Improved nonlinear slot waveguides

Integrated nonlinear plasmonics using slot waveguides: stationary states, bifurcation, stability, and time evolution

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V. Nazabal (CNRS ISCR, Univ. de Rennes I), J.-M. Fedeli (CEA-LETI, Grenoble) and M. Chauvet (CNRS FEMTO-ST, Univ. de Franche-Comté)

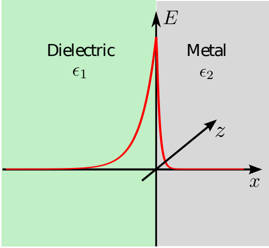
Former PhD student: W. Walasik (Univ. of New York at Buffalo)

META'16 conference, SP29

Outline

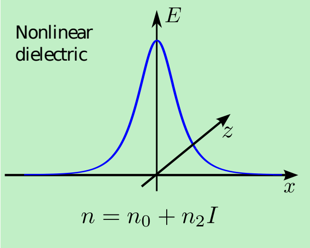
Plasmon–soliton wave building blocks

Surface plasmon polariton	Spatial optical soliton
Solution to a linear wave equation	Solution to a nonlinear wave equation



Propagation constant

$$\beta_p = k_0\sqrt{\frac{\epsilon_1\epsilon_2}{\epsilon_1+\epsilon_2}}$$

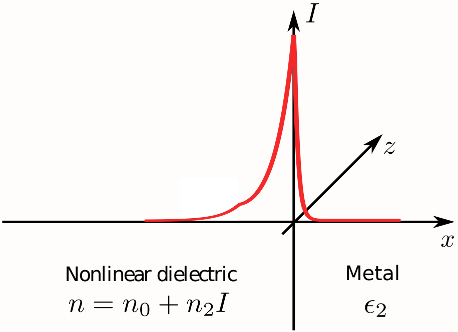


Propagation constant

$$\beta_s = k_0 n_0\sqrt{1+\frac{n_2 I}{n_0}}$$

What is a plasmon–soliton wave?

A nonlinear optical wave combining a spatial soliton and a plasmon field with a single propagation constant



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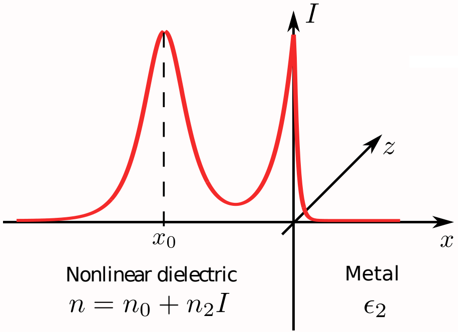
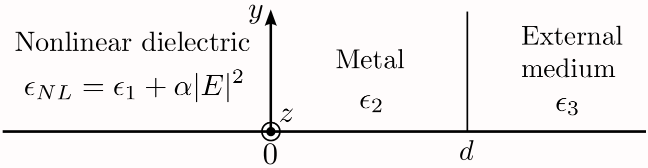
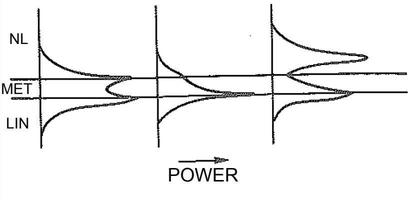


Motivation — Plasmon-soliton coupling in the semi-infinite NL region case



Geometry of the 3-layer nonlinear model

- Seminal articles:
  - V. M. Agranovich *et al.* Nonlinear surface polaritons. *Sov. Phys. JETP*, 32(8):512, 1980.
  - J. Ariyasu *et al.* Nonlinear surface polaritons guided by metal films. *J. Appl. Phys.*, 58(7):2460, 1985.



Motivation — Plasmon-soliton coupling in the semi-infinite NL region case

More recent articles:

- Using the 'interaction picture' approach:

K. Y. Bliokh, Y. P. Bliokh, and A. Ferrando.
Resonant plasmon-soliton interaction.
Phys. Rev. A, 79:41803, 2009.

C. Milián, D. E. Ceballos-Herrera, D. V. Skryabin, and A. Ferrando.
Soliton-plasmon resonances as Maxwell nonlinear bound states.
Opt. Lett., 37(20):4221–4223, 2012.

- Starting from nonlinear Schrödinger's equation:

A. Baron, T. B. Hoang, C. Fang, M. H. Mikkelsen, and D. R. Smith.
Ultrafast self-action of surface-plasmon polaritons at an air/metal interface.
Phys. Rev. B, **91**, 195412, 2015

Motivation — Plasmon-soliton coupling in the semi-infinite NL region case

More recent articles:

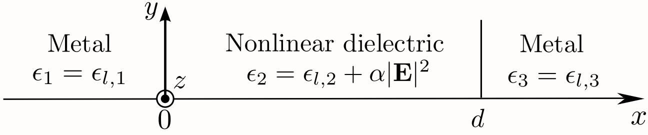
- Starting from Maxwell's equations:

A. R. Davoyan, I. V. Shadrivov, and Y. S. Kivshar.
Self-focusing and spatial plasmon-polariton solitons.
Opt. Express, 16(24):21732–21737, 2009.

-W. Walasik, V. Nazabal, M. Chauvet, Y. Kartashov, and G. Renversez, Low-power plasmon-soliton in realistic nonlinear planar structures, Opt. Lett., 37(22): 4579, (2012)

-W. Walasik, G. Renversez, and Y. Kartashov, Stationary plasmon-soliton waves in nonlinear planar structures: modeling and properties. Phys. Rev. A, 89: 023816, (2014)

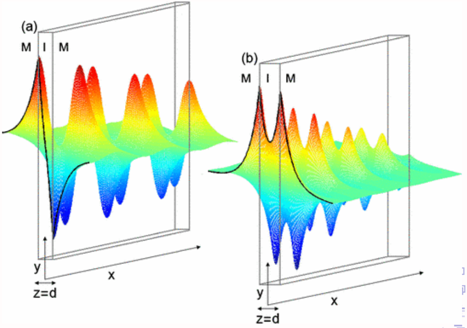
Nonlinear slot waveguide — Introduction



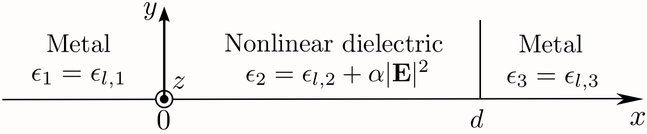
Linear case:

V. R. Almeida *et al.*
Guiding and confining light in void nanostructure,
Opt. Lett, 29:1209-1211, (2004)

J. A. Dionne *et al.*
Plasmon slot waveguides: Towards chip-scale propagation with subwavelength-scale localization,
Phys. Rev. B, 73(3):035407, (2006)

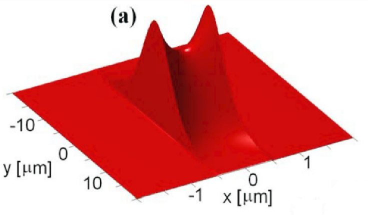


Nonlinear slot waveguide — Introduction



Nonlinear case:

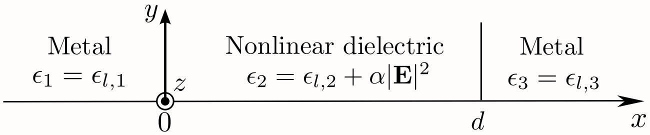
- E. Feigenbaum and M. Orenstein.
  Plasmon–soliton.
  Opt. Lett., 32(6):674, (2007)
- A. Davoyan, I. Shadrivov, and Y. Kivshar,
  Nonlinear plasmonic slot waveguides,
  Opt. Express, 16(26), (2008)



