Plasmon–soliton waves in nonlinear slot waveguides: size effect on bifurcations

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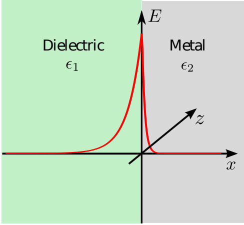
EOSAM, TOM 5, Berlin, September 2014

Outline

Plasmon–soliton wave building blocks

Surface plasmon polariton

Solution to a linear wave equation

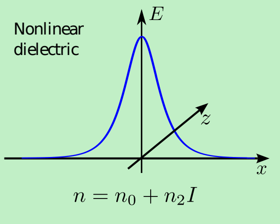


Propagation constant

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

Spatial optical soliton

Solution to a nonlinear wave equation

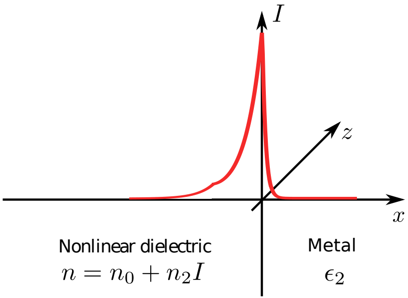


Propagation constant

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

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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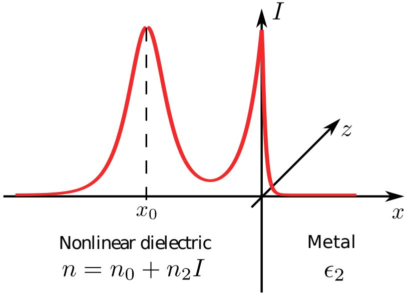
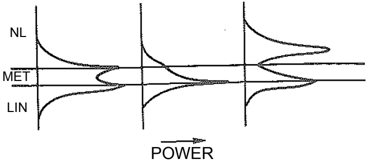


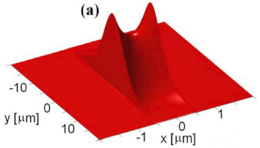
Motivation — no experimental realization since 80'

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.

E. Feigenbaum and M. Orenstein.
Plasmon–soliton.
Opt. Lett., 32(6):674, 2007.

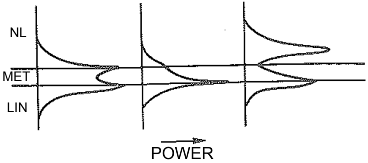


No experimental results about plasmon–soliton since 1980!

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

Motivation — no experimental realization since 80'

W. Walasik, et al.,
Opt. Lett., 37(22): 4579, 2012



W. Walasik, G. Renversez, Y. Kartashov,
Phys. Rev. A, 89: 023816, 2014

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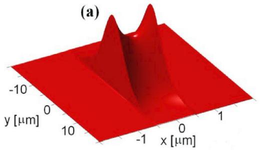

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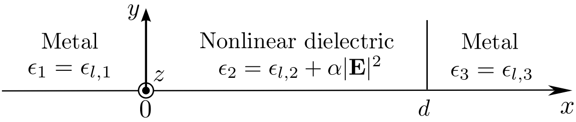
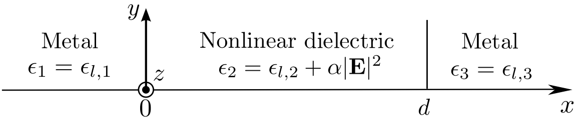
Nonlinear slot waveguide configuration — models



Focusing Kerr effect

Solution to Maxwell's equations for TM stationary waves using field continuity conditions in 1D structures

Nonlinear slot waveguide configuration — models



Jacobi Elliptic function based Model

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

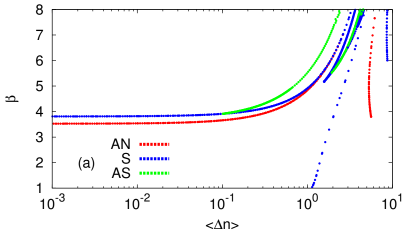
Interface Model

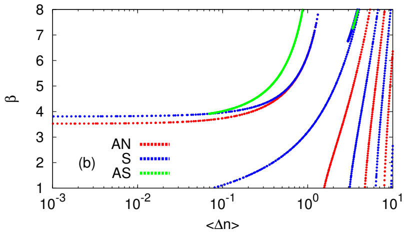
Adaptation to slot configuration of:
D. Mihalache et al.
Opt. Lett., 12, 187 (1987)

