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Session: II-2.6 / Plasmonics Antennas and Waveguides

Properties of Highly-Nonlinear Hybrid Silicon-Plasmonic Waveguides

A. Pitilakis and E. E. Kriezis

Dept. of Electrical & Computer Engineering
Aristotle University of Thessaloniki, Greece

Presentation Outline

- **Introduction**
  - Nonlinear Effects in Plasmonics
  - Objective, Motivation & Challenge
- **Modeling Propagation in Nonlinear Waveguides**
  - Nonlinear Schrodinger Equation (NLSE)
  - Derivation of Figures-of-Merit (FoM) in CW
- **Hybrid Silicon-Plasmonic Waveguides**
  - Review of Hybrid Silicon-Plasmonic (HSP) Waveguides
  - Optimization of HSP Waveguides for Kerr-type Applications
  - Comparison to Dominant SOI-based Platforms
  - Nonlinear Directional Coupler – Design & Applications
- **High-Power Illumination in Nanophotonic Waveguides**
  - An Unexplored Operation Regime – Accessibility and Modeling
  - Prospects & Considerations
- **Conclusion & Future Perspectives**

Nonlinear Effects and Silicon-Plasmonics

Introduction

Introduction: Nonlinear Effects

Effects **originating** from **material $\chi^{(3)}$** the (3rd order nonlinear susceptibility)

- ❖ **Magnitude** is **proportional to optical intensity** $I=|\mathbf{E}|^2$.
- ❖ **Potential** for **all-optical functionality**, i.e. "*light controlling light*"
- ❖ **Focus** only in **intra-band interactions**, i.e. $\Delta\omega << \omega_0$
- ❑ **Ultrafast/Instantaneous** response:
  - **Kerr Effect** → refractive index perturbation
  - **Two-Photon Absorption (TPA)** → attenuation **+** carrier generation
- ❑ **Delayed/Resonant** response:
  - **Free-Carrier Effects (FCE)** → From TPA in semiconductors
  - ❖ **Raman Scattering** → Interaction with optical phonons

Kerr-effect in NL-waveguides:

- ✓ Optical power (low)
- ✓ Material nonlinearity (high)
- ✓ Attenuation (low)
- ✓ Footprint (small)
- ❖ Phase matching

Free-Carrier Effects

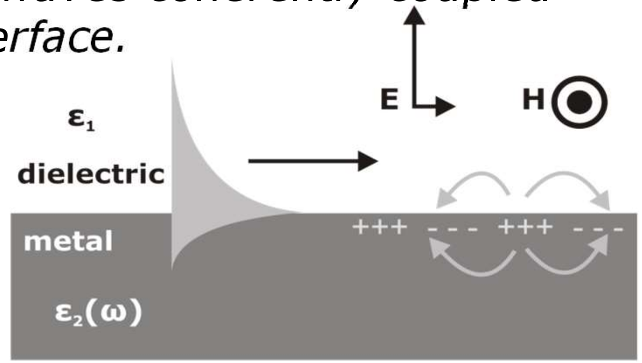
- Depend on FC-density
- Induce additional…
  - ❖ attenuation → limits power
  - ❖ dispersion → "masks" Kerr
- More critical than TPA

Introduction: Plasmonics

Surface Plasmon Polaritons (SPPs): *EM surface waves coherently coupled to free electron oscillations on a metal/dielectric interface.*

Metal at NIR → Drude model: Re{ε_2}<0

- SPP waves propagate along the interface.
- Fields decay exponentially away from it.



SPP at single metal/dielectric interface: An elementary plasmonic waveguide

Trade-off → losses vs. lateral confinement

- ✗ Suffer ohmic propagation losses (metal).
- ✓ Confinement surpasses Diffraction Limit.

Plasmonics for Optical Communications

Integrated photonic components with…

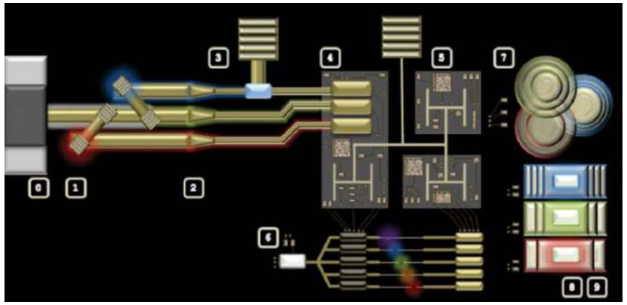
- ✓ **Lateral dimensions** → far-below diffraction limit (λ/2)
- ✓ **Control** & **Information** signals collocated @ metal/dielectric interface

…leading to **Nanoscale Opto-Electronic Devices**.

Scope: Guided-Wave Nonlinear Plasmonics

Objective: Design of novel integrated Components for optical communications with:

- ✓ **all-optical functionality**
- ✓ **minimal footprint & interaction lengths**
- ✓ **reduced power threshold** for Kerr
- ✓ **limited FCE impairments**



Future integrated plasmonic circuit (Dionne et al, 2010)

Motivation: High confinement → High waveguide nonlinearity

… leading to: **smaller interaction lengths** & **reduced power**

❖ **Plasmonic waveguides can truly excel in this aspect!**

Challenge: Counterbalance the **inherent ohmic losses** in plasmonic devices

Opportunities & Prospects: Towards efficient **nonlinear plasmonics**

- ❑ **Synergy** with dominant **silicon-photonics**
- ❑ **Exploitation** of novel materials such as **highly-NL polymers**

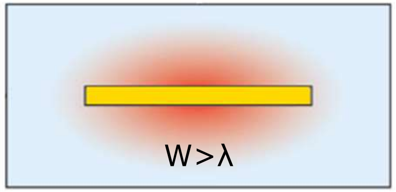
From Photonics to Silicon-Plasmonics

Hybrid Silicon-Plasmonic (HSP) Waveguides

Plasmonic Waveguides for Nonlinear Applications

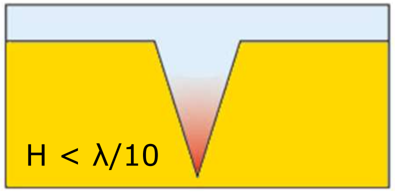
Overview of SPP Waveguides (Berini & De Leon, Nat. Phot., 2012)

Stripe



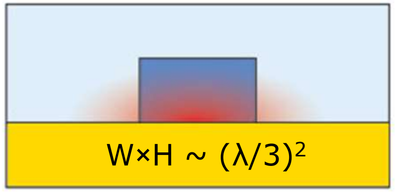
Poor confinement
Low losses

Channel



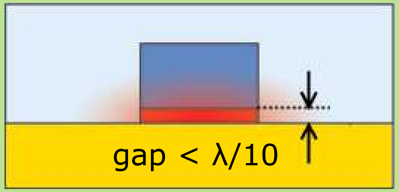
High confinement
Dramatic losses

Dielectric Loaded



Sub-optimal compromise…

Hybrid

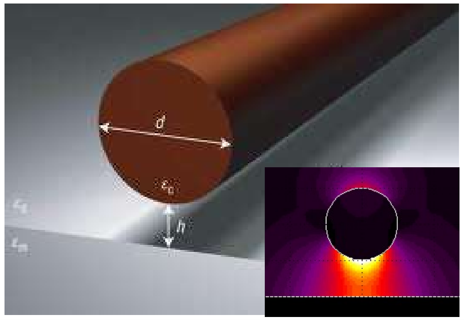


"Low-index gap"
High confinement, moderate losses, material interplay

Advantages & Prospects:

- ✓ Gap material → **nonlinear** (or electro-optic)
- ✓ **Small field penetration in Silicon** → low TPA & FCE
- ▪ **Carrier-sweeping circuit** (Si-slab & electrodes)
- ▪ Planar → **Easy fabrication** (lithography)
- ▪ **Efficient coupling** to SOI-waveguide
- ▪ **Thermal exhaustion** (through Si- and metal-slab)

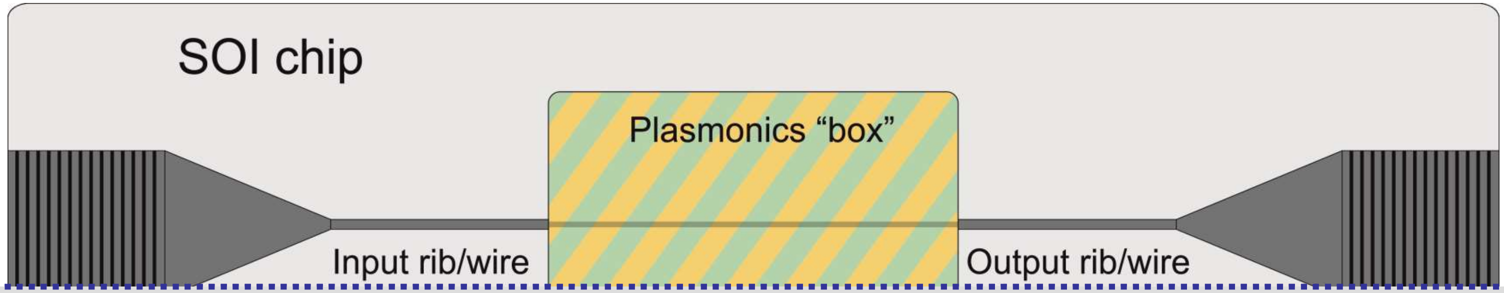
Oulton *et al.*, 2008, Nature Photonics



Merging Silicon-Photonics & Plasmonics

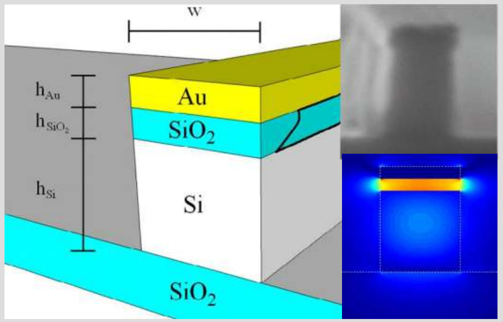
Integration on SOI motherboard:

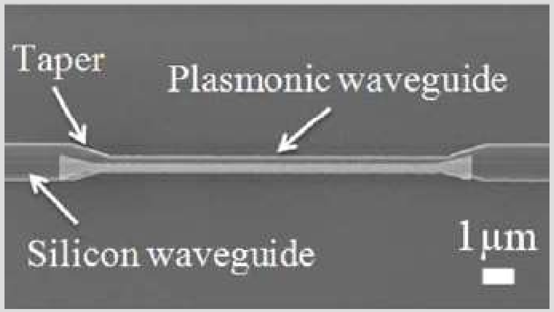
- **Host** for both HSP- and Si-waveguides.
- Provides **"seamless" interface** w/ silicon photonics at minimal losses.
- **Metals** → Au, Ag or Cu (CMOS-friendly).