No experimental results on plasmon–soliton in nonlinear slot

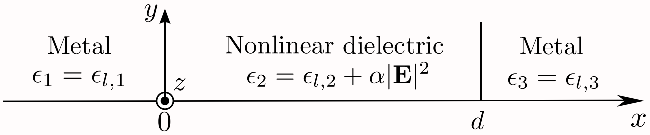
Too high nonlinear index change $\Delta n = n_2 I$

Nonlinear slot waveguide — Introduction



- **Waveguide configuration**
- **Subwavelength focusing**
- **Control the solutions with the power**
- **Peculiar nonlinear effects**

Nonlinear slot waveguide — Models



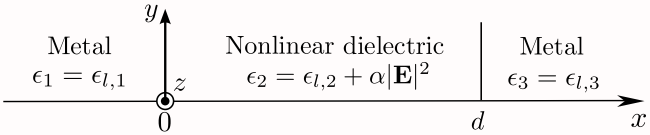
Focusing Kerr effect

Approach: the spatial dependency of transverse field components is kept

"Modal" nonlinear solutions of Maxwell's equations for TM stationary waves using field continuity conditions in 1D structure

Both n_{eff} and field profiles that depend on total power P_{tot} are computed

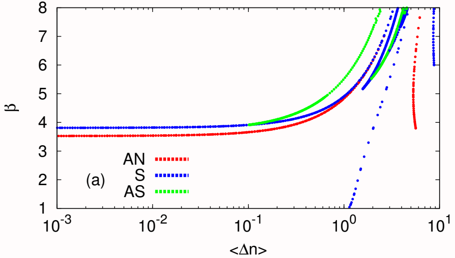
Nonlinear slot waveguide — Models

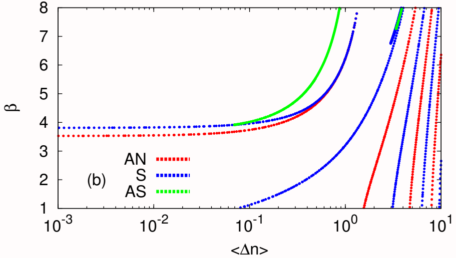


Common hypotheses to our two models

- **Stationary solutions of Maxwell's equations**:
  $$\begin{Bmatrix} \mathbf{E}(x,z,t) \\ \mathbf{H}(x,z,t) \end{Bmatrix} = \begin{Bmatrix} \mathbf{E}_{\mathrm{NL}}(x) \\ \mathbf{H}_{\mathrm{NL}}(x) \end{Bmatrix} \exp[i(\beta_{\mathrm{NL}} k_0 z - \omega t)]$$
  $k_0 = 2\pi/\lambda$, and β_{NL} is the effective index n_{eff} of this nonlinear wave
- **TM waves**:
  $\mathbf{E} = [E_x, 0, E_z]$ and $\mathbf{H} = [0, H_y, 0]$
- **Kerr nonlinearity**
- Maxwell's equations + boundary conditions
  $\longrightarrow$ **Nonlinear dispersion relation**

Nonlinear slot waveguide — Models





Jacobi Elliptic function based Model (JEM)

Extension to slot configuration of
W. Chen and A. A. Maradudin
J. Opt. Soc. Am. B, 5, 529 (1988)

Finite Element Method (FEM)

Adaptation to slot configuration of:
F. Drouart, G. Renversez, *et al.*
J. Opt. A: Pure Appl. Opt., 10, 125101J (2008)

− Low nonlinearity depending only on the transverse electric field

+ **Analytical formulas for field shapes and nonlinear dispersion relation**

+ **Exact treatment of Kerr-type nonlinearity**

− Field shapes and dispersion curves obtained numerically

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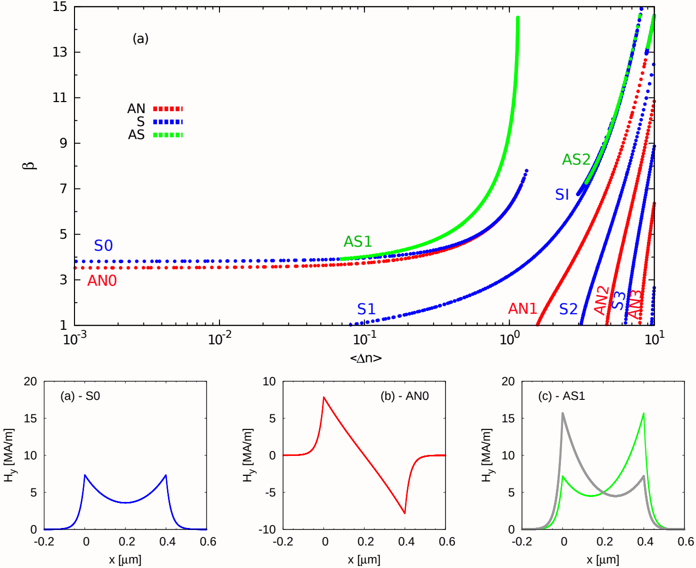
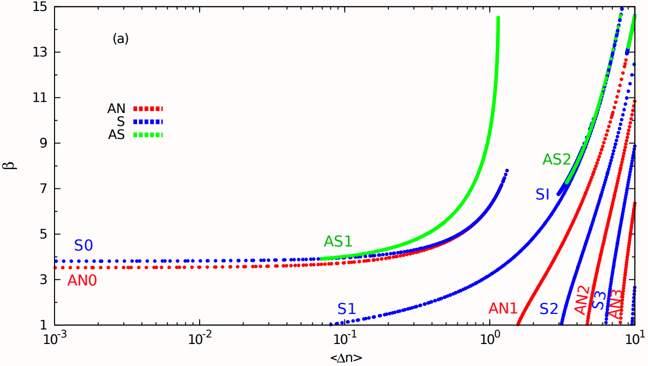
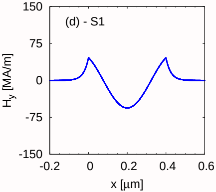
Nonlinear slot waveguide — Dispersion relations

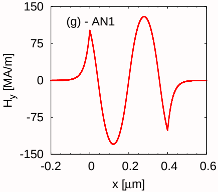


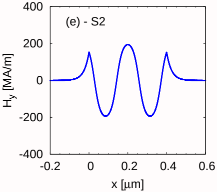
A. Davoyan, I. Shadrivov, and Y. Kivshar, Nonlinear plasmonic slot waveguides, *Opt. Express*, 16(26), 2008

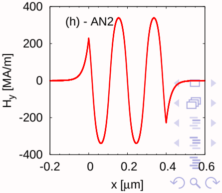
Nonlinear slot waveguide — Dispersion relations



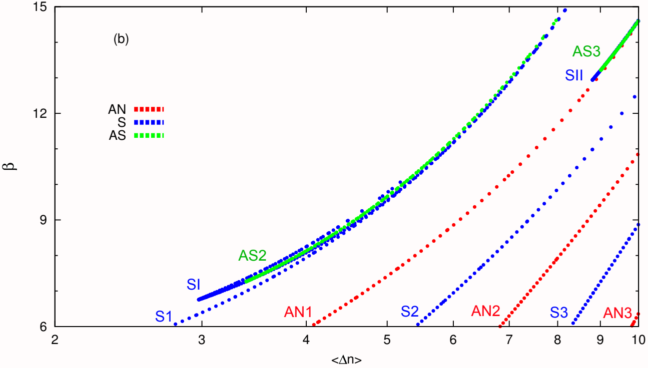


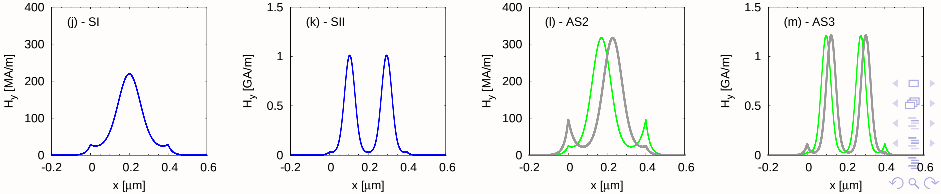




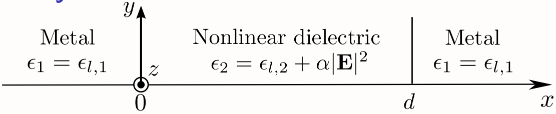


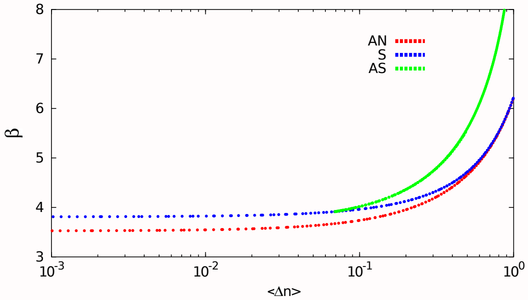
Nonlinear slot waveguide — Dispersion relations