– Low nonlinearity depending only on the transverse electric field
+ **Analytical formulas for field shapes and dispersion relation**

+ **Exact treatment of Kerr-type nonlinearity**
– Field shapes and dispersion curves obtained numerically

Nonlinear slot waveguide configuration — dispersion relations





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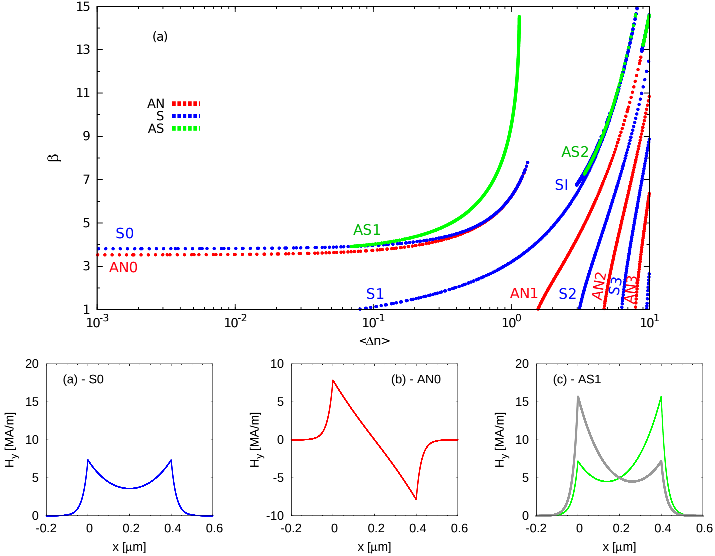
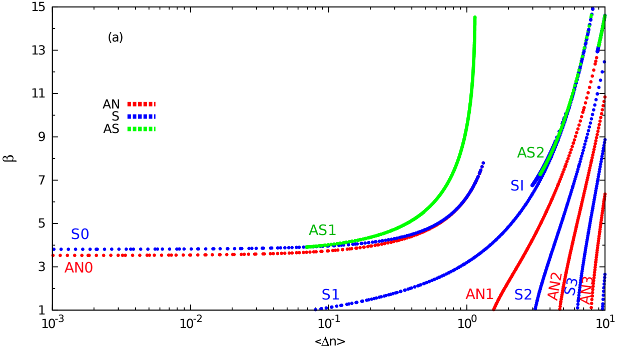
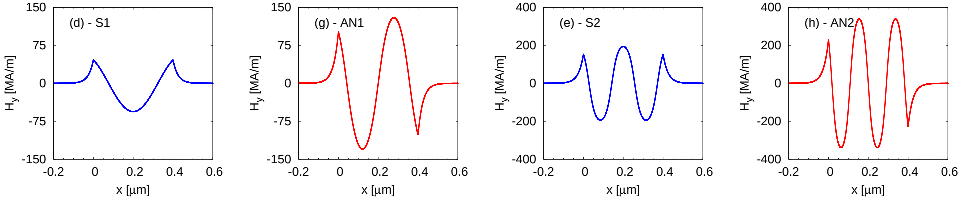
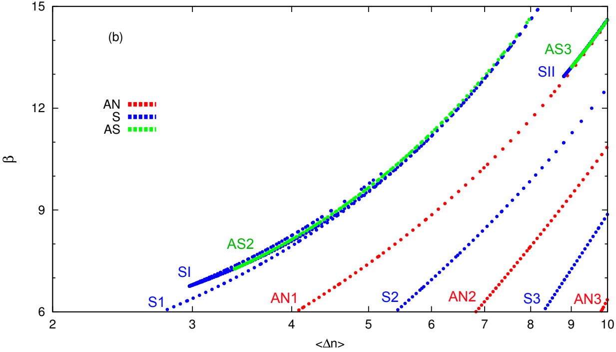


A. Davoyan, I. Shadrivov, and Y. Kivshar, *Opt. Express, 16, 21209 (2008)*


(a)
AN
S
AS
β
<Δn>
S0
AN0
AS1
S1
AN1
S2
AN2
S3
AN3
SI
AS2


(d) - S1
(g) - AN1
(e) - S2
(h) - AN2
H_y [MA/m]
x [μm]