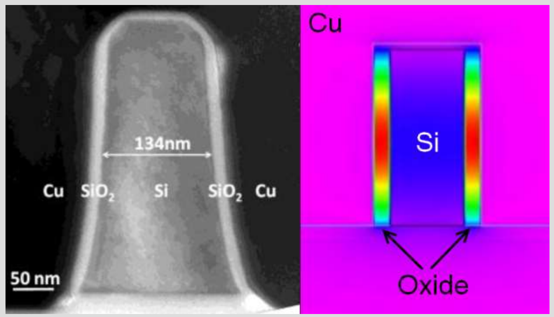


Wu *et al.*, 2010, Optics Express. **CGS: "Conductor-Gap-Silicon"**

Zhu *et al.*, 2011, Optics Express
"Plasmonic nano-slot"







Modeling Propagation in Si-comprising NL waveguides

Nonlinear Schrödinger Equation + Figures-of-Merit

The Nonlinear Schrodinger Equation (NLSE)

Models slowly-varying envelope propagation along the z-axis: $A(z,t)$

$$\frac{\partial A}{\partial z} = -\frac{a}{2}A + \left(\sum_{n=1}^{\infty}\beta_n \frac{i^{n+1}}{n!}\frac{\partial^n}{\partial t^n}\right)A + i\gamma_c |A|^2 A + i\delta_{\text{fc}} A \quad + \quad \boxed{\frac{d}{dt}\langle N\rangle = \langle G\rangle - \frac{1}{\tau_{\text{fc,eff}}}\langle N\rangle}$$

FC-rate eq.

- **Attenuation**: Ohmic loss, confinement, surface-roughness, …
- **Dispersion**: From material & waveguide engineering ➔ Vanishes in CW
- **Nonlinearity**: Instantaneous, complex-valued ➔ SPM & TPA
- **Free-Carrier Effects**: TPA@Silicon ➔ Dispersion & Absorption + **Dynamics**

$$\chi^{(3)}_{xxxx} = \frac{4}{3}c_0\varepsilon_0\varepsilon_r\left(n_2 + i\frac{\beta_{\text{TPA}}}{2k_0}\right)$$

$$\mathcal{N} \triangleq \text{Re}\left\{\iint(\mathbf{e}\times\mathbf{h}^*)\cdot\hat{\mathbf{z}}\,dxdy\right\}$$

$$\gamma_c = \frac{3\omega\varepsilon_0}{4\mathcal{N}^2}\sum_{\mu,\alpha,\beta,\gamma}^{x,y,z}\iint \chi^{(3)}_{\mu\alpha\beta\gamma}e^*_\mu e_\alpha e^*_\beta e_\gamma\,dxdy$$

$$\delta_{\text{fc}} = \left(k_0 n_{\text{Si}}\Gamma / n_{\text{eff}}\right)\langle\Delta u_{\text{fc}}\rangle$$

$$\Delta u_{\text{fc}} = [\Delta n_{\text{fc}} + (i/2k_0)\Delta a_{\text{fc}}] \approx \sigma_u N$$

$$\langle\Delta u_{\text{fc}}\rangle \triangleq \iint \Delta u_{\text{fc}}\,|\mathbf{e}|^2\,dxdy \Big/ \iint |\mathbf{e}|^2\,dxdy$$

$$G = \frac{1}{2\hbar\omega_0}\left(\frac{\partial P_{\text{TPA}}}{\partial z}\right) = \frac{1}{2\hbar\omega_0}\left(\beta_{TPA}\tilde{P}_z^2\,|A|^4\right)$$

Simplifying the NLSE for CW

Time-derivatives ➔ (1) Dispersion terms and (2) FC-rate Equation

Kerr FCD Loss TPA FCA

$$\frac{\partial A}{\partial z} = \left[i\left(\gamma |A|^2 - f_D |A|^4 \right) - \frac{1}{2}\left(a + 2r\gamma |A|^2 + 2 f_A |A|^4 \right) \right] A$$

Loss $a \triangleq 1 / L_{\text{prop}}$

Kerr $\gamma \triangleq \text{Re}\{\gamma_c\}$

TPA $r \triangleq \text{Im}\{\gamma_c\} / \text{Re}\{\gamma_c\}$

FCD, **FCA**
$$\begin{bmatrix} f_D \\ f_A \end{bmatrix} = \frac{\Gamma n_{\text{Si}}}{n_{\text{eff}}} \times \frac{\Xi \tau_{\text{fc}}}{2\hbar\omega_0} \times k_0 \times \begin{bmatrix} \text{Re}\{-\sigma_u\} \\ \text{Im}\{+\sigma_u\} \end{bmatrix}$$

NLSE parameters calc.:
→ FEM Eigenmode Solver

Importance of Free-Carrier Effects:
- FCA scales with $|A|^4$ → Faster than TPA
- FCD has an opposite sign from Kerr

Longitudinal Enhancement

$$\Gamma \triangleq \frac{c_0 \varepsilon_0 n_{\text{eff}}}{\mathcal{N}} \iint |\mathbf{e}|^2 \, dx dy$$

Γ≥1 → mode deviation from TEM

Free-Carrier complex Index-Perturbation

$$\sigma_u \triangleq \left[-\sigma_n + (i / 2k_0)\sigma_a \right]$$

Soref & Bennett → Drude fitting

Carriers/Field overlap

$$\Xi \triangleq \left\langle \beta_{\text{TPA}} \tilde{P}_z^2 \right\rangle \quad \text{m}^{-3}\text{W}^{-1}$$

Spatial matching of FC & field

Figure-of-Merit (FoM) Derivation

Conventional nonlinear waveguides → Kerr and Linear-losses only

- Nonlinear phase-shift: $\Phi_{\text{Kerr}} = \gamma P_{\text{in}} L_{\text{eff}}$ and $L_{\text{eff}} \equiv 0.6321 L_{\text{pr}}$ @ $L = L_{\text{pr}}$

❖ Basic **Figure-of-Merit FoM**: $\boxed{\mathcal{F} \triangleq \gamma / a = \gamma L_{\text{prop}}}$ (in 1/Watt)

✓ Kerr-related effects (FWM, SPM, XPM etc) need a power level $\propto 1 / \mathcal{F}$

Silicon-comprising waveguides → FCD & TPA+FCD affect the phase & loss

- CW-NLSE inspection: $\gamma' \to \gamma - f_D |A|^2$, $a' \to a + 2r\gamma |A|^2 + 2 f_A |A|^4$
- A power-dependent FoM $\boxed{\mathcal{F}' \triangleq \gamma' / a'}$ ← but, useful when power is given…

Threshold-power: FCD-equal-to-Kerr → $\gamma' \equiv 0 \Rightarrow P_{\text{th,FCD}} \triangleq \gamma / f_D = \zeta_{\text{fc}} \times \varpi$

where $\varpi \triangleq 2\hbar c_0 / (\tau_{\text{fc}} n_{\text{Si}} \sigma_n)$ in (W/m²) → ~constant (for a given w/g design)

❖ **Kerr-vs-FCE FoM** : $\boxed{\zeta_{\text{fc}} \triangleq \gamma n_{\text{eff}} / (\Xi\,\Gamma)}$ (in m²) → major contribution γ/Ξ

✓ **Overall:** $1 / \mathcal{F} \leq P_{\text{th,FCD}}$ → $\boxed{\mathcal{F} \times \zeta_{\text{fc}} \times \varpi \geq 1}$ **for FCE-free operation (CW)**

* Multimode Waveguides: Coupled NLSE System

Waveguide supports *K* modes → A **system of *K* differential NLSE**

Coupling via (1) Kerr/TPA and (2) free-carrier effects

$$\frac{\partial A_k}{\partial z} = -\frac{a_k}{2}A_k + \left(\sum_{n=1}^{\infty}\beta_n^{(k)}\frac{i^{n+1}}{n!}\frac{\partial^n}{\partial t^n}\right)A_k + i\sum_{l,m,n}^{K}\gamma_{klmn}A_l A_m^* A_n \mathrm{e}^{i\Delta\beta_{klmn}z} + i\delta_{kk}A_k$$

Nonlinear parameters (Eigenmode)

$$\gamma_{klmn} = \frac{3\omega\varepsilon_0}{4}\sum_{\mu,\alpha,\beta,\gamma}^{x,y,z}\iint \chi^{(3)}_{\mu\alpha\beta\gamma}\frac{e_\mu^{*(k)}e_\alpha^{(l)}e_\beta^{*(m)}e_\gamma^{(n)}}{\sqrt{\mathcal{N}_k\mathcal{N}_l\mathcal{N}_m\mathcal{N}_n}}dxdy$$

Phase-matching for Kerr/TPA

$$\Delta\beta_{klmn} = -\beta_0^{(k)} + \beta_0^{(l)} - \beta_0^{(m)} + \beta_0^{(n)}$$

FCE perturbation → depends on <*N*>$_k$ FC-density

$$\delta_{kk}(z,t) = \left(k_0 n_{\mathrm{Si}}\Gamma_{(k)} \,/\, n_{\mathrm{eff}}^{(k)}\right)\sigma_u\left\langle N\right\rangle_k$$

FC-generation Rate <*G*>$_k$ for each *k*-mode

$$\left\langle G\right\rangle_k = \frac{1}{2\hbar\omega_0}\sum_{m,n=1}^{K}\Xi_{mn}^{(k)}\left|A_m\right|^2\left|A_n\right|^2$$

