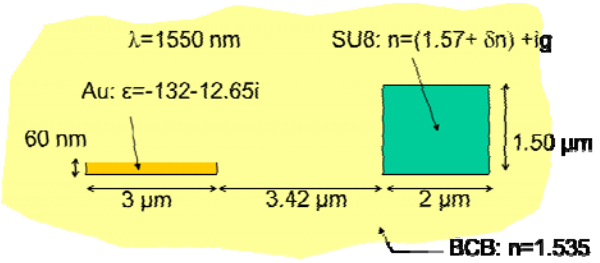
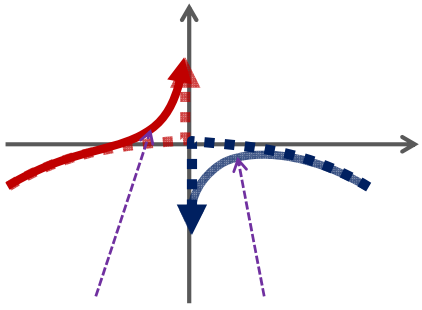
- Lecture 4 :
  - **Healing of the singularity at the exceptional point**
  - Multimode waveguide and transverse PT symmetry

The practical design problem

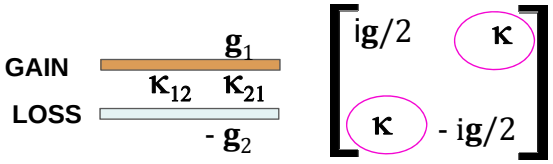
e.g. for PT symmetry & plasmonics, but not only

- Prepare two independent waveguides
- Adjust their optogeometric parameters for equal propagation constants
- Add gain to one of them
- And explore the EP…
  → no good singularity !??
  EP « opens up » !??





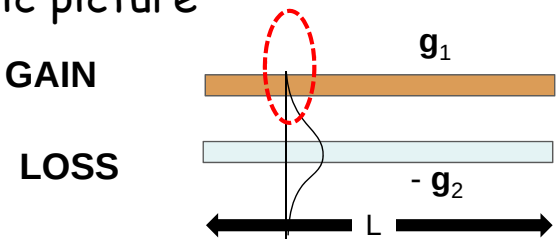
Origin is … complex coupling



- Complex coupling: Coupling depends on gain or loss of adjacent waveguide Looks like a departure from PT-symmetry

$$\kappa_{12}\kappa_{21} = e^{i\varphi}$$

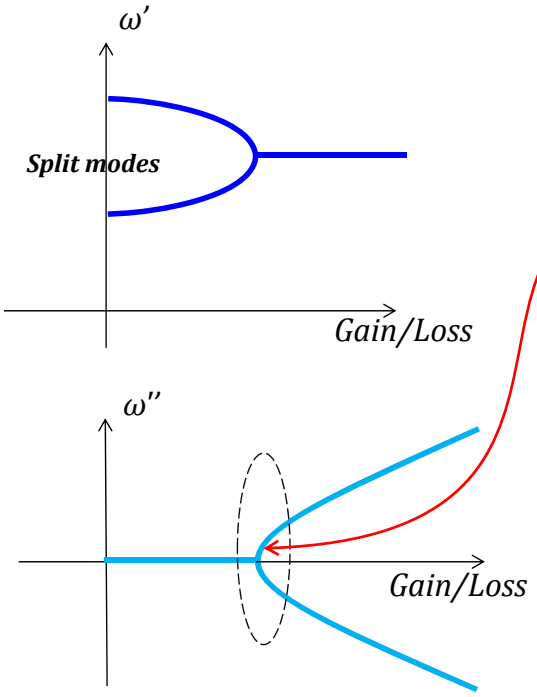
- microscopic picture



coupling constant : κ

→ coupling value κ_{21} also depends on g_1

At stake : the large « differential gain »



« High Differential gain region »

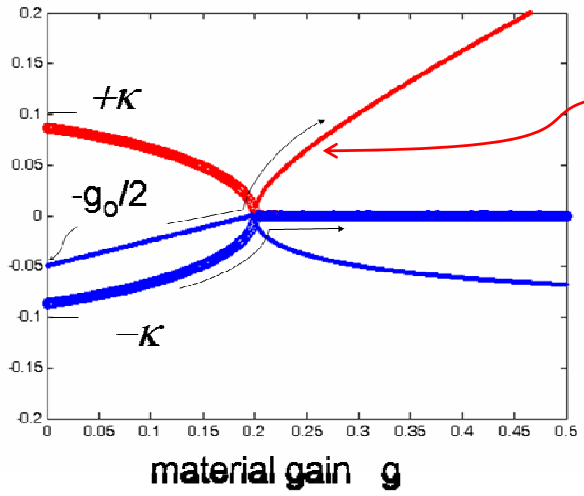
Locally very large $\frac{\partial \omega''}{\partial Gain}$

→ To be converted in large modal gain dependence of Total gain

$$\frac{\partial(\omega'' cL)}{\partial g_{\mathrm{mod}}}$$

→ Depends on length
We try $\kappa L = 1.5$ and $\kappa L = 2.5$

« Fixed losses » (plasmonics) PT sym reminder

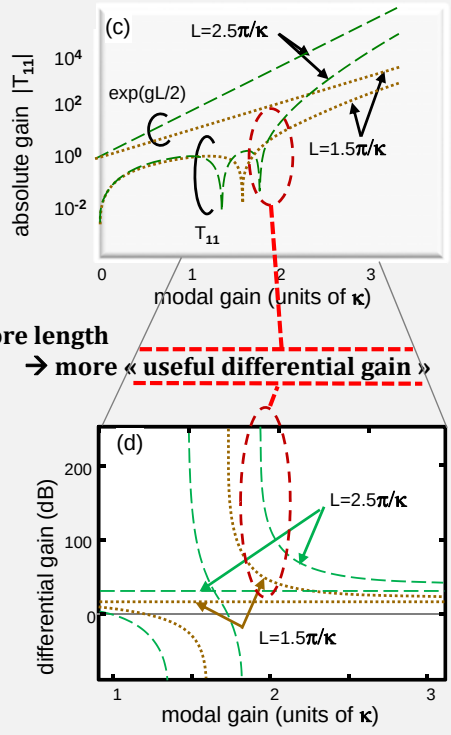


→ « High Differential gain region »