(b)
AN
S
AS
β
<Δn>
15
12
9
6
2
3
4
5
6
7
8
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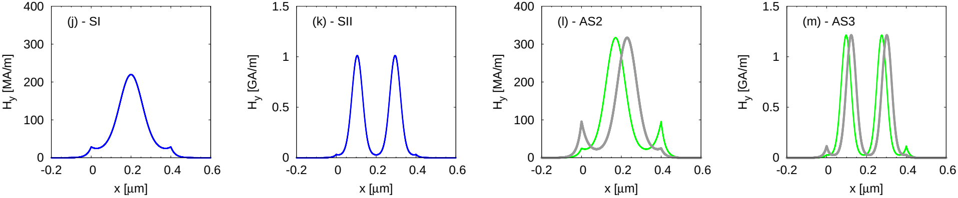
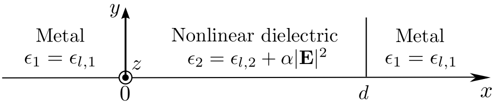
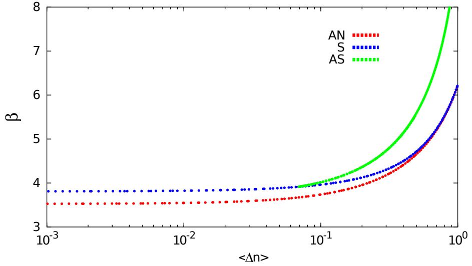
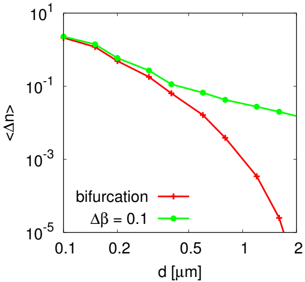
S1
SI
AS2
AN1
S2
AN2
S3
AN3
SII
AS3


(j) - SI
(k) - SII
(l) - AS2
(m) - AS3
H_y [MA/m]
H_y [GA/m]
H_y [MA/m]
H_y [GA/m]
x [μm]
x [μm]
x [μm]
x [μm]
400
300
200
100
0
1.5
1
0.5
-0.2
0.2
0.4
0.6

Size and permittivity contrast effects

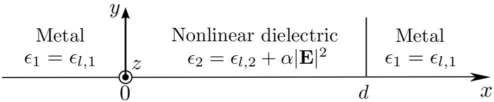


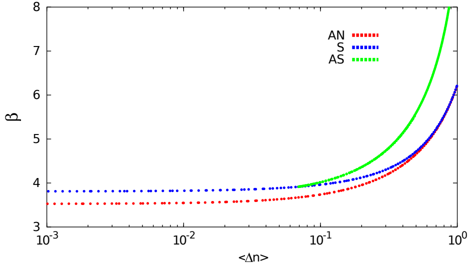


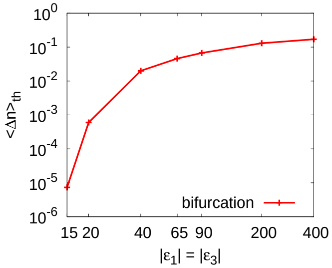


- Bifurcation — spontaneous symmetry breaking
- Asymmetric modes in symmetric structures
- Parameter optimization for low-power nonlinear effects