Density <*N*>$_k$ for each *k*-mode

$$\frac{d}{dt}\left\langle N\right\rangle_k = \left\langle G\right\rangle_k - \frac{1}{\tau_{\mathrm{fc,eff}}^{(k)}}\left\langle N\right\rangle_k$$

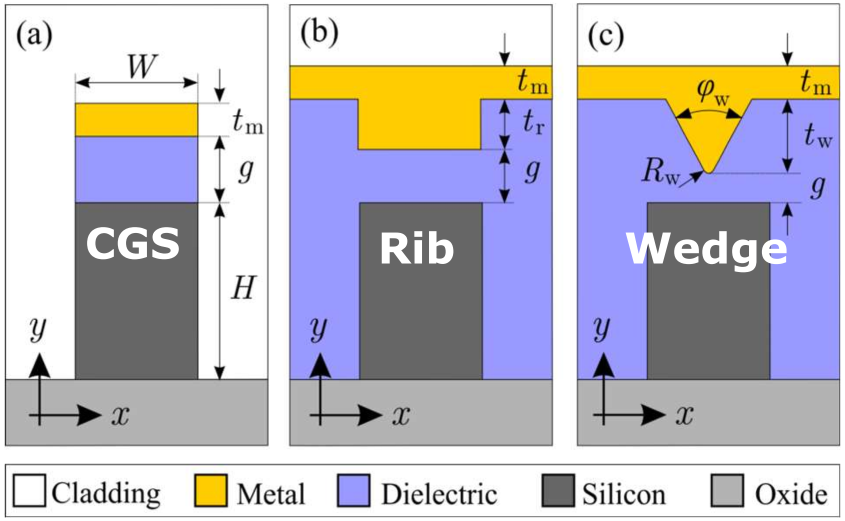
Generalized carrier-field spatial overlap

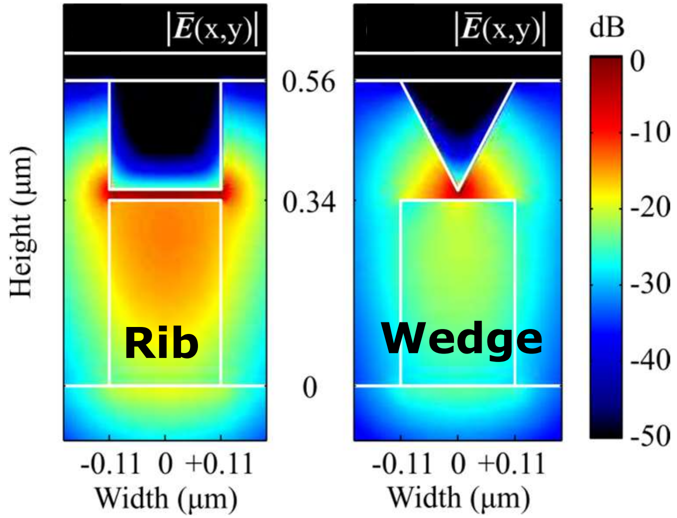
$$\Xi_{mn}^{(k)} \triangleq \left\langle \beta_{\mathrm{TPA}}\tilde{P}_z^{(m)}\tilde{P}_z^{(n)}\right\rangle_k$$

Kerr-type Nonlinear Applications & low FCE impairments

Optimizing the HSP waveguide

Optimization of HSP waveguides (1/3)





Materials

- Metal → **Silver** with n_0 = 0.145-j11.4
- Gap → **DDMEBT** nonlinear polymer
  $n_2 = 1.7\times10^{-17}$ m²/W, n_0 = 1.8
- Silicon → $\beta_{TPA} = 5\times10^{-12}$ m/W,
  $n_2 = 2.5\times10^{-18}$ m²/W, n_0 = 3.45,

Carrier-Lifetime: τ_{fc} = 1 nsec

ϖ ~10^{10} W/m² (as low as 10 ps)

Targeted performance @λ=1.55um

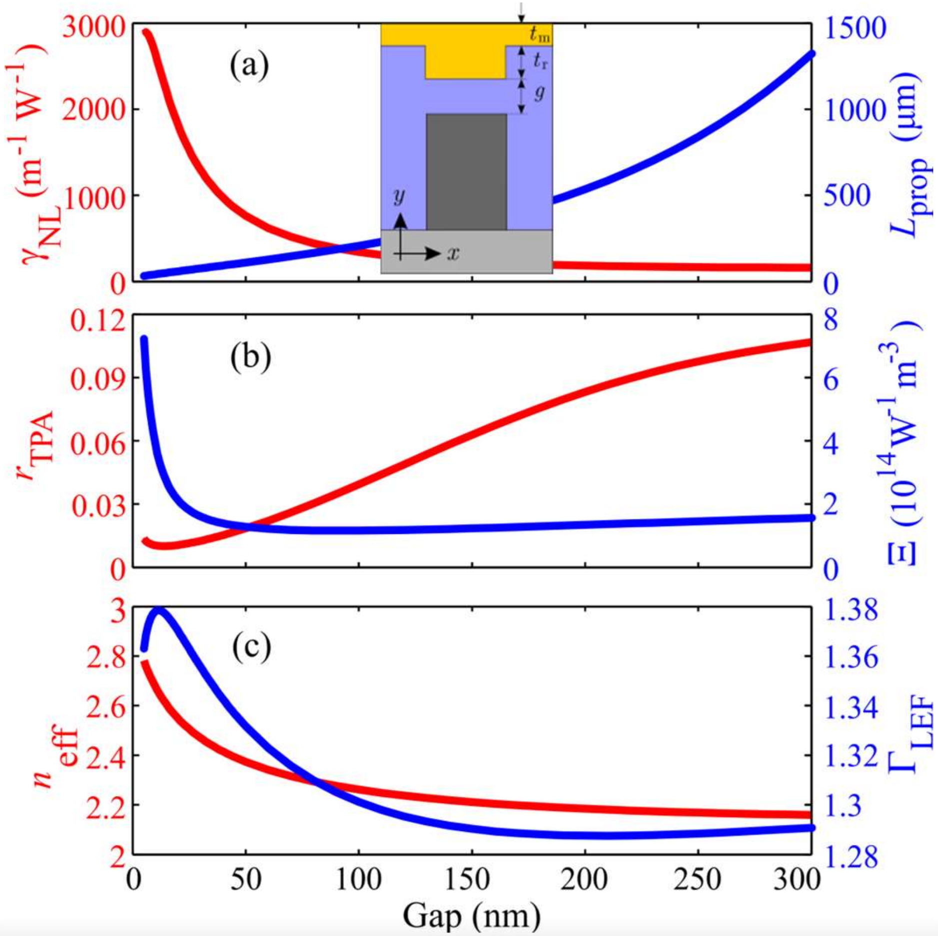
- ✓ γ_{NL} > 10 000 $m^{-1}W^{-1}$
- ✓ A_{eff} < 0.01 μm²
- ✓ L_{prop} > 30 um
- ✓ r_{TPA} < 0.1% + lowest possible "Ξ"

Critical parameter: gap-size

- ❖ tech/fab limitation of g ≥20 nm

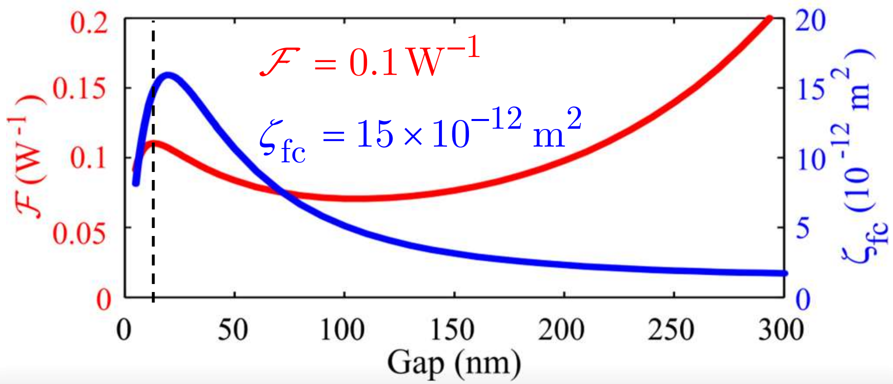
* Optimization of HSP waveguides (2/3) – Gap Effect

HSP w/g mode parameters



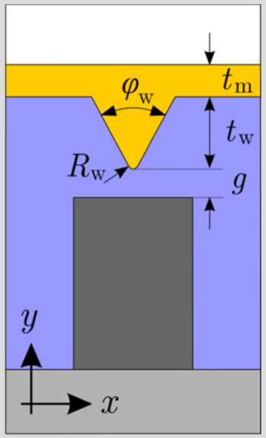
- **Trade-off**: confinement vs. loss
- **Large gaps:** modes degenerate into conventional Si-modes.
- **Small gaps:**
  - r_{TPA} is considerably suppressed
  - Ξ increases for g<20nm.
  - High γ_{NL} ~2000 m^{-1}W^{-1}