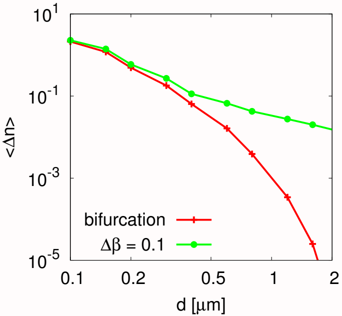




Size and permittivity contrast effects in nonlinear slot

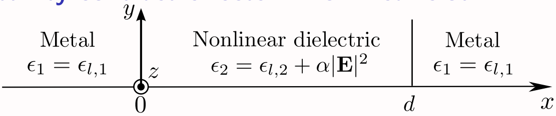


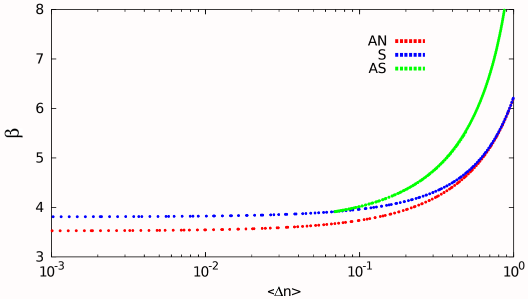


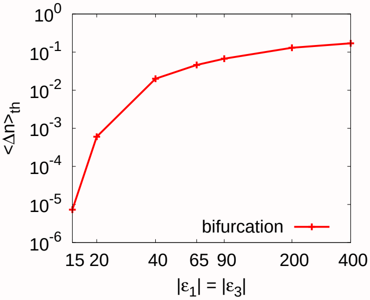


- Bifurcation — spontaneous symmetry breaking
- Asymmetric modes in symmetric structures
- Parameter rules to lower power needed for nonlinear effects

Size and permittivity contrast effects in nonlinear slot



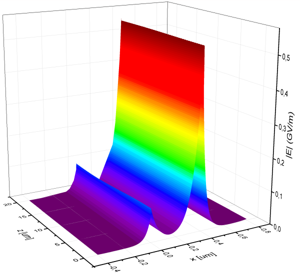




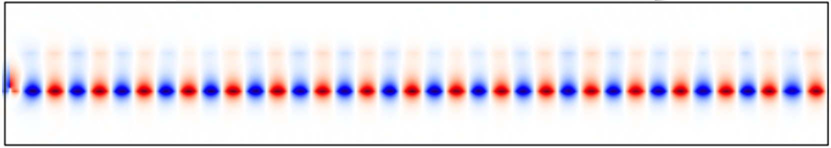
- Bifurcation — spontaneous symmetry breaking
- Asymmetric modes in symmetric structures
- Parameter rules to lower power needed for nonlinear effects

Stability analysis: summary of results from our 2 numerical methods

Temporal propagation simulation over 15λ for the asymmetric mode $|\mathbf{E}|$ (comsol based)



Temporal propagation simulation over 15λ
MEEP full vector nonlinear FDTD simulation for the asymmetric mode H_y



- stability of the asymmetric mode

Intermediate conclusions

- Two semi-analytical models for **nonlinear slot waveguide** configuration with a finite size nonlinear core
- Prediction of the existence of **higher order modes** in nonlinear slot waveguides
- Study of size and permittivity contrast effects on **bifurcation threshold**
  $\rightarrow$ ways to reduce it
- **Stability study** of plasmon–solitons using two numerical methods
  $\rightarrow$ stable asymmetric mode

-W. Walasik, A. Rodriguez, G. Renversez, Symmetric Plasmonic Slot Waveguides with a Nonlinear Dielectric Core: Bifurcations, Size Effects, and Higher Order Modes, Plasmonics, **10***, 33, (2015)*

-W. Walasik, G. Renversez, Plasmon–soliton waves in planar slot waveguides: I. Modeling. Phys. Rev. A, **93***: 013825, (2016)*

-W. Walasik, G. Renversez, F. Ye, Plasmon–soliton waves in planar slot waveguides: II. Results for stationary waves and stability analysis. Phys. Rev. A, **93***: 013825, (2016)*

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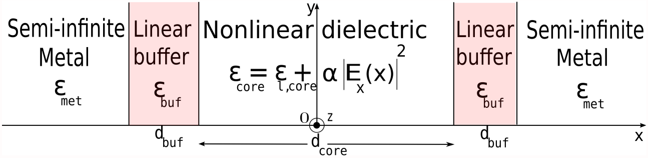
- Study of size and permittivity contrast effects on **bifurcation threshold**
  $\rightarrow$ ways to reduce it
- **Stability study** of plasmon–solitons using two numerical methods
  $\rightarrow$ stable asymmetric mode
- **But losses and bifurcation threshold are still high for realistic and useful parameters.**

Nonlinear slot waveguide configurations — Improved structures



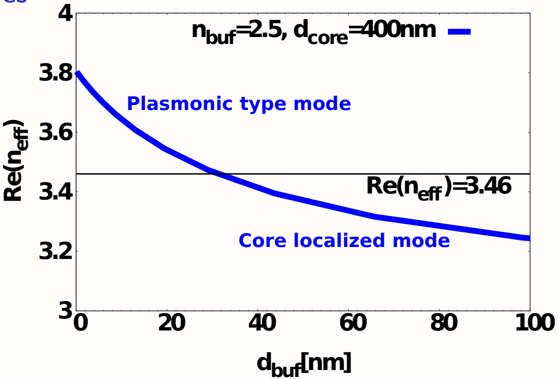
- **Reduce the overall losses**
- **Modify the type of solutions**

Realistic parameters:

- $\lambda = 1.55\ \mu$m
- $d_{core} = 400$ nm
- $\epsilon_{met} = -90 + i10$
- $\epsilon_{l,core} = 3.46^2 + i10^{-4}$, $n_2 = 10^{-17} m^2/w$

C. Lacava *et al.*
Nonlinear characterization of hydrogenated amorphous silicon waveguides and analysis of carrier dynamics.
Appl. Phys. Lett, 103: 141103 (2013)

Linear TM waves



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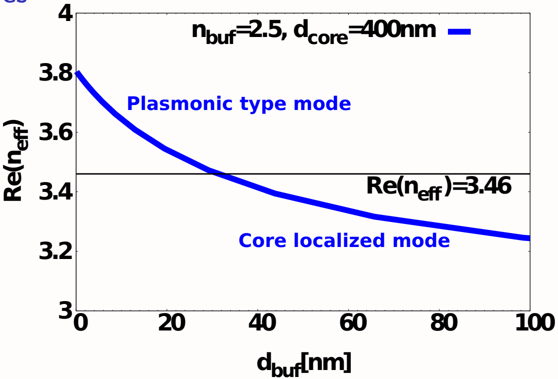