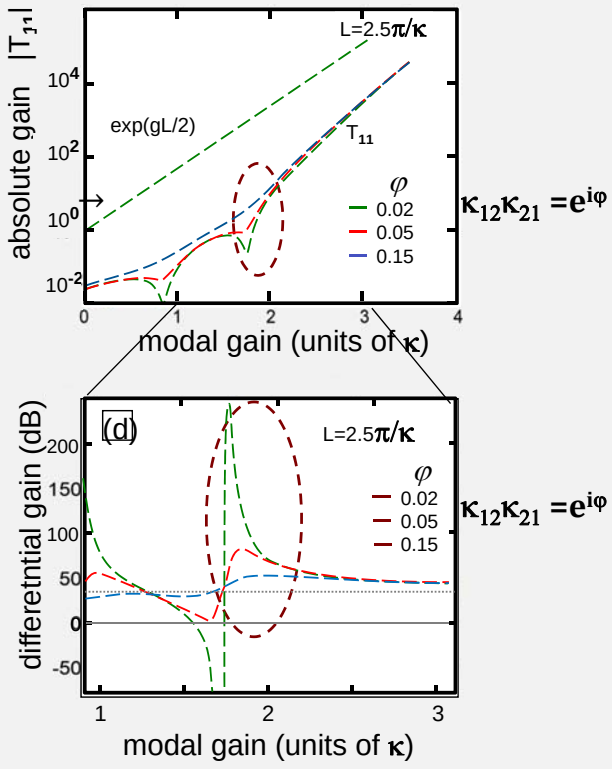
Still exists

« Differential gain » : {Ideal} vs. {Fixed losses and Complex coupling}

Ideal case
(and single wg reference)



Fixed losses & complex coupling (@ κL=2.5)

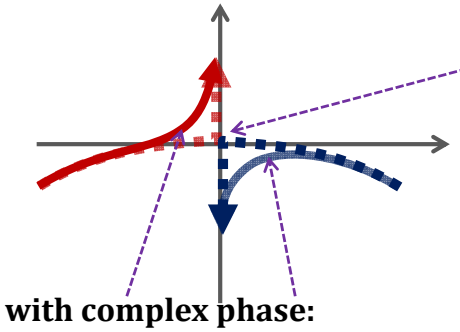


PT -symmetry with plasmonics

- **Exceptional point smoothed when complex phase occurs in coupling** $\kappa_{12}\kappa_{21} = e^{i(\text{phase})}$
- **Small margin to retain high differential gain** $\kappa_{12}\kappa_{21} = e^{i(\text{small phase})}$

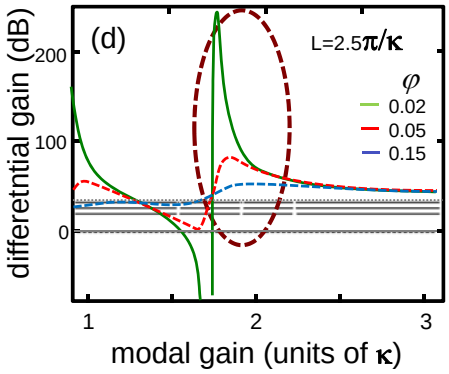
« Active-PT-structures"

Ideal exceptional point

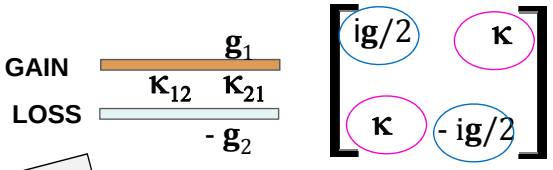


with complex phase:
EP missed
- **smoothed singularity !**

(*actual example below)

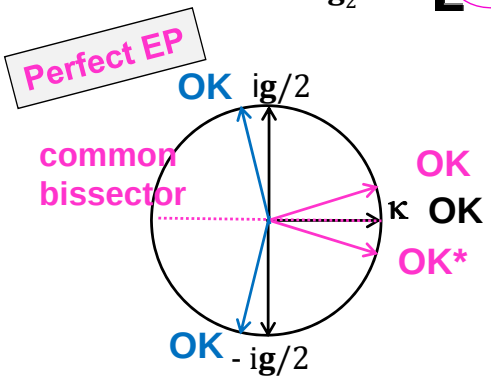


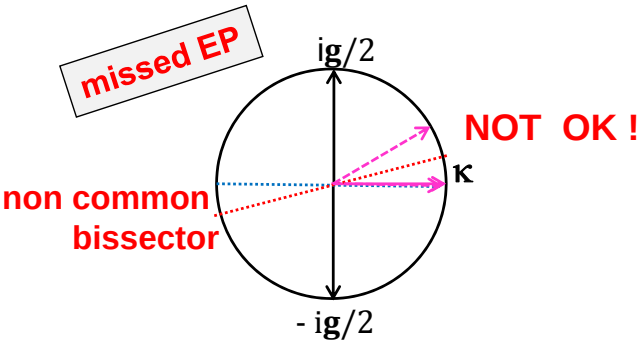
Analysis of matrix coefs (not poles or zeros) in complex plane



→ κ's defined **within a phase** (diffraction's structure factor)

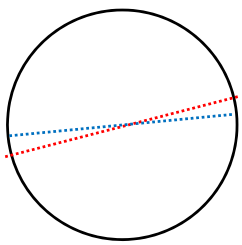
→ **g**'s defined within **common** detuning





$$+\begin{bmatrix} \delta & \\ & \delta \end{bmatrix}$$

So can we force common bissector .... ?