Figures-of-Merit

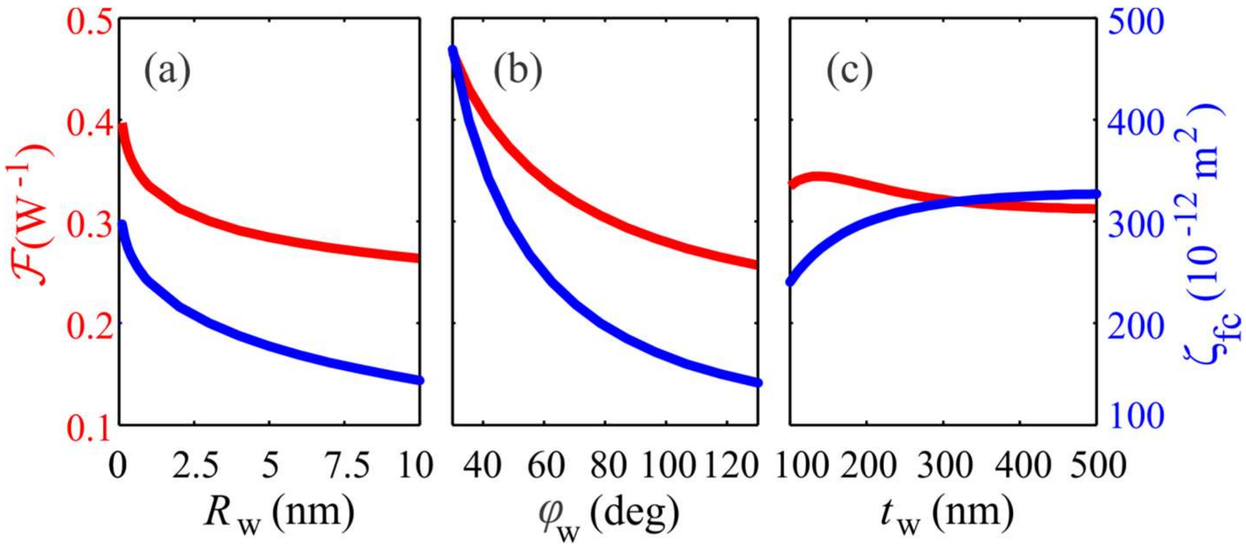


Optimization of HSP waveguides (3/3) : Inverted-Wedge

The "**paragon**" of HSP waveguides



Wedge-Parameter Investigation @ *g*=20nm

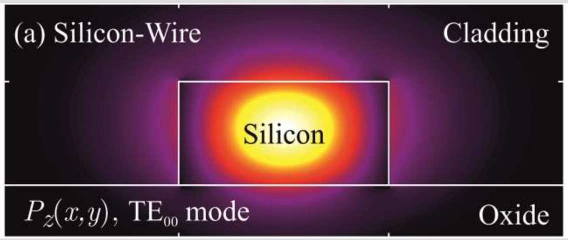


Significant **improvement in both FoM** → $\mathcal{F} \approx 0.4$/W and $\zeta_{fc} \approx 300 \times 10^{-12}$ m^2

- ✓ **Acute angles** provide better performance.
- ▪ Weak dependence on **tip-radius** and **wedge height**.
- ▪ Marginal dependence on **Si-wire dimensions** and **lateral misalignments**
- ❖ A wedge in uniform DDMEBT provides an order of magnitude smaller FoM.

Comparison with prominent Si-comprising waveguides

Conventional Si-wire
400x340 nm²

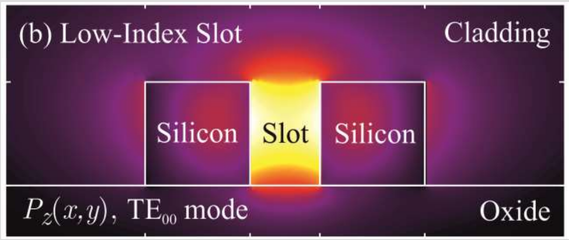


$$\mathcal{F} > 1\,\mathrm{W}^{-1}$$

$$\text{Length - scale} \sim \text{cm}$$

$$\mathcal{F} \times \zeta_{\text{fc}} \times \varpi \approx 0.05$$

NL-Slot, width=140nm
(Koos, Nat. Photonics 2009)

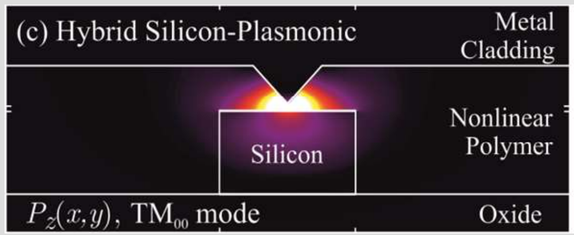


$$\mathcal{F} \approx 0.5\,\mathrm{W}^{-1}$$

$$\text{Length - scale} \sim \text{mm}$$

$$\mathcal{F} \times \zeta_{\text{fc}} \times \varpi \approx 0.5$$

Wedge-HSP
(This work)



$$\mathcal{F} \approx 0.4\,\mathrm{W}^{-1},$$

$$\text{Length - scale} \sim 50\mu\text{m}$$

$$\mathcal{F} \times \zeta_{\text{fc}} \times \varpi \approx 0.5$$

- ✓ Highest L_{prop}
- ✗ Lowest γ_{NL}
- ✗ **Lowest** FCE-threshold

- Moderate L_{prop}
- High γ_{NL}
- High FCE-threshold

- ✗ Smallest L_{prop}
- ✓ Highest γ_{NL}
- ✓ Highest FCE-threshold

HSP vs. Slot: comparable overall-performance @ 1/20 length

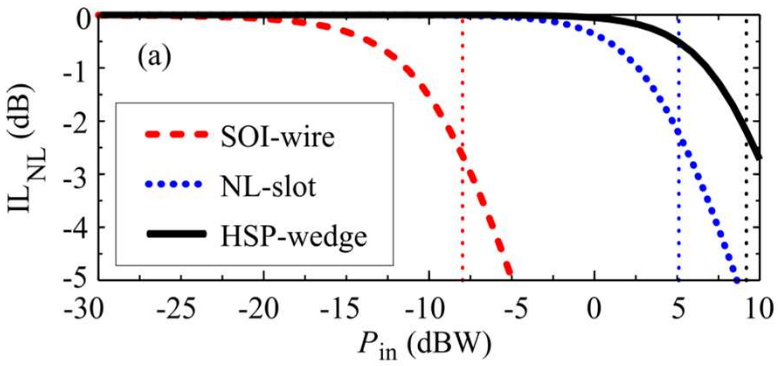
* Quantifying FCE power-thresholds (CW)

FCE threshold-power

- Set $L=L_{prop}$ → different for each w/g
- Integrate CW-NLSE for increasing P_{in}
- Quantify envelope phase and amplitude impairments → $A=|A|e^{i\Delta\Phi}$

NL-Threshold: FCA (and TPA)

$$\mathrm{IL_{NL}} = |A|^2 \exp(L / L_{\mathrm{prop}}) / P_{\mathrm{in}}$$



$$P_{\mathrm{th}}^{\mathrm{FCA}} = \sqrt{a / f_A} \to \mathrm{IL_{NL}} \approx -2.5\,\mathrm{dB}$$

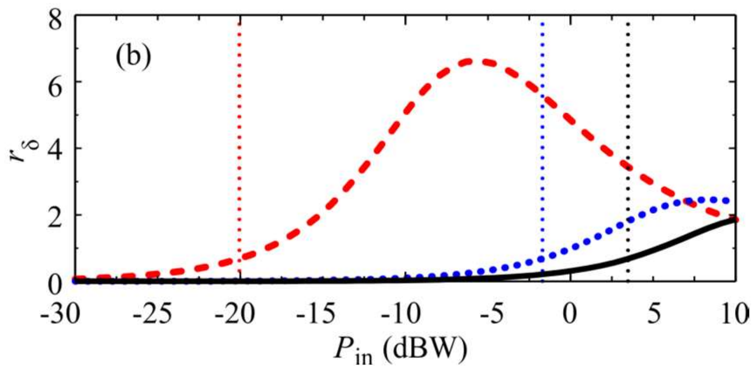
NL-Threshold: non-Kerr phase

$$\Delta\Phi_{\mathrm{NL}} \triangleq -i \ln\{\frac{A}{|A|}\} = \Phi_{\mathrm{Kerr}} + \Phi_{\mathrm{non\text{-}Kerr}}$$

$$r_\delta \triangleq \frac{-\Phi_{\mathrm{non\text{-}Kerr}}}{\Phi_{\mathrm{Kerr}}} = \frac{\gamma P_{\mathrm{in}} L_{\mathrm{eff}} - \Delta\Phi_{\mathrm{NL}}}{\gamma P_{\mathrm{in}} L_{\mathrm{eff}}} > 0$$

$\Phi_{\mathrm{Kerr}} = \gamma P_{\mathrm{in}} L_{\mathrm{eff}} > 0$ — γ and L_{eff} from Linear case

$\Phi_{\mathrm{non\text{-}Kerr}} < 0$ — From opposite FCD and ΔL_{eff} due TPA+FCA



$$P_{\mathrm{th}}^{\mathrm{FCD}} = \gamma / f_D \to r_\delta \approx 0.7$$

Nonlinear HSP-waveguide based component

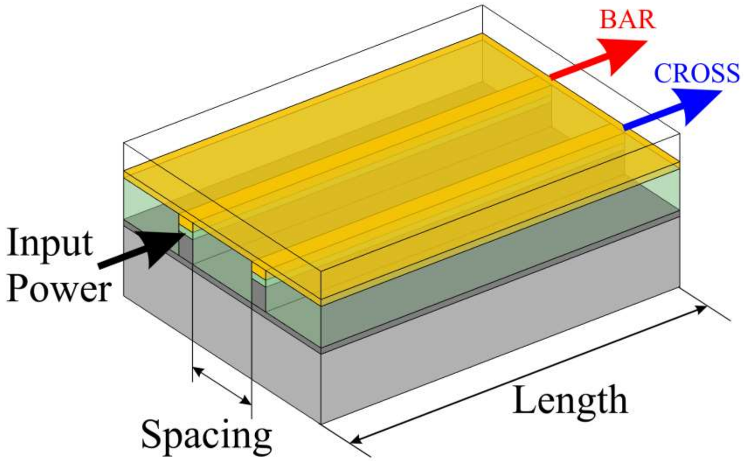
Directional Coupler 2×2 Switch

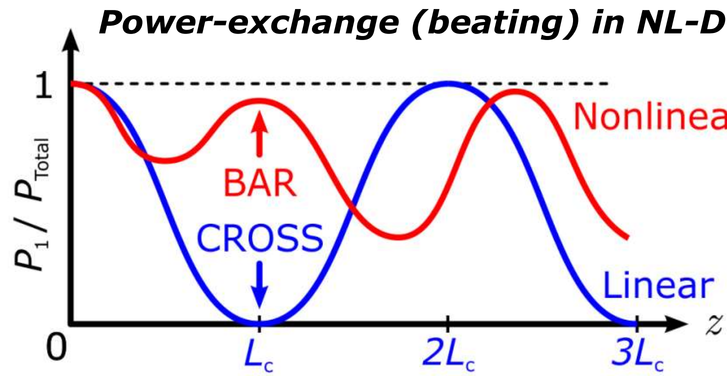
The Nonlinear Directional Coupler Switch (NL-DCS)

Directional Coupler formed by a pair of HSP waveguides

- ❑ CROSS-state @ low input power → Linear regime
- ❑ BAR-state @ high input power → Nonlinear regime

Operation Principle:
Self-focusing
Induced coupler
de-synchronization





Rough-estimate for **switching power**:

$$P_{sw} > \frac{\sqrt{3}\pi}{\mathcal{F}[1-\exp(-L_c / L_{prop})]}$$

$$\Delta\beta_{Kerr} L_c > \sqrt{3}\pi$$

$$\Delta\beta_{Kerr} L_c \approx \Delta\Phi_{NL} = \gamma P_{in} L_{eff}$$

$$L_c = 0.5\lambda / \Delta n_{eff}^{(S-A)}$$

* NL-DCS: Symmetric & Anti-symmetric Supermodes

The NL-DCS can be analyzed in the context of
multi-mode NLSE framework

HSP waveguide parameters:

- Si-wire: 320x220nm^2,
- DDMBER: g=20nm
- Ag-wedge: t_w=100nm, φ_w=53.2°, R_w=1nm
- Carrier Lifetime τ_{fc} =0.1nsec

Also supports TE modes!