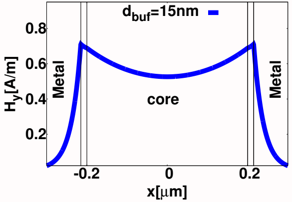

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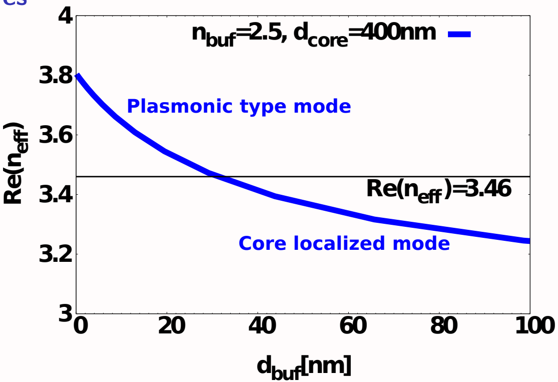

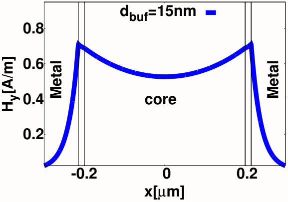

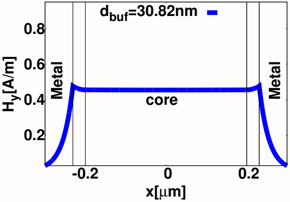

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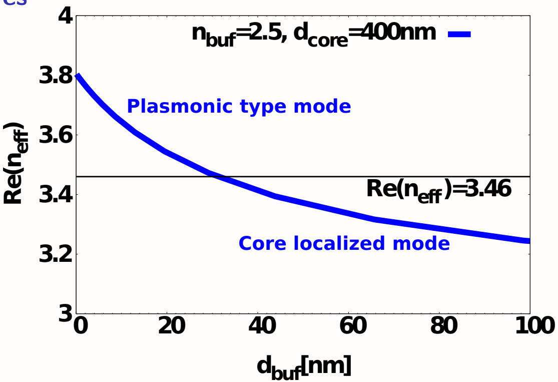

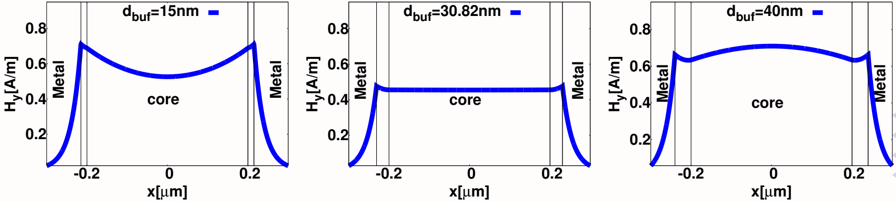

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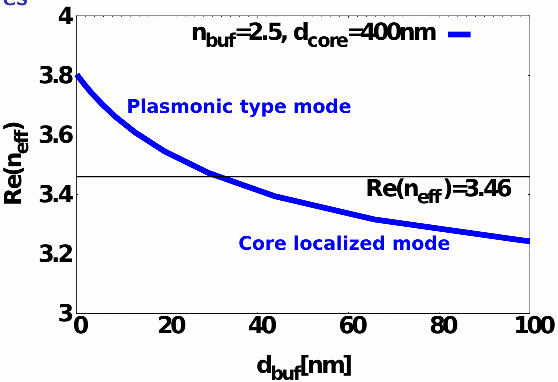
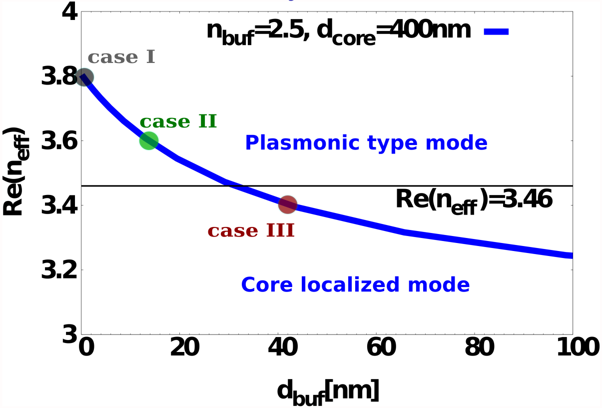


Analytical evaluation of d_{buf}^{up}

$$d_{buf}^{up} \approx \frac{\lambda}{4\pi\sqrt{Re(\epsilon_{l,core}) - \epsilon_{buf}}} \ln\left[\frac{Re(\epsilon_{met})\sqrt{Re(\epsilon_{l,core}) - \epsilon_{buf}} - \epsilon_{buf}\sqrt{Re(\epsilon_{l,core}) - Re(\epsilon_{met})}}{Re(\epsilon_{met})\sqrt{Re(\epsilon_{l,core}) - \epsilon_{buf}} + \epsilon_{buf}\sqrt{Re(\epsilon_{l,core}) - Re(\epsilon_{met})}}\right]$$

Linear TM waves: Different buffer layer thicknesses

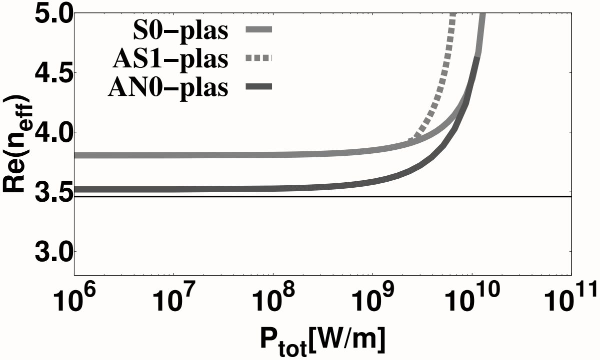


case I (limit case): $d_{buf} = 0nm \rightarrow$ **simple slot configuration**

case II: $d_{buf} < d_{buf}^{up}$ **(The main linear symmetric mode is of plasmonic type)**

case III: $d_{buf} > d_{buf}^{up}$ **(The main linear symmetric mode is mostly core localized)**

Nonlinear TM waves: case I $d_{buf} = 0$ nm $\rightarrow$ Simple slot configuration



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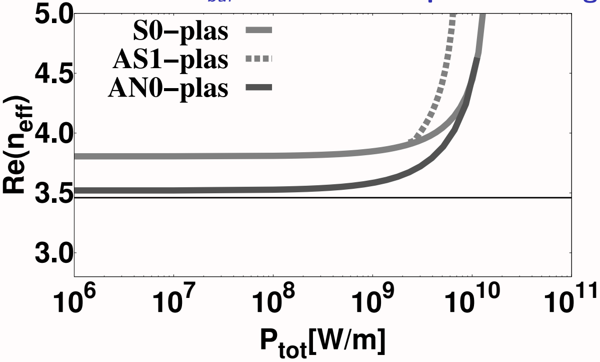
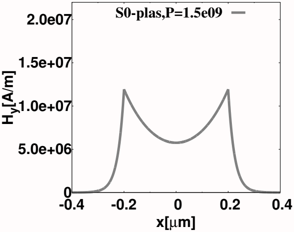
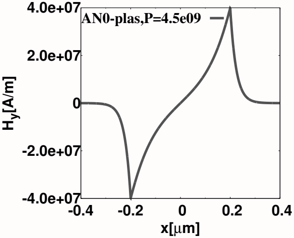
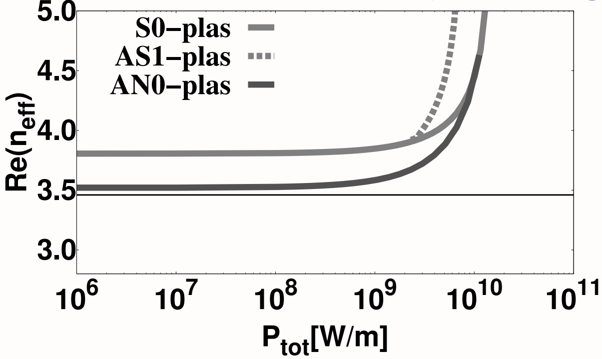
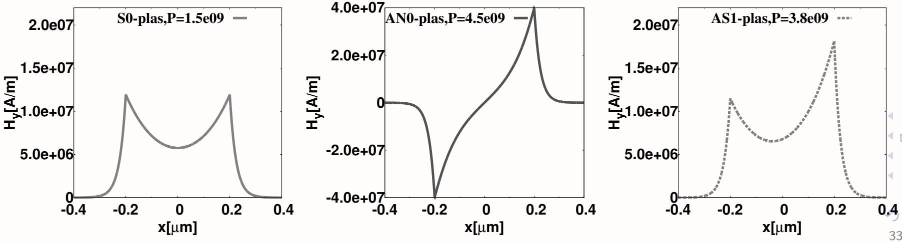