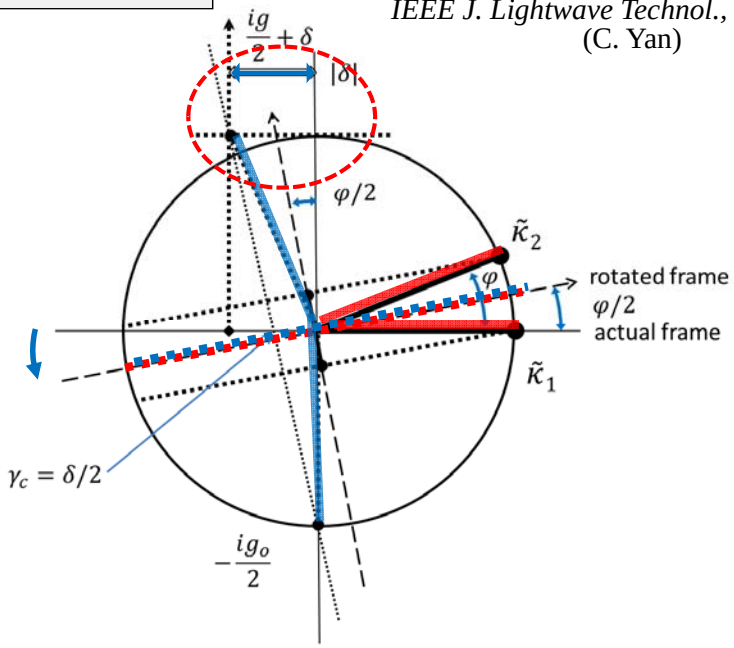


HEALING BY DETUNING

Detuning restores coincidence of bissectors

$$\begin{cases} \delta_{opt} = -2\sqrt{K_{opt}}\sin\left(\frac{\varphi}{2}\right) = (g_0/2)\tan\left(\frac{\varphi}{2}\right) \\ \sqrt{K_{opt}} = \frac{(g_0/2)}{\cos(\varphi/2)} \end{cases}$$

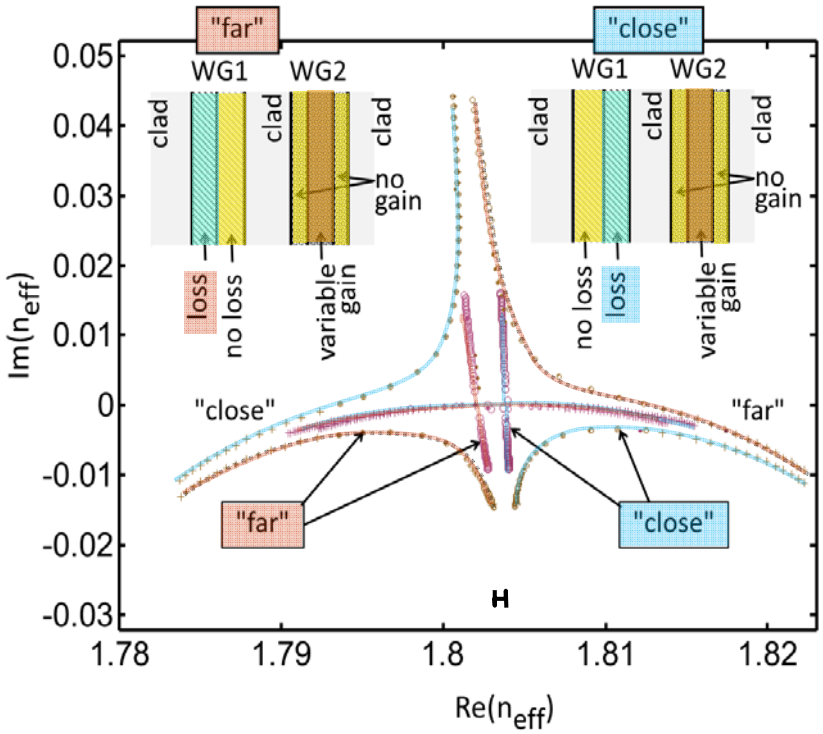
IEEE J. Lightwave Technol., vol. 30, pp. 2675-2683, 2012.
(C. Yan)



$$+\begin{bmatrix} \delta(<0) & \\ & 0 \end{bmatrix}$$

Canonical example

- Strategic placement of loss fraction within loss-wg : *Far* or *Close* from gain wg



« Far" &« Close": opposite φ !

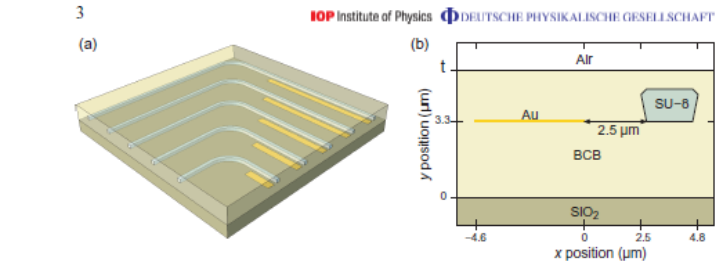
$\rightarrow \delta_{far} = -\delta_{close}$

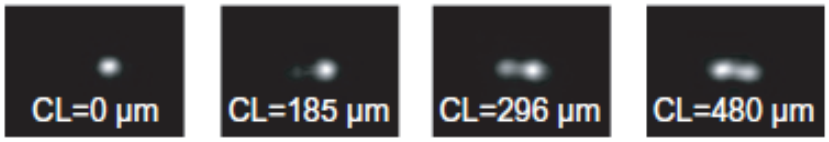
IEEE J. Lightwave Technol., vol. 30, pp. 2675-2683, 2012.

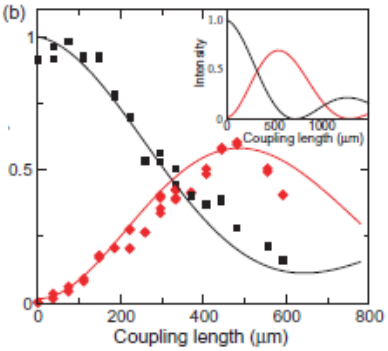
Dielectric and plasmonic waveguides

polymer + Au-LRSPP

New Journal of Physics **11** (2009) 015002 A. Degiron et al. (@ Duke U.)