Size and permittivity contrast effects







- Bifurcation — spontaneous symmetry breaking
- Asymmetric modes in symmetric structures
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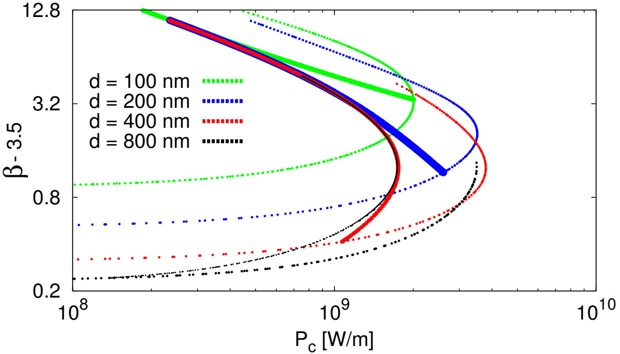
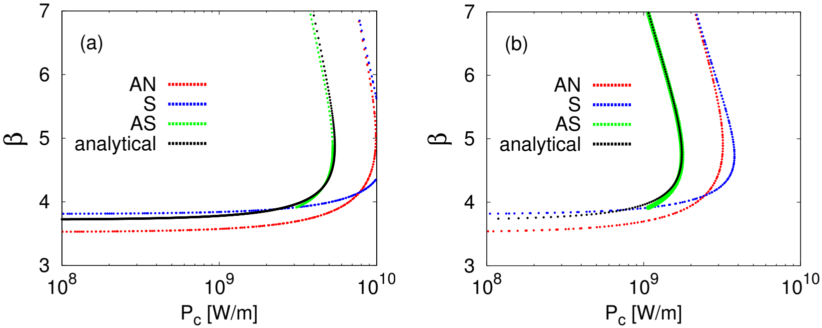
Invariant part of the asymmetric dispersion curves



Dispersion curves for different slot thicknesses as a function of P_c

Invariant part of the asymmetric dispersion curves

- Limiting case: single interface limit between a metal and a nonlinear dielectric



For the Jacobi Elliptic Model — For the Interface Model

For the JEM: $\beta = \sqrt{\epsilon_1 \epsilon_{l,2}(\epsilon_{l,2} - \epsilon_1)/\left[\epsilon_{l,2}^2 - \epsilon_1^2 + n_2 \epsilon_1^2 H_0^2/(2\epsilon_0 c \epsilon_{l,2})\right]}$

Conclusions

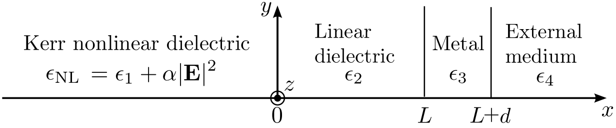
- Two semi-analytical models for **nonlinear slot waveguide** configuration with a finite size nonlinear core
- Prediction of the existence of **higher order modes** in nonlinear slot waveguides
- Study of size and permittivity contrast effects on **bifurcation threshold**
- Structure optimization for **low power nonlinear plasmon–solitons**

W. Walasik, A. Rodriguez, G. Renversez,
Symmetric Plasmonic Slot Waveguides with a Nonlinear Dielectric Core: Bifurcations, Size Effects, and Higher Order Modes
Plasmonics, doi: 10.1007/s11468-014-9773-5, Aug. 2014.

Perspectives

- **Propagation study** using nonlinear FDTD simulations for plasmon–solitons in NSW $\longrightarrow$ stability study
- **Experimental observation** of the predicted waves in collaboration with EVC-ISCR, FEMTO-ST, and CEA-Leti
- New design to lower again bifurcation threshold
- Study of the properties of asymmetric nonlinear slot waveguides

Model formulation



- **Stationary solutions of Maxwell's equations**:
  $$\begin{Bmatrix} \mathbf{E}(x,z,t) \\ \mathbf{H}(x,z,t) \end{Bmatrix} = \begin{Bmatrix} \mathbf{E}_{\rm NL}(x) \\ \mathbf{H}_{\rm NL}(x) \end{Bmatrix} \exp[i(\beta_{\rm NL} k_0 z - \omega t)]$$
  $k_0 = 2\pi/\lambda$, and $\beta_{\rm NL}$ is the effective index of this nonlinear wave

- Metal layer $\longrightarrow$ **TM waves**:
  $\mathbf{E} = [E_x, 0, E_z]$ and $\mathbf{H} = [0, H_y, 0]$

- **Kerr nonlinearity**

- Maxwell's equations + boundary conditions $\longrightarrow$

  Analytical formulas for the nonlinear dispersion relation

Nonlinear dispersion relation (NDR) — semi-infinite nonlinear medium

Boundary conditions $\longrightarrow$ NDR of the 4-layer model

$$\Phi_{+}\left(\widetilde{q}_4+\widetilde{q}_3\right)\exp(2k_0\widetilde{q}_3\epsilon_3 d)+\Phi_{-}\left(\widetilde{q}_4-\widetilde{q}_3\right)=0, \qquad (1)$$