Performance metric for switching:

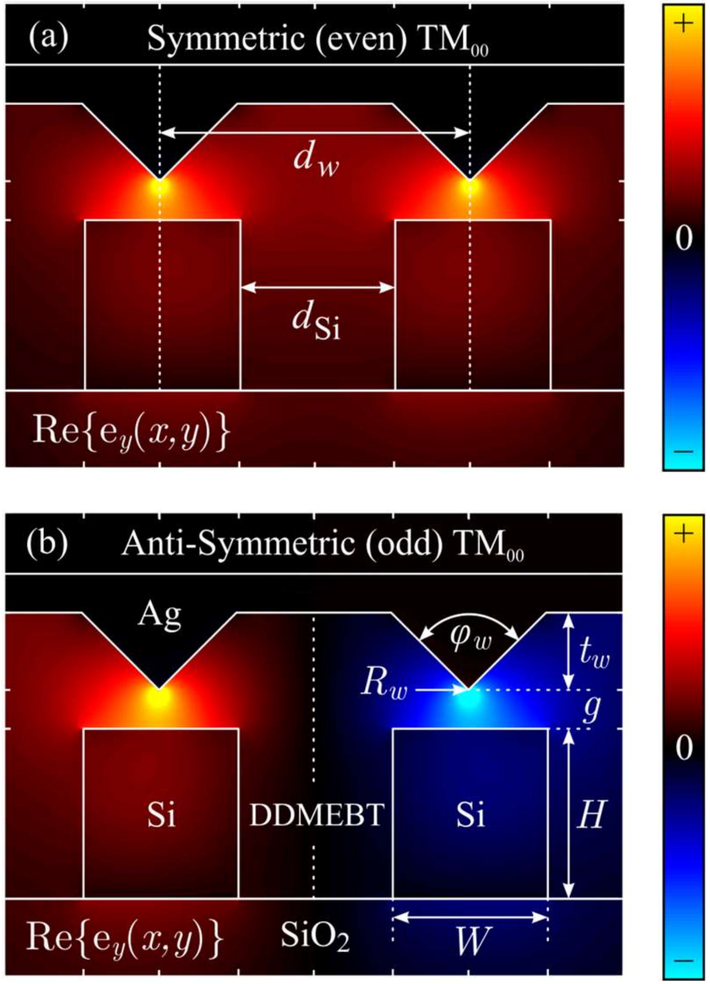
Output-port Crosstalk $\mathrm{XT} = |A_L|^2 / |A_R|^2$

$$A_{L/R} = \left[A_S \exp^{i\beta_0^{(S)} z} \pm A_A \exp^{i\beta_0^{(A)} z} \right] / \sqrt{2}$$

Parametric Investigation: w/g separation

$$d_{\mathrm{Si}} = \quad 280, \quad 380, \quad 480\,\mathrm{nm}$$
$$L_c^{\mathrm{TM}} = \quad 14.6, \quad 28.2, \quad 54.0\,\mu\mathrm{m}$$

Linear Coupler



NL-DCS: Switching Power

Integrate coupled-NLSE system for the three w/g separations.

- ❑ XT vs. P_{in} at left input-port

Increasing w/g separation (d_w):

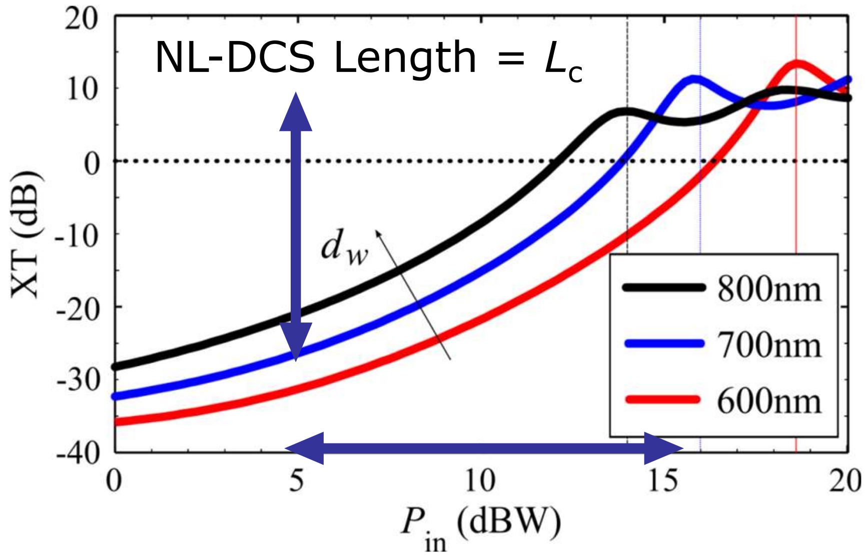
- ✓ reduces power @ 1st XT-peak (P_{sw})
- × increases component length (L_c) → IL
- × reduced XT values

Comparison with theoretical predictions:

P_{in} @ max{XT}

empirical (dBW)	*simulation* (dBW)
16	18.5
14	16
12.7	14

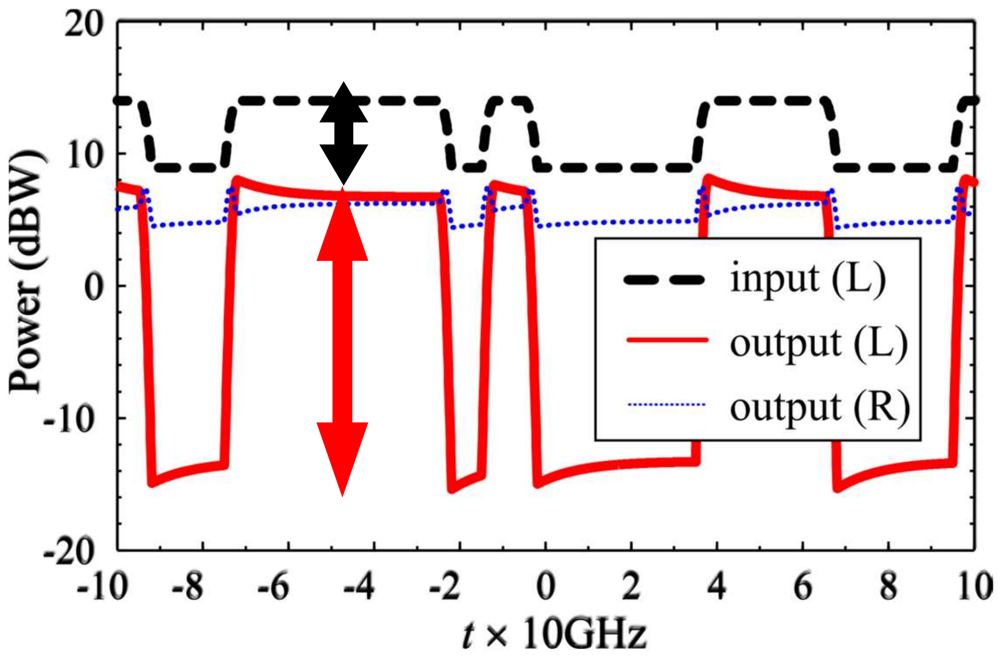
Power-penalty ~2 dB due to FCE.



Observation:
A P_{in}-change of 10 dB corresponds to an output-XT-change of >30 dB.

Application:
Potential for improvement of the ER of modulated signals.

NL-DCS: Boosting ER of Modulated Signals



Modulated Input @ left-input

- 10Gbps NRZ
- TM-polarization
- 30ps rise/fall-time
- **ER=5dB**
- **P_{peak}=14 dBW**

HSP-wedge DCS:

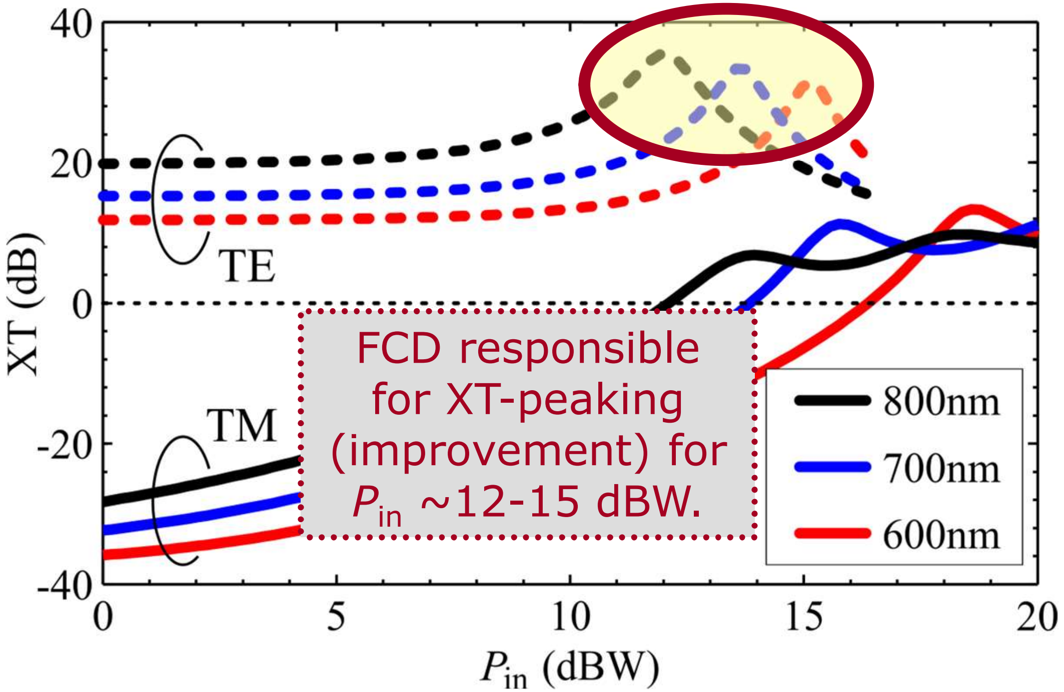
- d_{Si}=380nm & L=28.2um

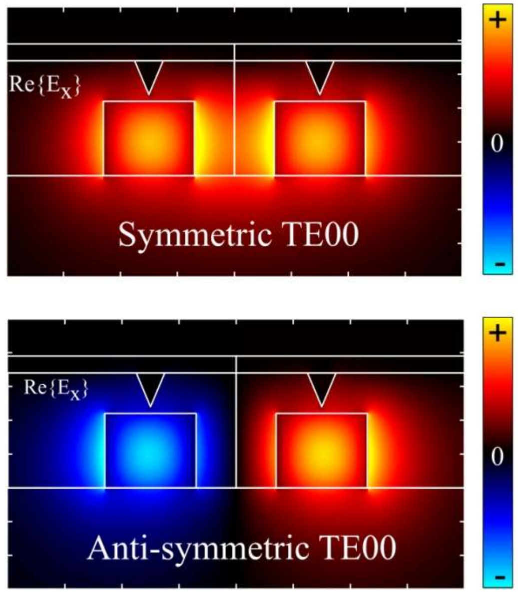
❖ **Numerical integration** (SSFM) of NLSE-pair for the S/A TM-supermodes.

❖ **Dispersive effects → negligible** for these length-scales

✓ **Output ER > 20dB** (15dB improvement) + penalty of IL ~ 4.5dB.

* NL-DCS: TE modes





- L_c(TM) / L_c(TE) ~ 2 → DCS functions as **Polarization Splitter**
- NL-switching power is too high → **XT>10dB for P_{in}<20dBW**
- **Negligible polarization crosstalk** (TE/TM) <-40dB

Extremely Nonlinear Waveguides

High Power Illumination

What happens?

HSP waveguides: increased FCE-threshold allows for **high peak-power**.

- ❖ **Inaccessible regime** for Si-core & NL-Slot waveguides
  - Assuming: length-scales of $L \sim L_{prop}$ and P_{in} below FCE-threshold
- ❖ **Instantaneous nature** of Kerr-type nonlinearity

High-Power + High-nonlinearity + Instantaneous = ...

- ❑ Considerable perturbation in the material refractive-index
- ❑ Eigenmode-profile is perturbed (for nano-sized w/g)
- ❑ Waveguide parameters (linear & nonlinear) are affected

Become Power-dependent!

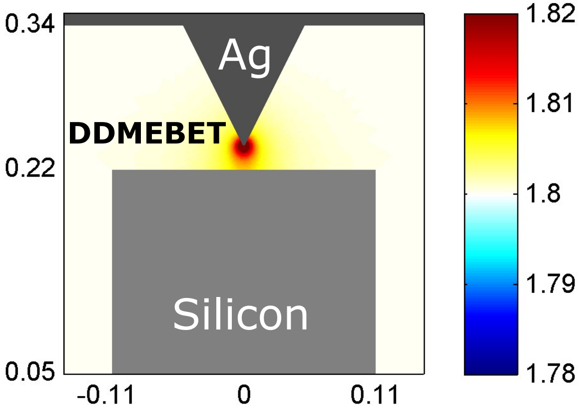
n_{eff} & L_{prop}

γ_{NL} & r_{TPA}

Ξ_{fc} & $\tau_{\mathrm{fc,eff}}$

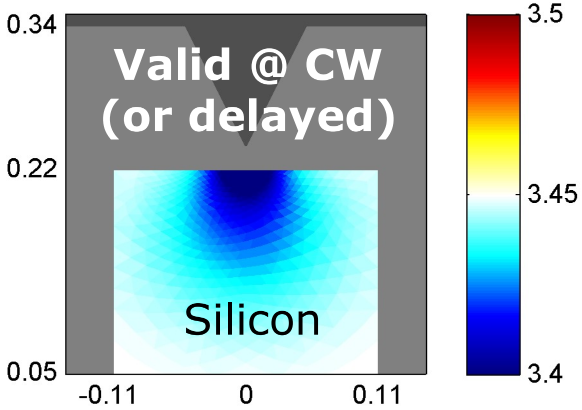
Index-profile @ $n \sim n_{\mathrm{DDMEBT}}$

Kerr-Effect ➔ +Δ*n*



Index-profile @ $n \sim n_{\mathrm{Silicon}}$

FC Dispersion ➔ -Δ*n*



Self-Consistent Eigenmode Solver (SCEMS)

Iterative Algorithm → for a given P_{in}

1. Extract "linear" eigenmode (normally)
2. Normalize eigenmode's E-field to P_{in}
3. Calc./apply refr. index perturbation
4. Extract eigenmode of perturbed w/g
5. Repeat (3)-(4) until convergence
6. Calculate mode parameters

Implementing Step #3

$$\Delta\varepsilon_{r,\mathrm{NL}} = \varepsilon_{r,\mathrm{lin}} n_2 \,|\mathbf{E}|^2 / Z_0 \qquad \text{(Scalar)}$$

$$\Delta\tilde{\varepsilon}_{r,\mathrm{NL}} = \frac{3}{4} \sum_{\alpha,\beta}^{x,y,z} \chi^{(3)}_{\mu\alpha\beta\gamma} E^*_\alpha E_\beta \qquad \text{(Tensor)}$$

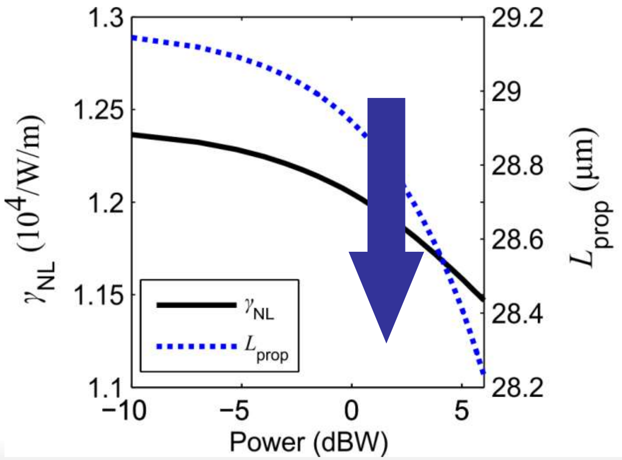
NLSE: Mode-parameters now **depend on** $\boxed{|A(z,t)|^2}$

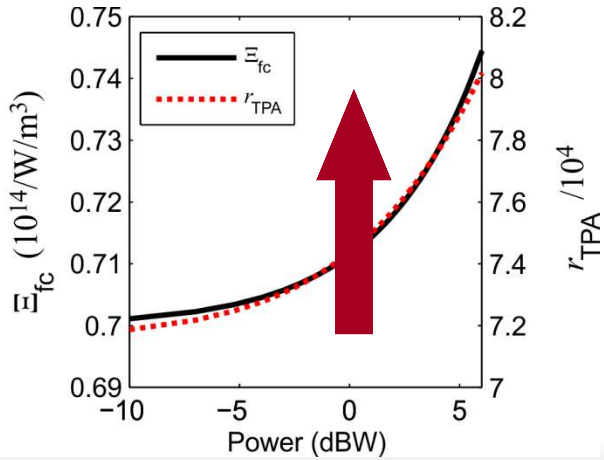
SCEMS @ HSP waveguide TM_{00} mode:

Threshold power

$$n_2 P_{\mathrm{in}} / A_{\mathrm{eff}} > 0.01$$

(vs. FCE-threshold)

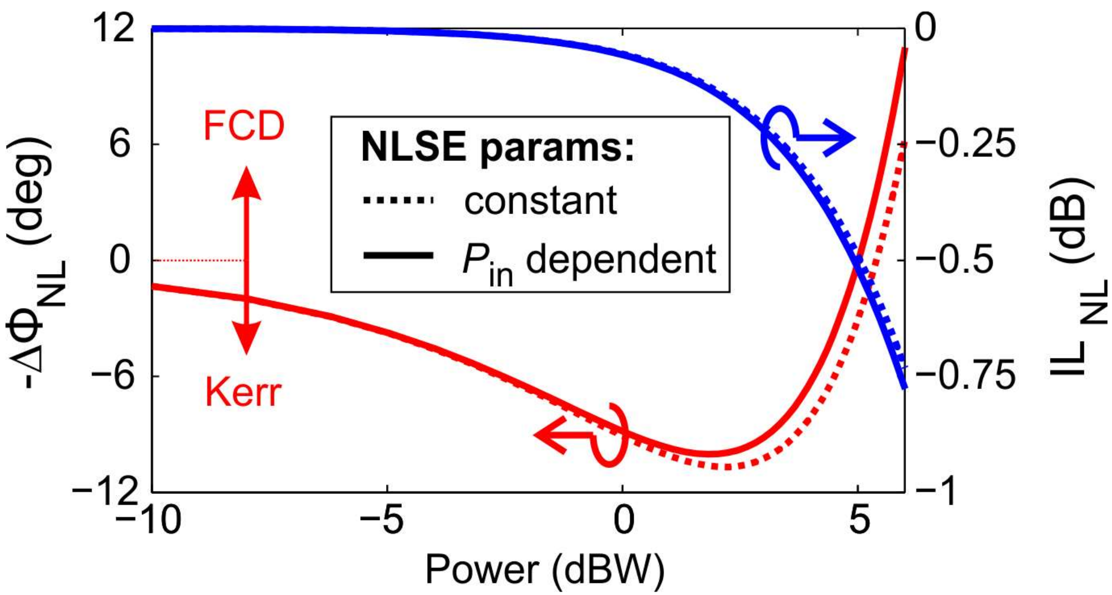




FoM drop → $\mathcal{F}$ & ζ_{fc}

Why? Index-contrast at the silicon/dielectric interface decreases. HSP w/g TM_{00} mode shifts towards the Si-area (from the gap)