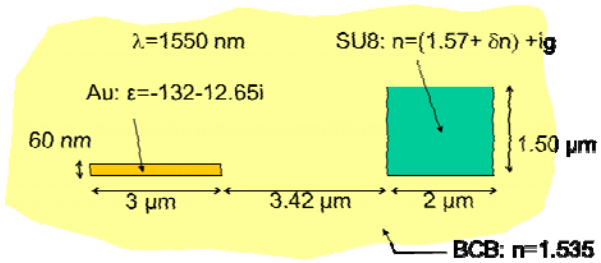




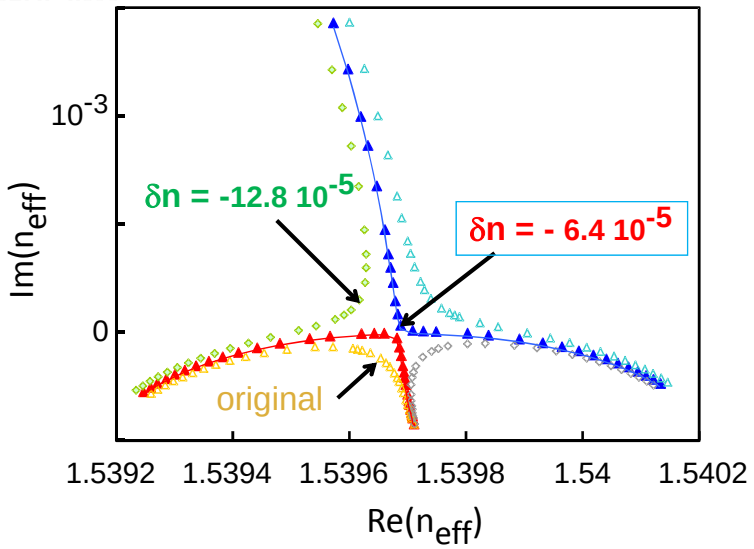


passive regime;
« Switching » based on detuning of Re(ε)

« Healing » in this realistic architecture ?



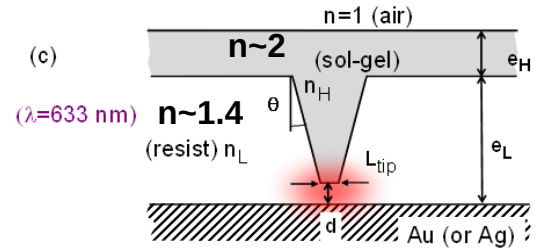
No problem !

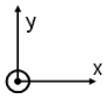


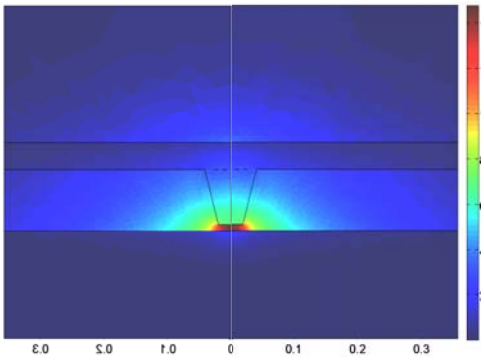
IEEE J. Lightwave Technol., vol. 30, pp. 2675-2683, 2012.

Hybrid plasmonic waveguide : the «PIROW »

PIROW: Plasmonic Inverse-Rib Optical Waveguide

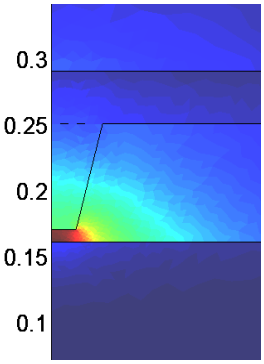




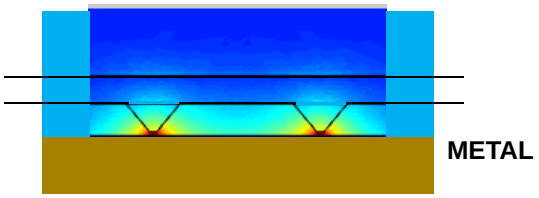


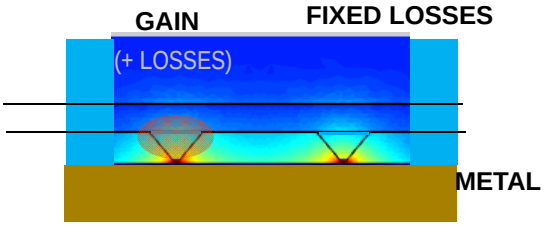


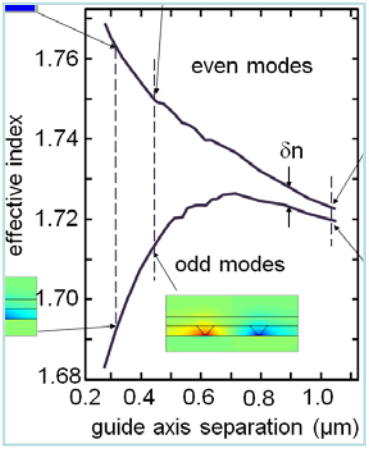
- **JAP 2010, H. Benisty and M. Besbes**
  E-field in 30-50 nm tip...
- **Like Oulton's nanorod/spaser, but deterministic**



PT-symmetry with PIROWs ?