$$\Phi_{\pm}=\left(1\pm\frac{\widetilde{q_{1\mathrm{NL}}}}{\widetilde{q}_3}\right)+\left(\frac{\widetilde{q_{1\mathrm{NL}}}}{\widetilde{q}_2}\pm\frac{\widetilde{q}_2}{\widetilde{q}_3}\right)\tanh(k_0\widetilde{q}_2\epsilon_2 L), \qquad (2)$$

where $\widetilde{q}_j = q(x)/\epsilon(x)$ in the j-th layer,

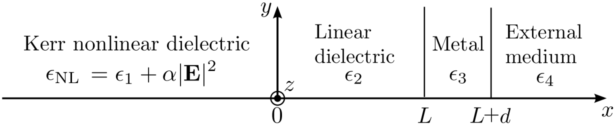
and $\widetilde{q_{1\mathrm{NL}}} = \widetilde{q}_1 \tanh(k_0\widetilde{q}_1\epsilon_1 x_0)$

1. Eq. (1) $\longrightarrow$ allowed β_{NL} of 1D nonlinear problem
2. β_{NL} and $H_{\mathrm{NL},y}(x)$ $\longrightarrow$ electric field $\mathbf{E}_{\mathrm{NL}}(x)$ and power P
3. Limiting cases: $\left|\begin{array}{c}\text{3-layer } (L\to 0) \text{ structure}\\ \text{2-layer } (L,d\to 0) \text{ structure}\\ \text{linear problems } (\alpha\to 0)\end{array}\right|$ $\longrightarrow$ known formulas

Choice of a proper structure

Can we design a **feasible simple** structure supporting **low power plasmon–solitons** that can be **excited directly and recorded?**

4-layer model must be developed



Solution to Maxwell's equations for TM stationary waves using field continuity conditions in 1D structures

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

Comparison of two semi-analytical models and FEM results

Field based model - Ariyasu *et al.*

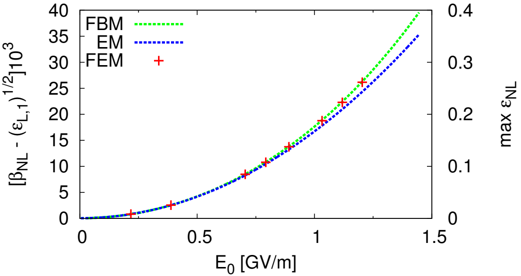
Extension to 4 layers and improvement

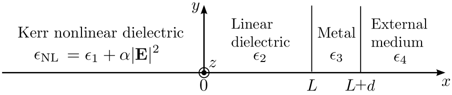
- – Nonlinearity depends only on the transverse electric field component
- – Low nonlinearity $\Delta n \ll n$
- + **Analytical formulas for field shapes and dispersion relation**

Exact model - Yin *et al.*

Extension to 4-layers of:
Appl. Phys. Lett., 94, 221102 (2009)

- + **Exact treatment of Kerr-type nonlinearity**
- + **Analytical dispersion relation**
- – Field shapes calculated numerically





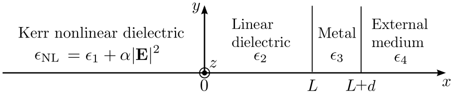
Realistic opto-geometric structure parameters

- Chalcogenide glasses ($\epsilon_1 = 2.47^2$, $n_2 = 10^{-17}$ m^2/W)
- Silica ($\epsilon_2 = 1.443^2$, $L = 15$ nm)
- Gold ($\epsilon_3 = -96$, $d = 40$ nm)
- Air as external medium ($\epsilon_4 = 1$)

Realistic plasmon–soliton parameters $\longrightarrow$ **peak power P $\simeq$ 1.07 GW/cm^2**

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

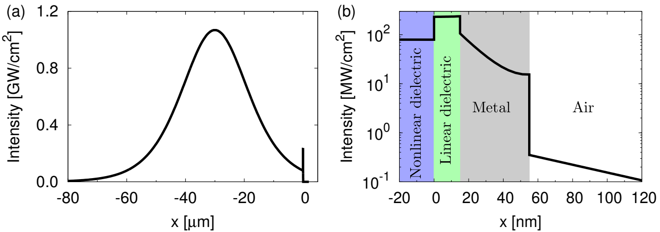
First example of low power plasmon–soliton waves at 1.55 μm