Example CW-NLSE



Optimized HSP waveguide

- ❑ Length equal L_{prop}
- ❑ Threshold power ~0dBW
- ☒ Reduces Kerr-Phase
- ☑ Extra IL are negligible

Perturbative effect:

- ❑ Appreciable only at higher-powers
- ❑ But, "masked" by FCE

❖ **Pulsed NLSE**: Similar behavior. Perturbation follows the shape on the pulse → **no spectrum-deformation**

High-Power Illumination – Prospects & Considerations

Prospects:

Materials/Platforms with higher nonlinearity (n_2) and smaller FCE (e.g. τ_{fc})

Interplay between linear and nonlinear indices of waveguide materials

Considerations:

- **Perturbative NLSE** formulation → Limits breached?
- **Multimode waveguides** → (more) power-dependent birefringence!
- **Free-Carrier Effects**
  - Effective Lifetime → Accurate calculation + power-dependence
  - Carrier Density limits → Soref & Bennett model validity range
  - CW case → "worst case"
- **Technological Concerns**
  - Dielectric-breakdown thresholds
  - Nonlocal effects in metal interfaces (ponderomotive nonlinearity)
  - Thermal generation & exhaustion
  - Material properties at high powers – quintic nonlinear susceptibility?

Nonlinear Plasmonics

Conclusion & Perspectives

Concluding remarks & perspectives

Hybrid silicon-plasmonic waveguides: an **alternative platform** for photonic components with **nonlinear functionality**.

❖ **Performance** is catching up with that of Si-based components.

✓ Allow for **reduced on-chip interaction lengths**.

✓ Extreme **suppression of impairments** due to TPA and FCE.

✓ Opens new vistas, e.g. **high-power illumination** in integrated circuits

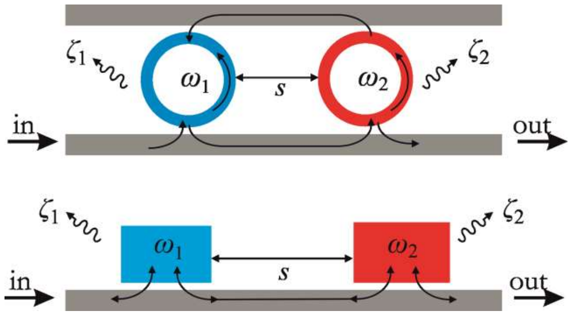
Technological steps that could unlock an **order-of-magnitude boost** in the nonlinear **Figures-of-Merit** (i.e., lower optical power threshold):

- Novel **nonlinear polymers** with n_2~2×10^{-16} [m^2/W], such as PDA/pTS.
- More accurate **control in thin layer deposition**, down to few-nm.

Future perspectives for nonlinear hybrid-plasmonics:

❖ **Resonant configurations** can further assist the nonlinear response.

❖ **Interplay** between all-optical and semiconductor dynamics



Thank you!
Questions?

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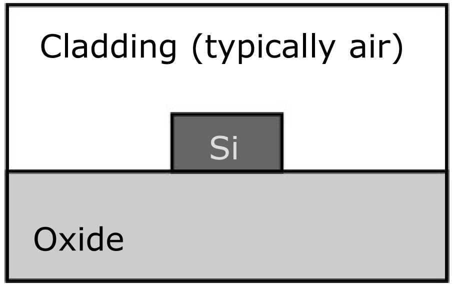
programme for development
EUROPEAN SOCIAL FUND

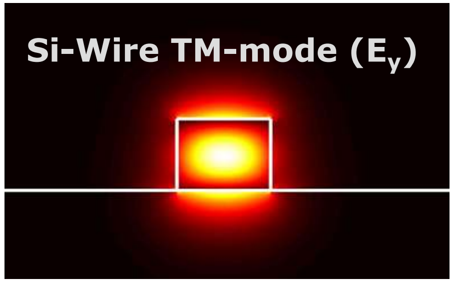
Backup Material

* Nonlinear Effects @ Silicon (SOI) Waveguides

Typical Parameters @ λ=1550nm operation

- ❑ A_{eff} ~ 0.1μm²
  - Si-ridge ~ 400x300nm²
- ❑ γ_{NL} ~ 100m⁻¹W⁻¹
  - n_2 ~ 6×10⁻¹⁸ m²/W
  - r_{TPA}~0.2
- ❑ a ~ 1dB/cm
- ❑ $\tau_{FC,eff}$ ~1nsec (as low as 10ps)



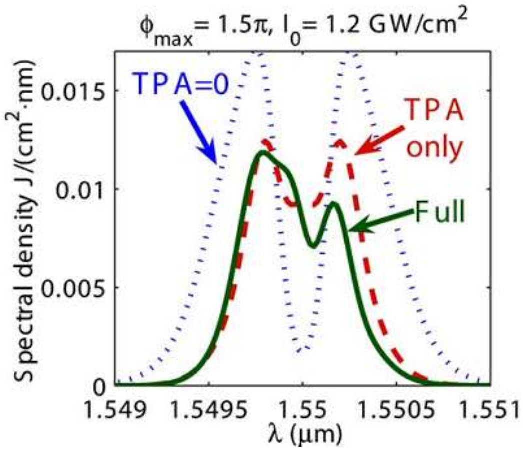


Typical Performance → for Kerr-induced **$\Delta\Phi_{NL}$~π**

- ❖ **Peak intensity** ~1GW/cm² → ~1W @ A_{eff}~0.1μm²
- ❖ **Waveguide length** ~1cm
- ✓ **Dispersion** → typically negligible

Issues of nonlinear SOI w/g:

- × **TPA** → more attenuation limits Kerr-effect
- × **FCA** → even more attenuation…
- × **FCD** → large effect + opposite-sign to Kerr



Spectral broadening (due to SPM) reduction by TPA & FC-Effects
Yin & Agrawal, Opt. Lett., 2007

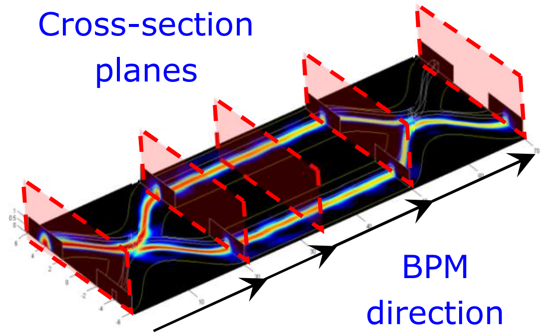
Nonlinear/CW Applications

Beam Propagation Method

Validation against the BPM: basic concepts

A full-3D treatment of the problem

- Field-envelope propagation with a stepping algorithm
- Cross-section discretized with 2D finite elements
- Ideal for longitudinal structures
- Spectral method → CW radiation



Modeling Propagation under Nonlinear Effects

The waveguide's **refractive-index profile is modified** at each Δz-step by the **Kerr**, **TPA** and **FCE** perturbations that are dependent on **E**(x,y,z)

$$\mathbf{D} = \varepsilon_0 \varepsilon_{r,\mathrm{lin}} \mathbf{E} + \mathbf{P}_{3o} + \mathbf{P}_{\mathrm{fc}} = \varepsilon_0 \left(n_0^2 + \underbrace{\boxed{\Delta\tilde{\varepsilon}_{r,3o}}}_{\text{Kerr \& TPA}} + \underbrace{\boxed{\Delta\varepsilon_{r,\mathrm{fc}}}}_{\text{FCE}} \right) \mathbf{E} = \varepsilon_0 \left(n_0^2 + \Delta\tilde{\varepsilon}_{r,\mathrm{T}} \right) \mathbf{E}$$

- Results in an **overall refractive-index modification** $\Delta\tilde{\varepsilon}_{r,\mathrm{T}}(x,y,z)$
- **Iterative trapezoidal-rule algorithm** for numerical stability
  - Rule-of-thumb for BPM step-size
  - Step is adaptively-set as power decreases

$$\Delta z < \frac{\lambda \,/\, 40}{\max\{|\sqrt{\Delta\varepsilon_{r,T}}\,|\}}$$

Validation against the BPM: implementation of $\chi^{(3)}$, TPA&FCE

Implementation of $\chi^{(3)}$ nonlinear susceptibility (Kerr & TPA)

- Index-modification is a **2nd rank complex tensor** (e.g. a 3x3 matrix)
  - ✓ Accounts for hybrid-modes and tensor-anisotropy in $\chi^{(3)}$ (e.g. silicon)
  - ✓ Requires fully anisotropic BPM formulation

$$\boxed{\Delta\tilde{\varepsilon}_{r,3\mathrm{o}}[\mu,\gamma] = 0.75\sum_{\alpha}\sum_{\beta}\chi^{(3)}_{\mu\alpha\beta\gamma}E^{*}_{\alpha}E_{\beta}} \qquad \chi^{(3)}_{\mu\alpha\beta\gamma}(x,y)$$

  - ✓ Reduces to simpler form for isotropic $\chi^{(3)}$

$$\boxed{\Delta\tilde{\varepsilon}_{r,3\mathrm{o}}[\mu,\gamma] = 0.5\chi_c E^{*}_{\mu}E_{\gamma}\delta_{\mu\gamma} + 0.25\chi_c E^{*}_{\mu}E_{\gamma}} \qquad \chi_c(x,y) = \frac{4}{3}\times\frac{n_0^2 n_2}{Z_0}(1+jr_{\mathrm{TPA}})$$

Implementation of Free-Carrier Effects (FCD & FCA)

- Index-modification is a **scalar complex** proportional to the FC-density generated by TPA (+lifetime).