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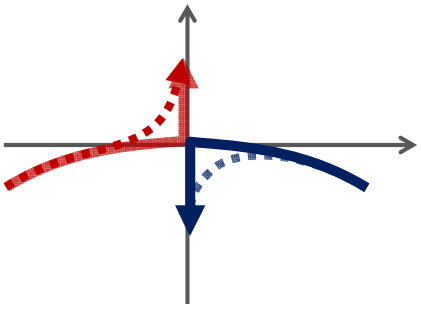
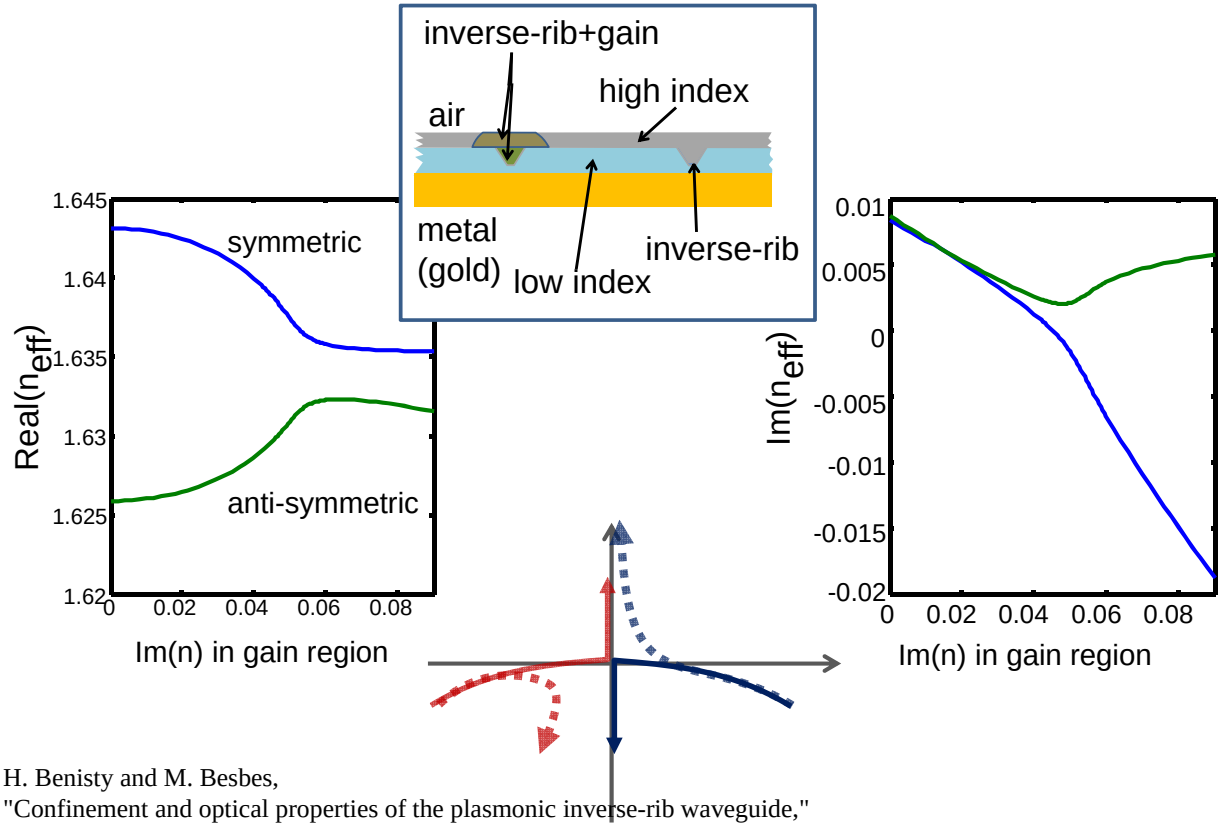


= ?

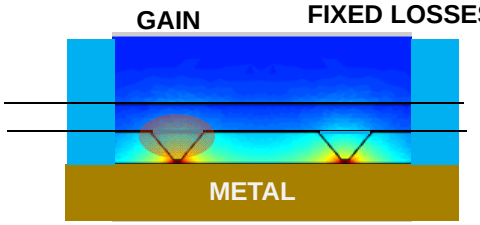
PT-symmetry with PIROWs : EP much avoided



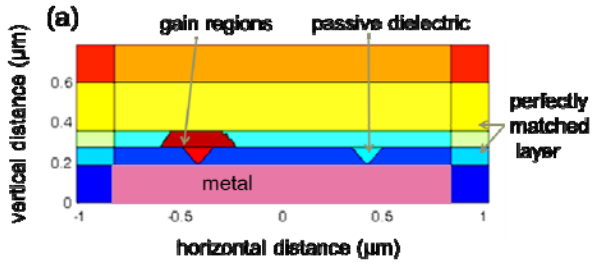
H. Benisty and M. Besbes,
"Confinement and optical properties of the plasmonic inverse-rib waveguide,"
JOSA. B, vol. 29, pp. 818-826, 2012.

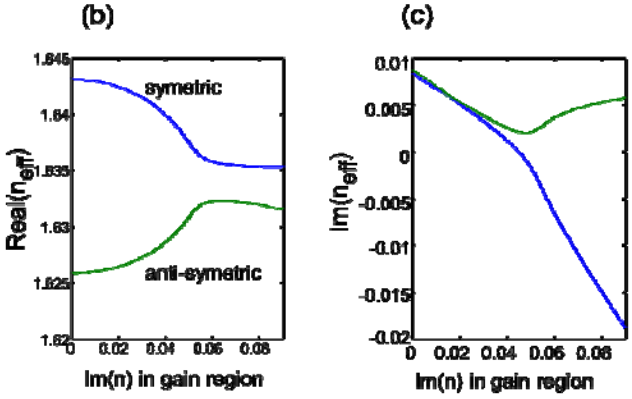
Two coupled «PIROWs »

A normal one and a gain one



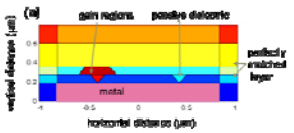
Can we have a good EP ?





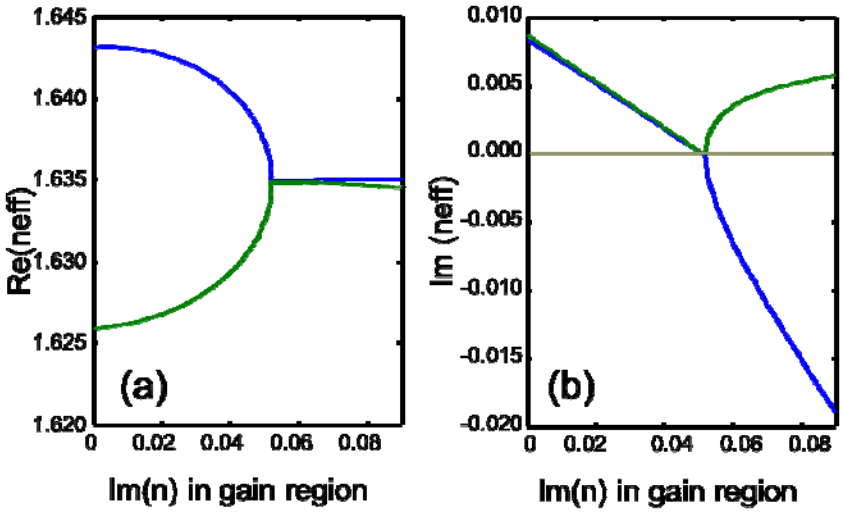
H. Benisty and M. Besbes,
"Confinement and optical properties of the plasmonic inverse-rib waveguide,"
JOSA. B, vol. 29, pp. 818-826, 2012.

