2010.
8. H. Benisty, A. Degiron, A. Lupu, A. De Lustrac, S. Chenais, S. Forget, et al., "Implementation of PT symmetric devices using plasmonics: principle and applications," *Optics Express*, vol. 19, pp. 18004-18019, Sep 2011.
9. J. Čtyroký, "3-D Bidirectional Propagation Algorithm Based on Fourier Series," *Journal of Lightwave Technology*, vol. 30, pp. 3699-3708, 2012.
10. A. A. Sukhorukov, S. V. Dmitriev, S. V. Suchkov, and Y. S. Kivshar, "Nonlocality in PT-symmetric waveguide arrays with gain and loss," *Optics Letters*, vol. 37, pp. 2148-2150, 2012.
11. ...and many others...
12. ...