$$\boxed{\Delta\varepsilon_{r,\mathrm{fc}} = 2n_0\times\Delta u_{\mathrm{fc}}(x,y)}$$

Validation against the Beam Propagation Method

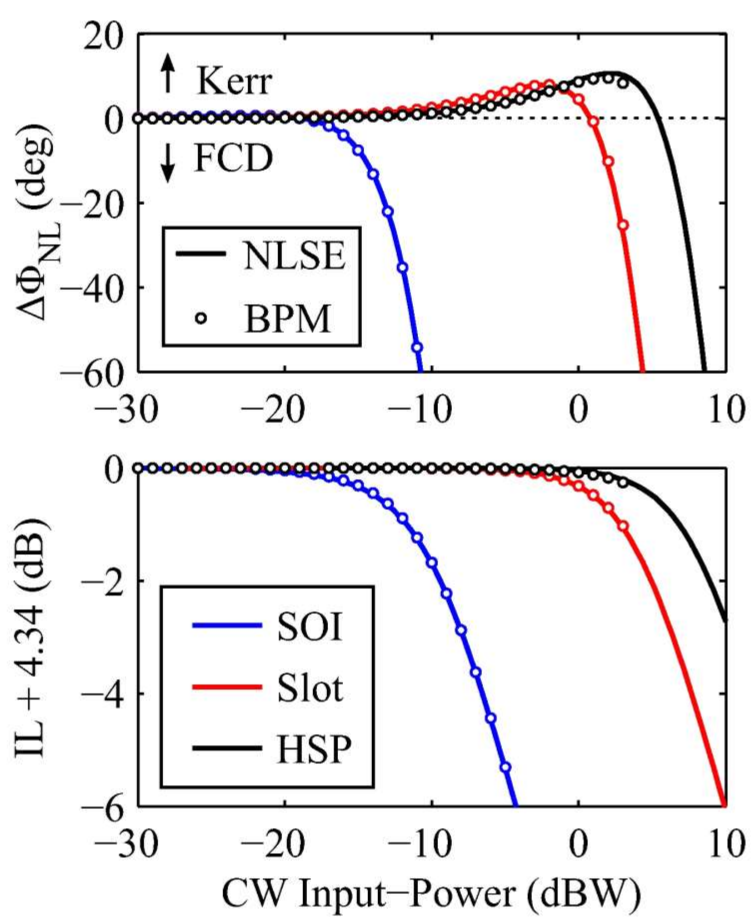
Comparison: Overall **phase-shift** ($\Delta\Phi_{NL}$) and **nonlinear insertion losses** (IL_{NL}) for the three L_{prop}-long waveguides.

- Input-profile & reference-index from **mode-solver**.
- Output $\Delta\Phi_{NL}$ & IL are calculated with **overlap-integrals** on the input-mode.

BPM vs. NLSE: Only needs the material properties and waveguide geometry, but is restricted to CW or quasi-CW.

Attention: The **local FC-density** $N(x,y)$ might exceed the validity-limit of the Soref-Bennett model ($10^{26}/m^3$) for powers where the **spatially-averaged FC-density** $<N>_k$ used in the NLSE is much lower.

Excellent agreement!

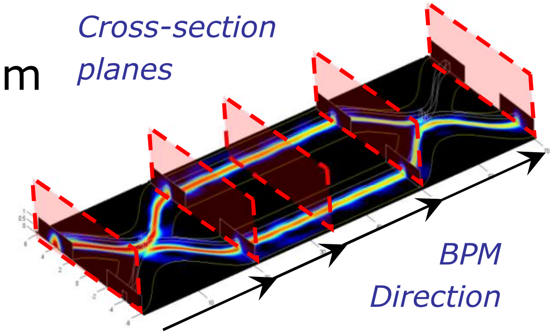


Design Method #2: Nonlinear Beam Propagation Method

A more rigorous full-3D treatment of the problem

Beam Propagation Method (BPM)

- ❑ Field-envelope propagation with a stepping algorithm
- ❑ Cross-section discretized with 2D finite elements
- ✓ Ideal for longitudinal structures
- ✓ Spectral method → CW radiation



Modeling Propagation under Nonlinear Effects

- ❑ Cross-section **refractive-index profile** → **Modified** @ each Δz-step
  - ❖ **Kerr**, **TPA** and **FC-effects** with respect to the **electric-field intensity**

$$\mathbf{D} = \varepsilon_0 \varepsilon_{r,\mathrm{lin}} \mathbf{E} + \mathbf{P}_{\mathrm{NL}} + \mathbf{P}_{\mathrm{FC}} = \varepsilon_0 \tilde{\varepsilon}_r \mathbf{E} = \varepsilon_0 \left(\varepsilon_{r,\mathrm{lin}} + \Delta\varepsilon_{r,\mathrm{NL}} + \Delta\varepsilon_{r,\mathrm{FC}} \right) \mathbf{E}$$

- ❑ **Scalar** or **Tensor** implementation for refractive-index modification
- ❑ **Iterative trapezoidal-rule algorithm** → numerical stability @ larger Δz

Design Method #2: BPM-Implementation of NL Effects

❖ **3D-BPM** → Accounts for **Heterogeneity** in (x,y,z) for **E**, *n* & $\chi^{(3)}$

Implementation of $\chi^{(3)}$ nonlinear susceptibility (Kerr & TPA)

Scalar → Index-modification is a **scalar value**

$$\Delta\varepsilon_{r,\mathrm{NL}} = \varepsilon_{r,\mathrm{lin}} n_2 \,|\,\mathbf{E}\,|^2 / Z_0$$

- ✗ Does not account for vector-nature

r_{TPA} included in n_2

Tensor → Index-modification is a **2nd rank tensor**

- ✓ Accounts for hybrid-modes and tensor-anisotropy in $\chi^{(3)}$ (e.g. silicon)
- ✓ Requires fully anisotropic BPM formulation

$$\Delta\varepsilon_{r,\mathrm{NL}} \rightarrow \Delta\tilde{\varepsilon}_{r,\mathrm{NL}}[\mu,\gamma] = \sum_\alpha \sum_\beta \chi^{(3)}_{\mu\alpha\beta\gamma} E^*_\alpha E_\beta \qquad \mu,\alpha,\beta,\gamma \rightarrow \{x,y,z\}$$

- ✓ Reduces to simpler form for isotropic $\chi^{(3)}$

$$\Delta\tilde{\varepsilon}_{r,\mathrm{NL}}[\mu,\gamma] = 0.5\chi_c E^*_\mu E_\gamma \delta_{\mu\gamma} + 0.25\chi_c E^*_\mu E_\gamma \qquad \chi_c = \frac{4}{3} \times \frac{\varepsilon_{r,\mathrm{lin}} n_2}{Z_0}(1 + j r_{\mathrm{TPA}})$$

Implementation of Free-Carrier Effects (FCD & FCA)

Introduced as a **complex scalar index-modification**, proportional to the number of FCs generated by TPA (+lifetime).

$$\Delta\varepsilon_{r,\mathrm{FC}} = 2n_{\mathrm{lin}}(\Delta n_{\mathrm{FC}} + j\Delta a_{\mathrm{FC}} / 2k_0)$$

Free-Carrier Effects in Silicon Waveguides

Implementing the FCEs

Backup: Free-Carrier Effects Modeling

Electric Displacement: $\mathbf{D} = \varepsilon_0 \varepsilon_{r,\mathrm{lin}} \mathbf{E} + \mathbf{P}_{\mathrm{FC}}$

Electric Polarization (due to FCs): $\mathbf{P}_{\mathrm{FC}} = \varepsilon_0 \Delta\varepsilon_{r,\mathrm{FC}} \mathbf{E}$

Relative Dielectric Constant: $\Delta\varepsilon_{r,\mathrm{FC}}(x,y) = 2n_{\mathrm{lin}}(\Delta n_{\mathrm{FC}} + j\Delta a_{\mathrm{FC}} / 2k_0)$

- (only for materials with TPA≠0)

Real (phase) & **Imaginary** (loss) parts:

$$\Delta n_{\mathrm{FC}} = +\sigma_a N$$
$$\Delta a_{\mathrm{FC}} = -\sigma_n^e N - (\sigma_n^h N)^{0.8}$$

- Soref-model cross-sections

Free-Carrier Density:

$$\frac{dN}{dt} = G - \frac{N}{\tau_{\mathrm{FC,eff}}} \xrightarrow{\mathrm{CW}} N = G \times \tau_{\mathrm{FC,eff}}$$

- Rate Equation

TPA & |E|² dependence:

$$G \propto \frac{1}{A_{\mathrm{TPA}} hf} \mathrm{Imag}\left\{ \sum_{m,n}^{1\ldots N} (2-\delta_{mn}) \gamma_{mn} \left| A_m A_n \right|^2 \right\}$$

- from all modes’ contributions

FCE parameters (*G* & *N*) are inserted:
(1) NLSE → “effective” value weighted over xy-plane
(2) 3D-BPM → a function of (x,y) for the “local” |E| and TPA

A Simpler Approach

Scalar NLDCS

Backup: NL-DCS w/ Coupled-waveguide Eqs. + SPM

A heuristic approach:

Coupled-waveguide formulation + **SPM term**

Left WG

$$\frac{\partial A_L}{\partial z} = \underbrace{-\frac{a}{2} A_L}_{\text{Losses}} + \underbrace{j\frac{\pi}{2L_c} A_R}_{\text{Coupling}} + \underbrace{j\gamma_{\text{NL}} \left|A_L\right|^2 A_L}_{\text{SPM}}$$

Right WG

$$\frac{\partial A_R}{\partial z} = \underbrace{-\frac{a}{2} A_R}_{\text{Losses}} + \underbrace{j\frac{\pi}{2L_c} A_L}_{\text{Coupling}} + \underbrace{j\gamma_{\text{NL}} \left|A_R\right|^2 A_R}_{\text{SPM}}$$

Parameters are common for the two waveguides

- ❑ **Losses (a)** → From single-waveguide analysis
- ❑ **Nonlinearity (γ_{NL})** → From single-waveguide analysis
- ❑ **Beating Length (L_c)** → From super-mode Δn_{eff}