« Healing » of Two coupled PIROWs



$$(\tilde{n}_H) = (n_H) + ig(1 + i\alpha)$$

α=-0.174



« Healing » obtained here by changing both Im(ε) and Re(ε) the latter with a small factor...
equivalent to detuning of waveguides with fixed Re(ε) of EP...

Issues on « Healing » in transverse case

« Complex coupling » in transverse case looks like PT broken symmetry in longitudinal (Bragg, DBR) PT symmetry ?

The analogy is tempting since an EP detuned from Bragg frequency then exists

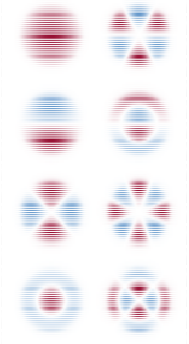
But we rather have a full sequence with « continuous breaking » that we heal, not just exact or broken symmetry states

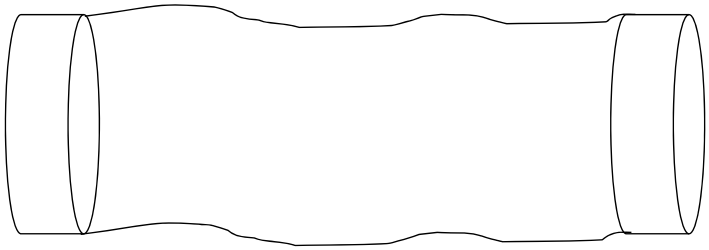
- Course 4 :
  - **Healing of the singularity at the exceptional point**
  - **Multimode waveguide and transverse PT symmetry**

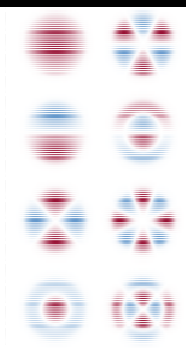
Multimode transmission









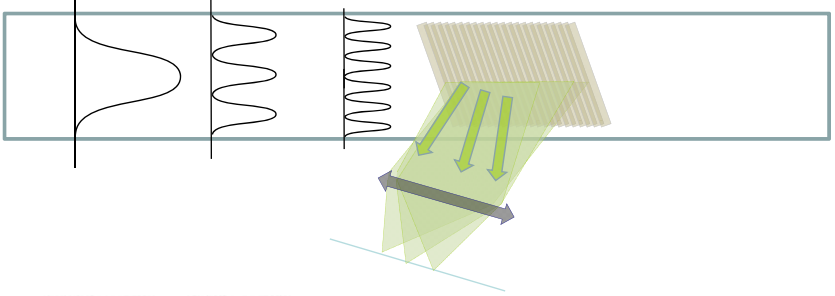


without crosstalk !
→ short
→ datacom

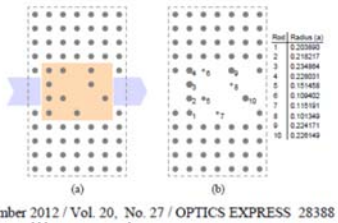
Mode selection recipes ?

m=1,2,3,...

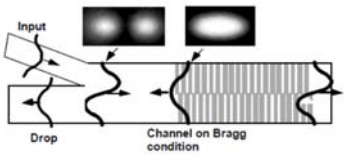
How to select one mode (at given ω)?



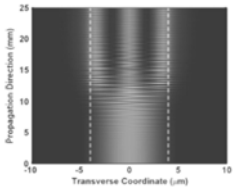
By Grating (+ Lens)?
By MMI variant ?
By grating variants ?



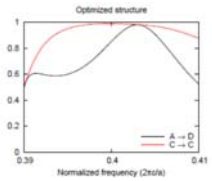
17 December 2012 / Vol. 20, No. 27 / OPTICS EXPRESS 28388
Liu, Miller and Fan,



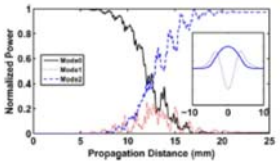
Vol. 13, No. 11 / OPTICS EXPRESS 4182
Castro et al.



S.H. Cheng, (2012) et al.
IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 22, NO. 16, AUGUST 15, 2010

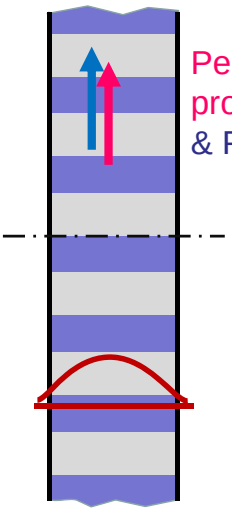


? Confined hologram ?



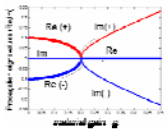
Three flavours of PT-symmetry

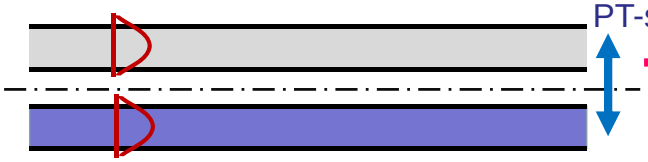
Kulishov
« pseudo -nonreciprocal… »