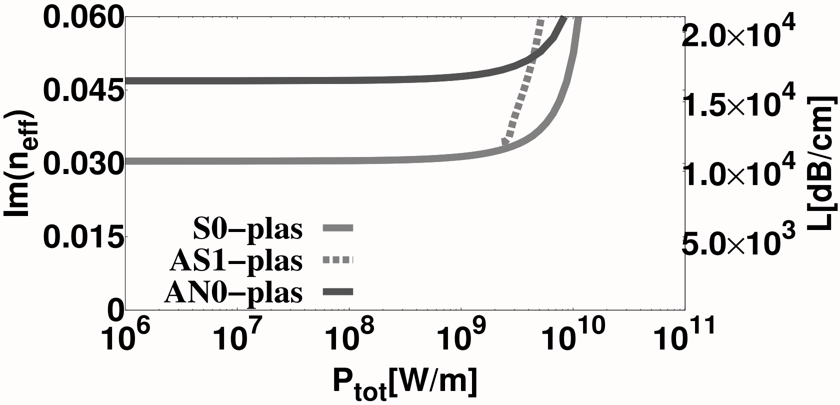


Nonlinear TM waves: case I $d_{buf} = 0$ nm $\rightarrow$ Simple slot configuration



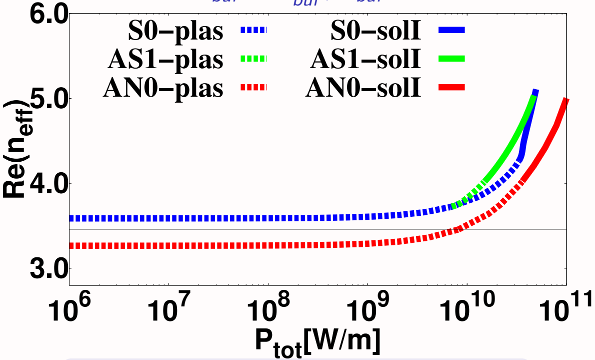


Nonlinear TM waves. case I $d_{buf} = 0$ nm $\rightarrow$ Simple slot configuration (Losses)



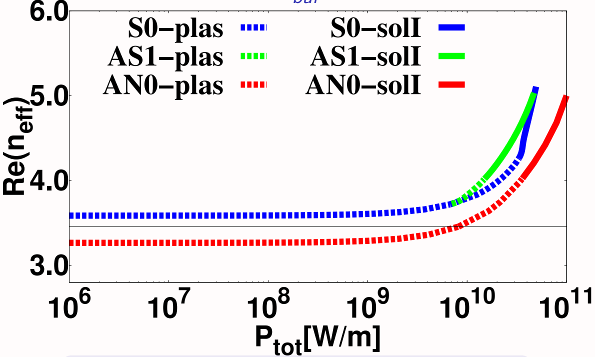
Losses increase with the increase of the power

Nonlinear TM waves: case II $d_{buf} < d_{buf}^{up}$, $d_{buf} = 15$ nm

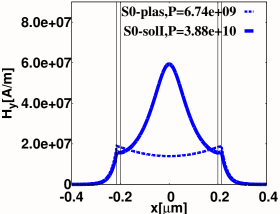


Nonlinear spatial modal transition

Nonlinear TM waves: case II $d_{buf} < d_{buf}^{up}$, $d_{buf} = 15$ nm



Nonlinear spatial modal transition



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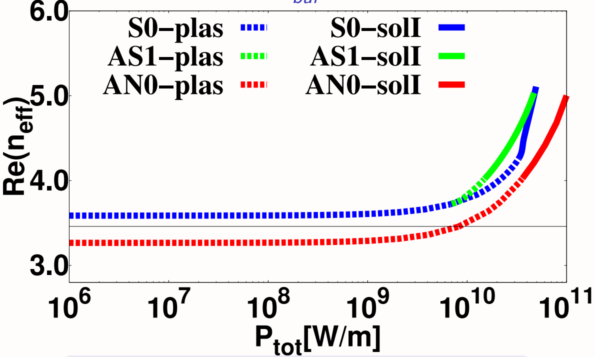

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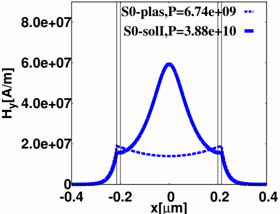

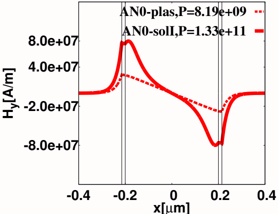

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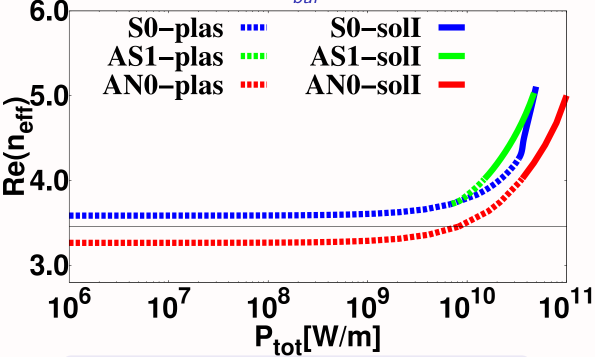

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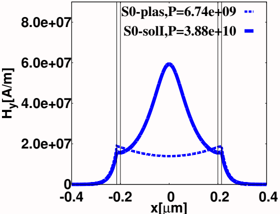
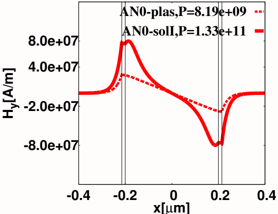
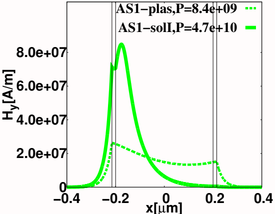
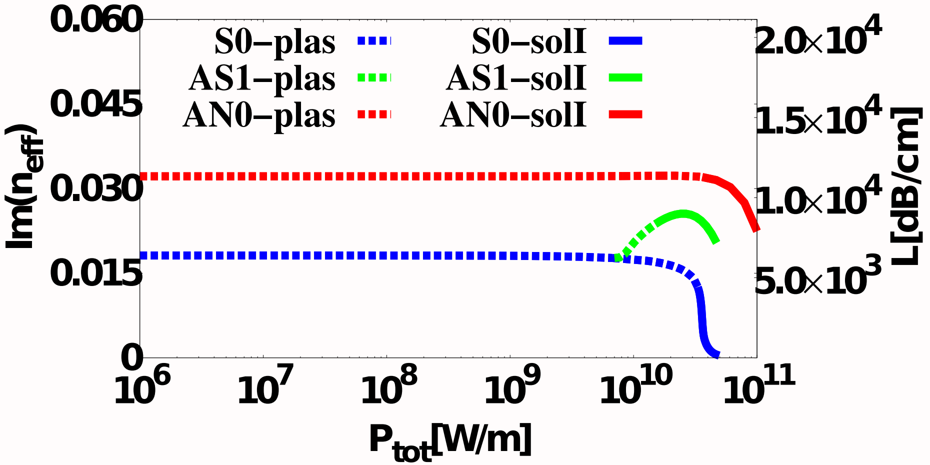