Realistic opto-geometric structure parameters

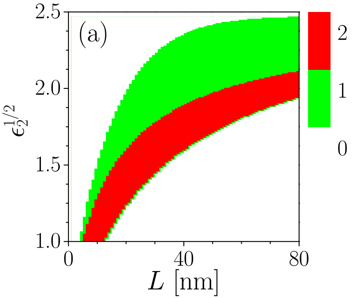
- Chalcogenide glasses ($\epsilon_1 = 2.4707^2$, $n_2 = 10^{-17}$ m^2/W) $\longrightarrow$ high nonlinear coefficient
  - Coated planar chalcogenide waveguides already fabricated (*V. Nazabal et al., Int. J. Appl. Ceram Technol.*, **8**, *2011*)
  - Spatial solitons already observed in planar chalcogenide waveguides (*M. Chauvet et al., Opt. Lett.*, **34**, *2009*)
- Silica ($\epsilon_2 = 1.443^2$, $L = 15$ nm) $\longrightarrow$ well known, good compatibility
- Gold ($\epsilon_3 = -96$, $d = 40$ nm) $\longrightarrow$ low loss, good compatibility
- Air as external medium ($\epsilon_4 = 1$) $\longrightarrow$ Near field optics to record the plasmon part of the field

Realistic soliton parameters $\longrightarrow$ feasible excitation of the plasmon–soliton
peak power P $\simeq$ 1.07 GW/cm^2
(P $\simeq$ 2 GW/cm^2 reported by *M. Chauvet et al., Opt. Lett.,* **34**, *2009*)

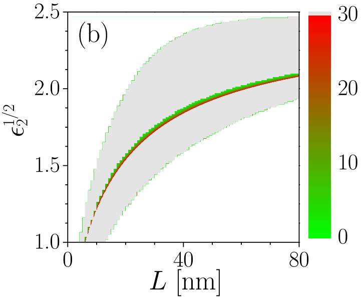


Recordable plasmon field ($E \simeq$ 4.5 MV/m)

Number of solitonics solutions



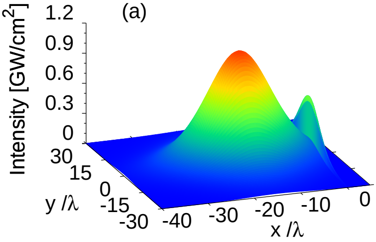
Peak power



Generalization of 1D model

Extension to the 2D case: First approximation

- The same arrangement of materials along the x-axis and suppose that they are infinite along the y-axis.
- **Use of $\mathbf{E}_{\mathrm{NL}}(\mathbf{x})$ from the 1D nonlinear problem to look for nonlinear solutions that are also localized along y-axis in the 2D model**



Different types of solutions

- more pronounced plasmon part
- out-of-phase plasmon–soliton
  C. Milián et al., Opt. Lett., 37(20), 4221 (2012)

Nonlinear dispersion relation (NDR) — finite nonlinear medium

Field shapes in the slot waveguide core

$$H_y(x) = \sqrt{m}\delta_- \, \mathrm{sd}\big[-\sqrt{s/A}\,(x - x_0)|m\big], \quad (3)$$

where

$$\delta_\pm^2 = \big(\sqrt{A^2Q^2 + 4Ac_0} \pm AQ\big)/2, \quad (4)$$

$$x_0 = \sqrt{A/s}\,\mathrm{sd}^{-1}\big[H_y(0)/(\sqrt{m}\delta_-)|m\big]. \quad (5)$$

Here $Q = k_0^2 q_2^2$, $A = (k_0^2 a/2)^{-1}$,
$s = \delta_+^2 + \delta_-^2$, $m = \delta_+^2/s$,
and $\mathrm{sd}[x|m]$ the Jacobi elliptic function.

Boundary conditions ⟶ **NDR of the slot waveguide**

$$-k_0 q_3 \epsilon_{l,2}\sqrt{A/s}\,\mathrm{sd}\big[\sqrt{s/A}\,(d - x_0)|m\big] =$$
$$\epsilon_3\,\mathrm{cd}\big[\sqrt{s/A}\,(d - x_0)|m\big]\,\mathrm{nd}\big[\sqrt{s/A}\,(d - x_0)|m\big], \quad (6)$$