Periodicity
propagation
& PT-symmetry

Simple case

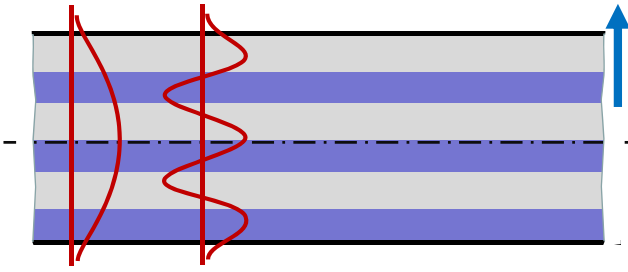




PT-symmetry

propagation

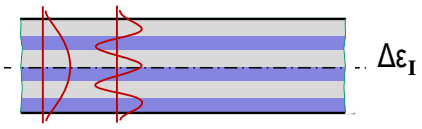
New case

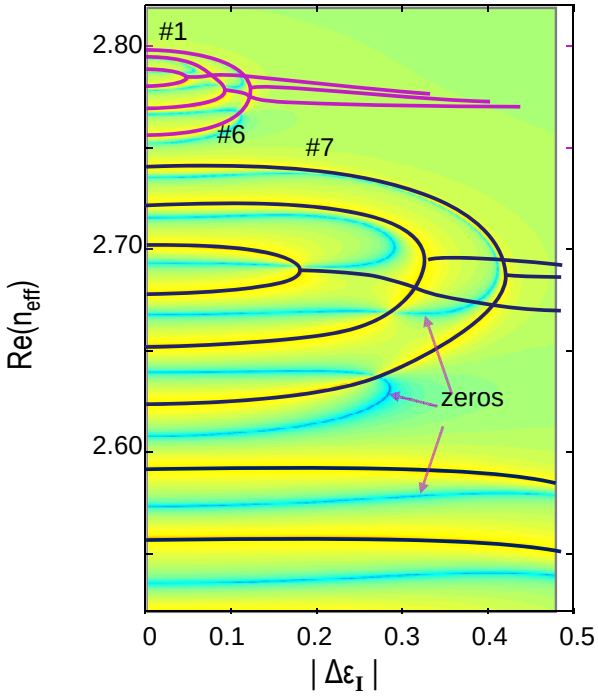


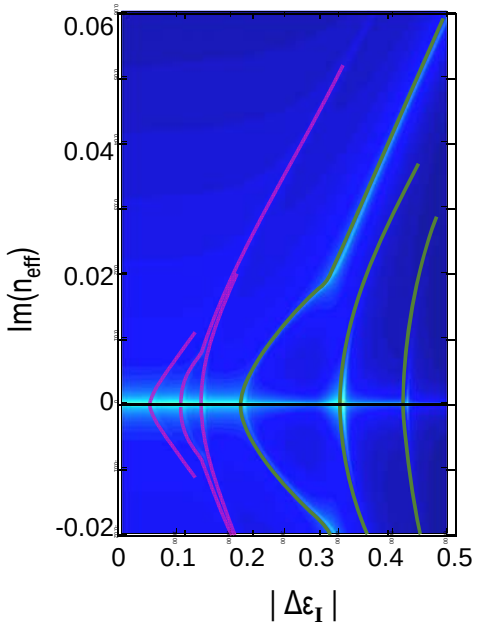
Periodicity
(bounded)
& PT-symmetry

propagation

Modes by 1D TMM calculation







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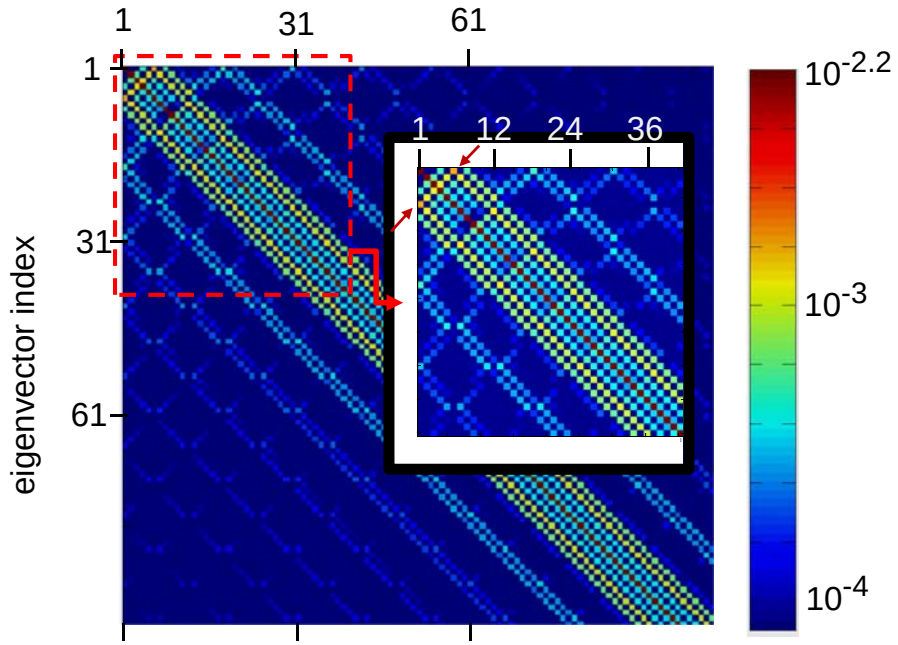
$|\langle\psi|\Delta\varepsilon_I|\psi\rangle|^2$