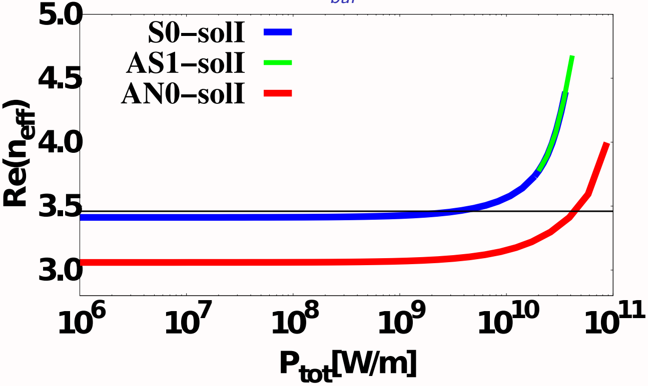


Nonlinear TM waves: case II $d_{buf} < d_{buf}^{up}$, $d_{buf} = 15$ nm (Losses)



Losses decrease with the increase of the power

Nonlinear TM waves: case III $d_{buf} > d_{buf}^{up}$, $d_{buf} = 40$ nm



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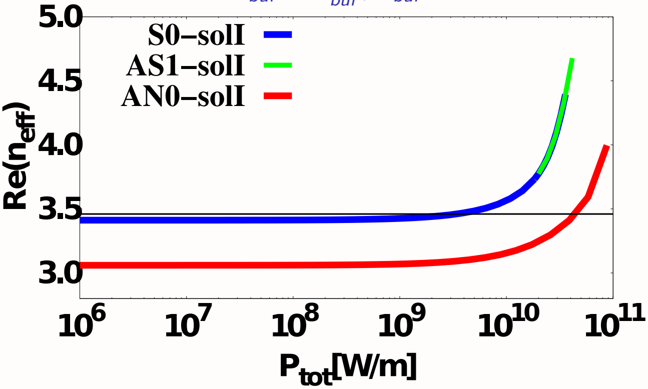

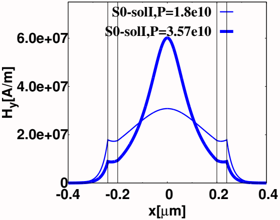

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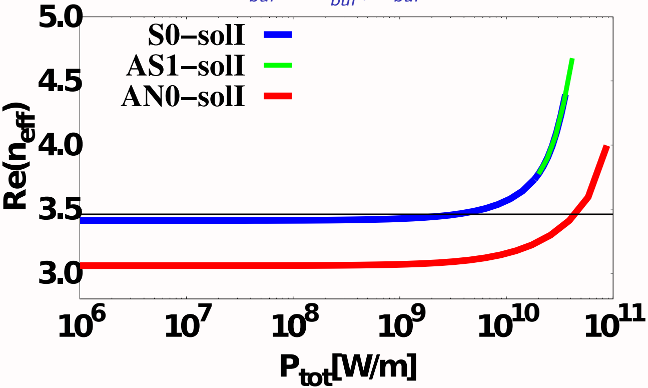

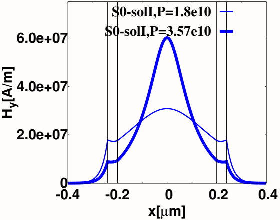

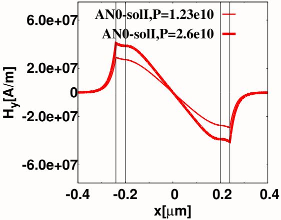

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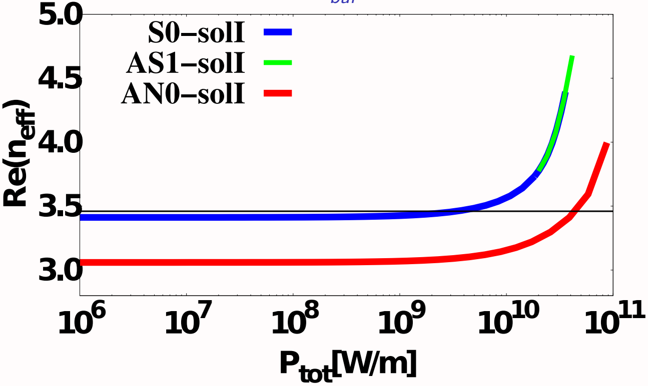
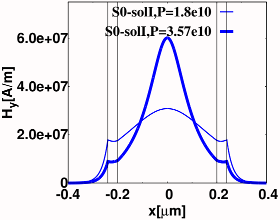
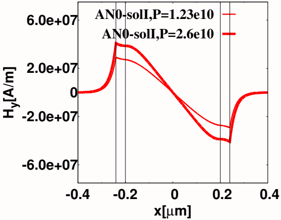
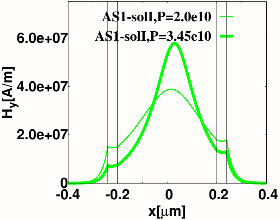
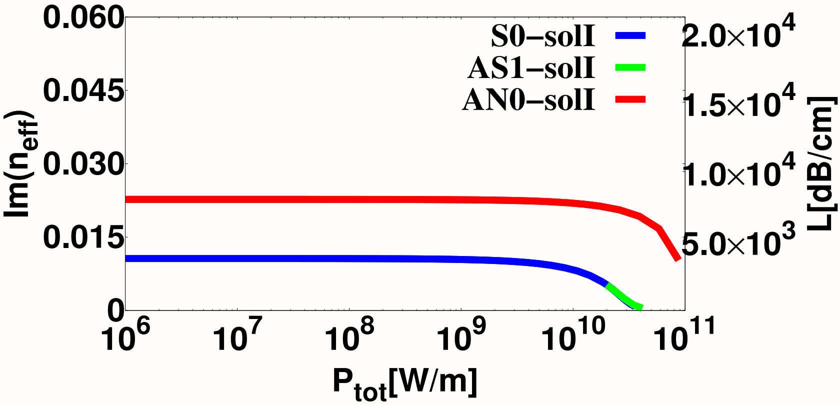






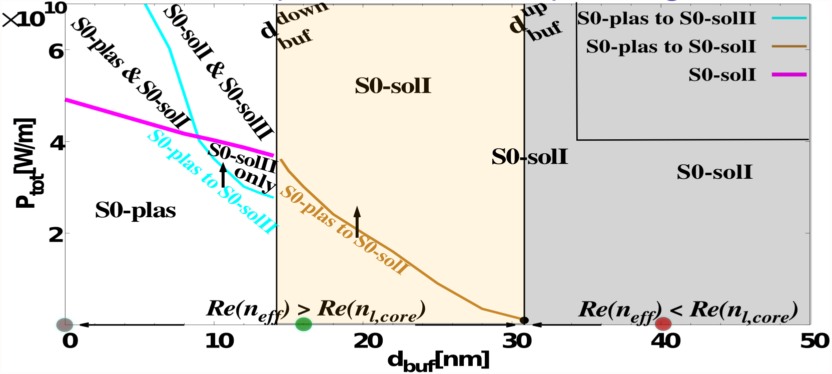


Nonlinear TM waves: case III $d_{buf} > d_{buf}^{up}$, $d_{buf} = 40$ nm (Losses)

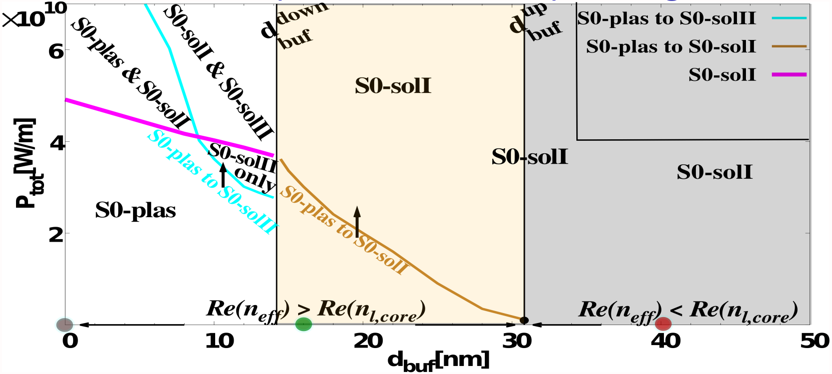


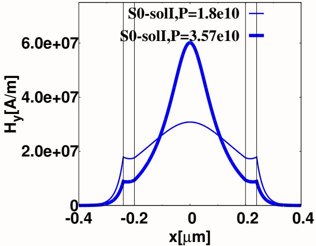
Losses decrease with the increase of the power

Nonlinear TM waves in improved slot: nonlinear phase diagram



Nonlinear TM waves in improved slot: nonlinear phase diagram





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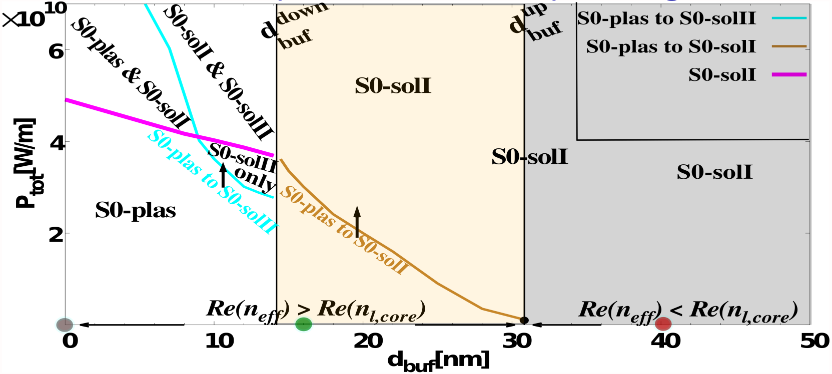

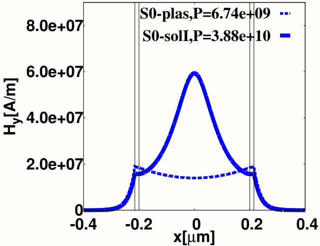

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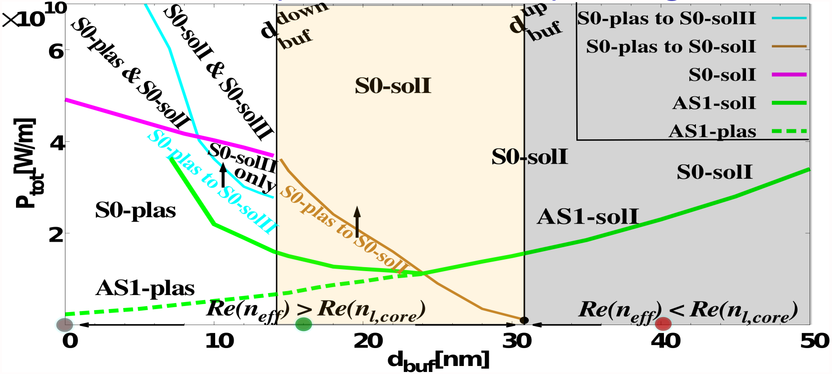

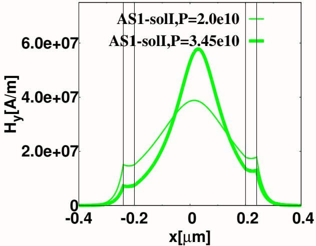

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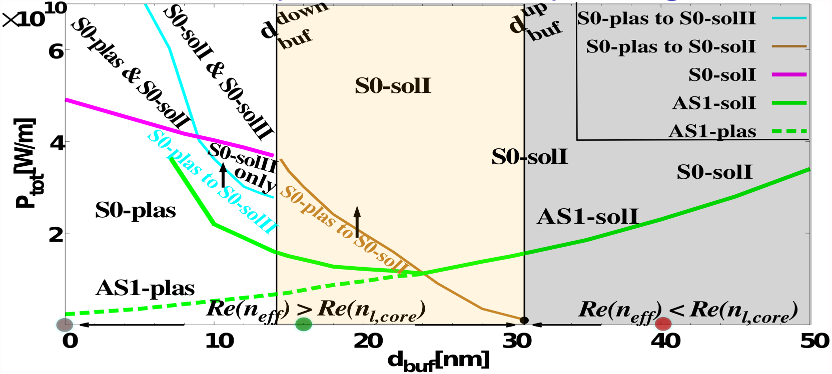

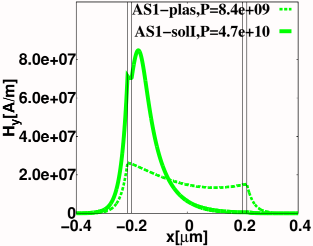

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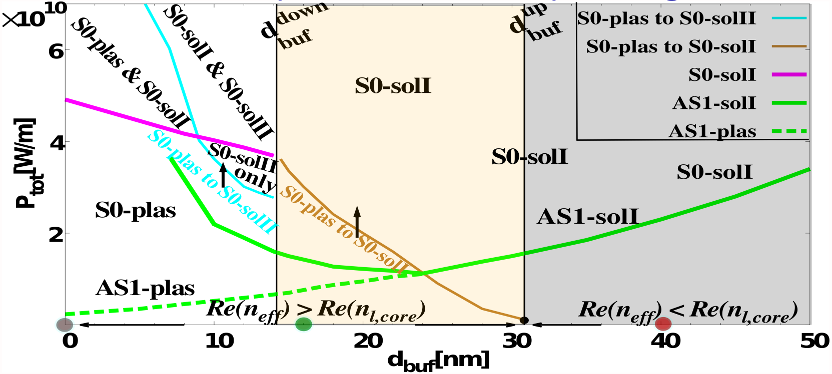


-M. M. R. Elsawy and G. Renversez, *Improved nonlinear slot waveguides using dielectric buffer layers: properties of TM waves.*, Opt. Lett., **41**, 1542-1545, (2016)

-M. M. R. Elsawy, V. Nazabal, M. Chauvet, G. Renversez, *Improved nonlinear plasmonic slot waveguide: a full study.*,Proc. SPIE 9884, Nanophotonics VI, 98840J, (2016)

Slot with a metamaterial nonlinear core — Introduction

The idea to use metamaterial and/or epsilon-near-zero (ENZ) materials to enhance nonlinear effects was already proposed several times:

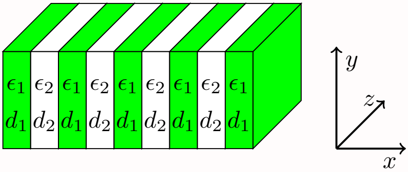
A. Husakou and J. Hermann
Steplike transmission of light through a Metal-Dielectric Mutilayer Structure due to an Intensity-Dependent Sign of the Effective Dielectric Constant
Phys. Rev. Lett., 99, 127402, (2007)