2nd order perturbation theory explains mode clusters



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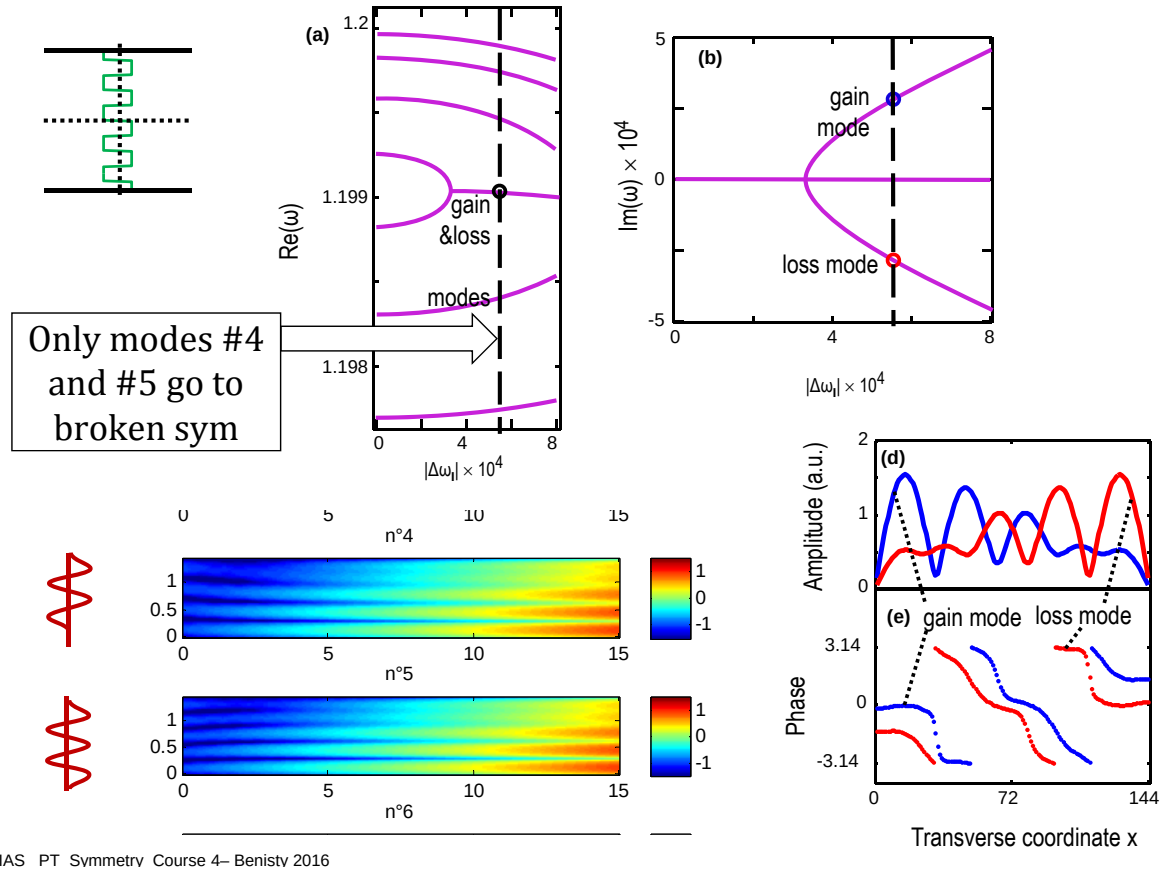
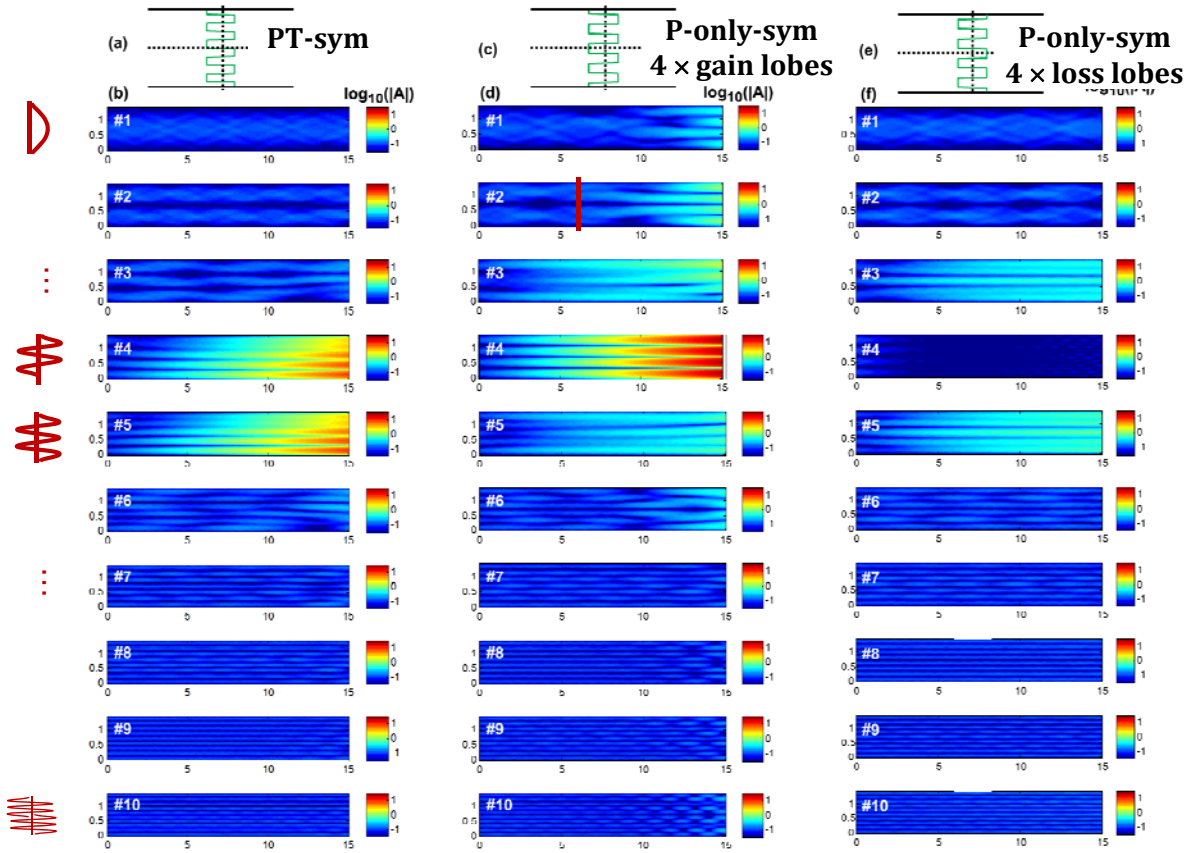
9 stripes gain/loss pattern



Field evolution with PT-sym/just-sym stripes



Work not (not yet) in progress

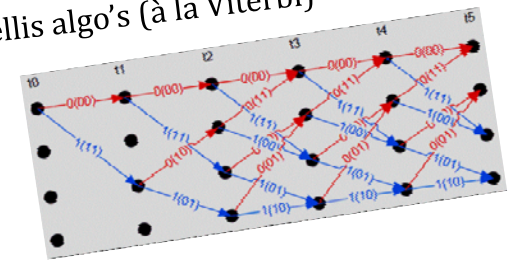


Entropy

Optimizing switch operations with minimal gain

Multimode fibers

Symmetry-Breaking and Trellis algo's (à la Viterbi)



Astigmatism/Peterman factor

$$\frac{(W_{spont})\ \text{“improper”}}{(W_{spont})\ \text{index guided}} = \sqrt{1+\chi^2}.$$

Yariv & Margalit 1982

CONCLUSION

⇨ $\mathcal{PT}$ **–symmetry**

- « Hologram » of gain and losses
- Many Emerging features @ Exceptional Point.

⇨**Several avenues for worthwile photonic devices**

- Plasmonics → Replace Electro-optics by **Gain&Loss**
  Good switching conditions exist below Sym.-Breaking point.
- Transverse mode management