A. Ciattoni *et al.*
Extreme nonlinear electrodynamics in metamaterials with very small linear permittivity,
Phys. Rev. A., 81, 043839, (2011)

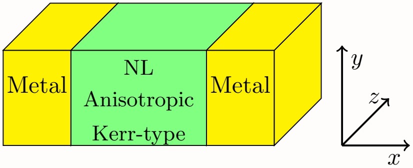
A. D. Neira *et al.*
Eliminating material constraints for nonlinearity with plasmonic metamaterials
Nature Comm., 6, 7757, (2015)

Nevertheless, **nonlinear ENZ waveguide problems and the key role of anisotropy seem to have been partially overlooked.**

Slot with a metamaterial nonlinear core



Metamaterial based nonlinear core



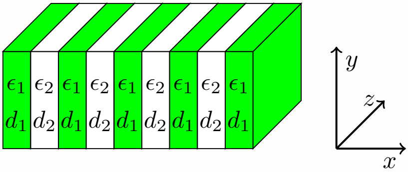
Full slot with its metamaterial nonlinear core

$$\varepsilon_{core} \longrightarrow \bar{\bar{\varepsilon}}_{core} = \begin{pmatrix} \varepsilon_x = \varepsilon_\perp & 0 & 0 \\ 0 & \varepsilon_y = \varepsilon_{//} & 0 \\ 0 & 0 & \varepsilon_z = \varepsilon_{//} \end{pmatrix} \quad (1)$$

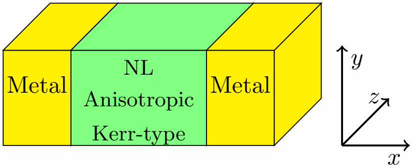
- Effective Medium Theory (EMT) $\rightarrow$ $\bar{\bar{\varepsilon}}_{core}$ tensor for uniaxial anisotropic medium as:

$$\begin{aligned} \varepsilon_y &= \varepsilon_z = r\varepsilon_2 + (1-r)\varepsilon_1 = \varepsilon_{//} \\ \varepsilon_x &= \frac{\varepsilon_1\varepsilon_2}{r\varepsilon_1 + (1-r)\varepsilon_2} = \varepsilon_\perp \\ r &= \frac{d_2}{d_1+d_2} \text{is the ratio of the 2nd material in the layered structure} \end{aligned}$$

Slot with a metamaterial nonlinear core



Metamaterial based nonlinear core



Full slot with its metamaterial nonlinear core

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- As first order approximation, the nonlinear part of the permittivity is isotropic. This hypothesis can be overcame in the nonlinear FEM method if needed.

Slot with a metamaterial nonlinear core — Effective nonlinearity

- In the frame of our semi-analytical 1D model (Maxwell's equations & stationnary TM waves), we obtain for the **effective nonlinearity** α using Eq.(1):

$$\alpha_{ANISOTROPIC} \propto \frac{-1}{\varepsilon_\perp^2}\left(n_{eff}^2\left(\varepsilon_\perp - \varepsilon_{//}\right) - \varepsilon_\perp^2\right)\alpha_{ISOTROPIC} \tag{2}$$

- $\alpha_{ANISOTROPIC} \longrightarrow \alpha_{ISOTROPIC}$ when $\varepsilon_\perp \longrightarrow \varepsilon_{//}$
- Metamaterial properties $\Rightarrow \varepsilon_\perp = f(\varepsilon_1, d_1, \varepsilon_2, d_2)$ and $\varepsilon_{//} = g(\varepsilon_1, d_1, \varepsilon_2, d_2)$
- n_{eff} depends on the total power P_{tot} and on the opto-geometric parameters of the slot

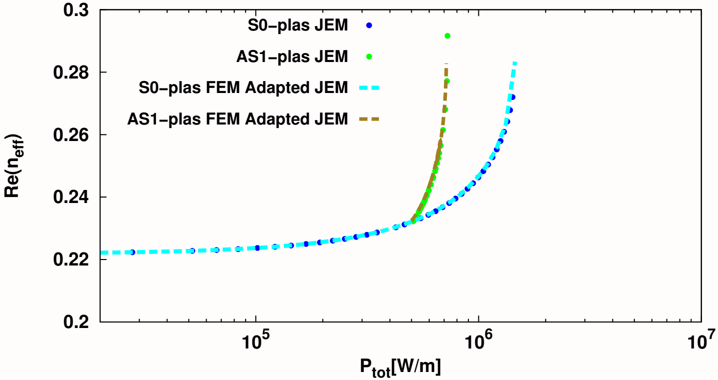
Consequences in the elliptical case

- Lowering the bifurcation threshold for symmetry breaking :
  1 GW/cm^2 $\longrightarrow$ 1 MW/cm^2

Elliptical and hyperbolic cases: M. M. R. Elsawy and G. Renversez, *Spatial nonlinearity at low power in metamaterial plasmonic slot waveguides*, *submitted*, (2016)

Slot with a metamaterial nonlinear core — Numerical results

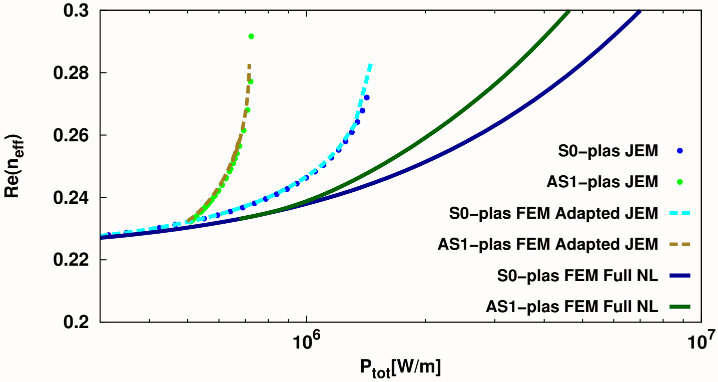
with our 2 models: semi-analytical Jacobi Elliptic function based Model (JEM) and nonlinear FEM (adapted)



Full nonlinear dispersion relation for the symmetric and asymmetric modes as a function of total power P_{tot}. $\lambda = 1.55\,\mu$m ,$\varepsilon_{\perp} = 0.042$ $\varepsilon_{//} = 9.07$, $d_{core} = 400$ nm and $n_2 = 2.10^{-17} m^2/W$.

- Here, in the *FEM Adapted JEM* only E_x is in the nonlinear term so as to correspond with JEM

Slot with a metamaterial nonlinear core — Numerical results
with our 2 models : JEM and nonlinear FEM (adapted and full)



Zoom of the nonlinear dispersion relation for the symmetric and asymmetric modes as a function of total power P_{tot}, around the bifurcation.

- Here, our 2 FEM models: full nonlinearity and E_x only in the nonlinear term

Conclusions

- **Stability of the asymmetric mode**
- **Loss reduction** and new nonlinear spatial modal transitions for the buffer improved isotropic structure
- **2 or 3 orders of magnitude reduction of the bifurcation threshold using realistic metamaterial based nonlinear core**
  $\longrightarrow$ **Important nonlinear effects in plasmonic waveguides at low power**

Perspectives

- **Fabrication** of the designed waveguides by technological facilities
  -Use of recent ENZ materials like ITO in Alam, De Leon and R. Boyd's article in Science April 2016 or like Al-doped ZnO in Caspani *et al.* PRL article June 2016
  -Use of enhanced manufacturing capabilities (like CEA-LETI ones, or see E. Shkondin and A. V. Lavrinenko works shown yesterday in 2-A24 session)

- **Experimental observations** of the predicted waves in collaboration with experimental groups

Job opening in my group: Post-doc in computational photonics (semi-analytical approach, FEM, FDTD, GNLSE) to work on *integrated nonlinear plasmonics with metamaterials*