PT-symmetric photonics: hidden reefs on the route toward practical applications

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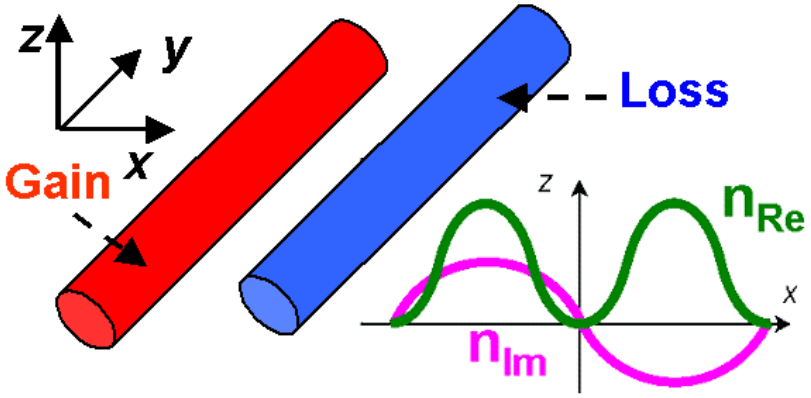
Outline

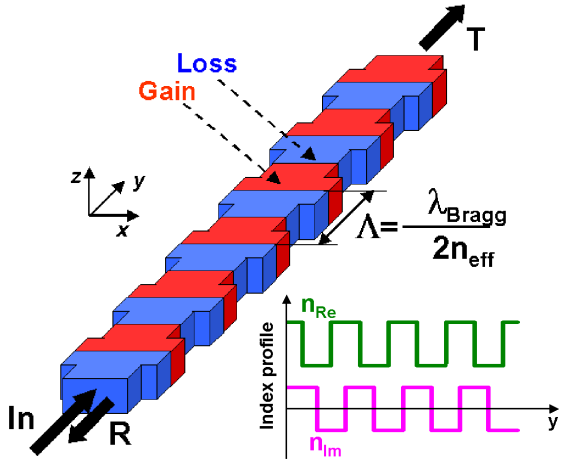
- **Using PT-symmetry for switching applications**
- **Locally PT-symmetric Bragg gratings**
- **PT-symmetry: a new platform for active optical devices**
- **Summary and conclusions**

Parity-Time symmetry in photonics functionalities

PT-symmetric directional coupler



PT-symmetric Bragg grating



PT-symmetry genuine feature:

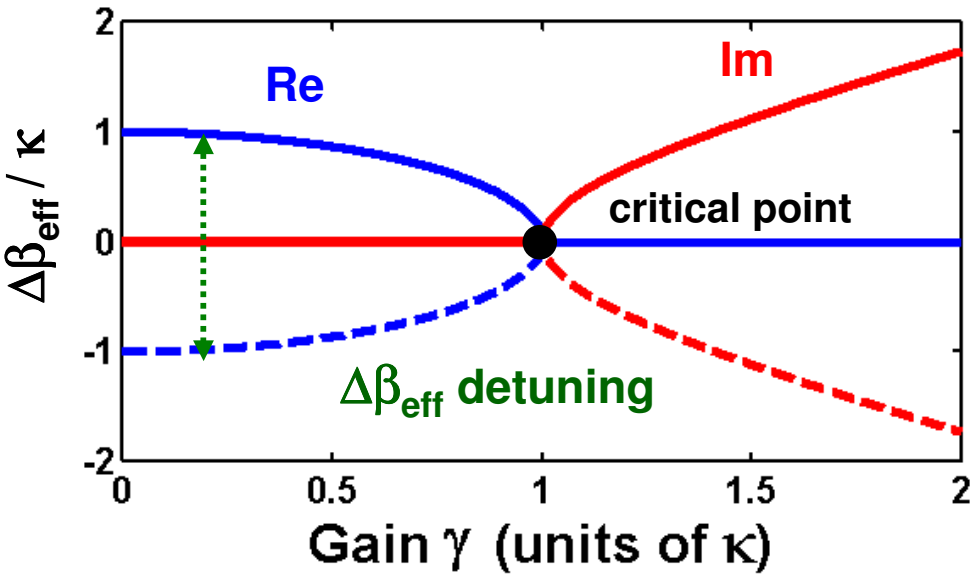
- **Functional role of losses**

Gain-loss modulated PT-symmetric structures functionalities :

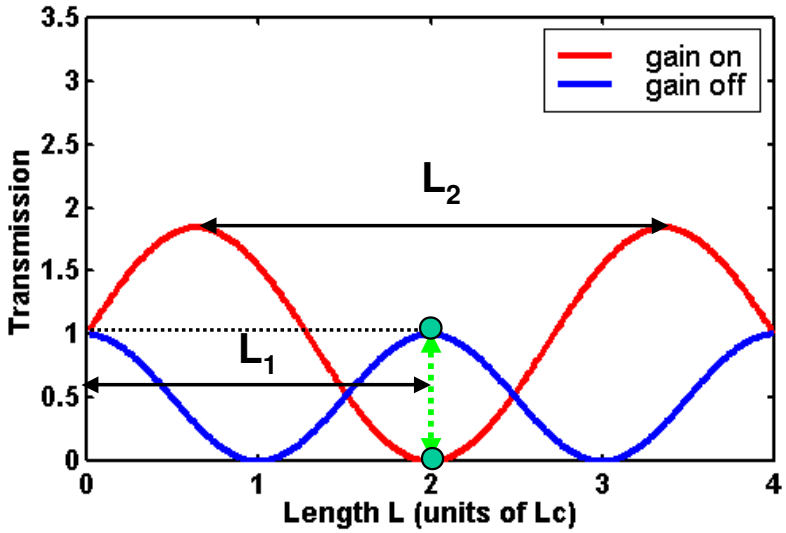
- **Switching and tunability**
- **Spatial (modal) non-reciprocity**
- **Active tailoring of the grating spectral response and dispersion**

Gain-loss modulation electro-optical switching

PT coupled WGs detuning variation



Transmission variation



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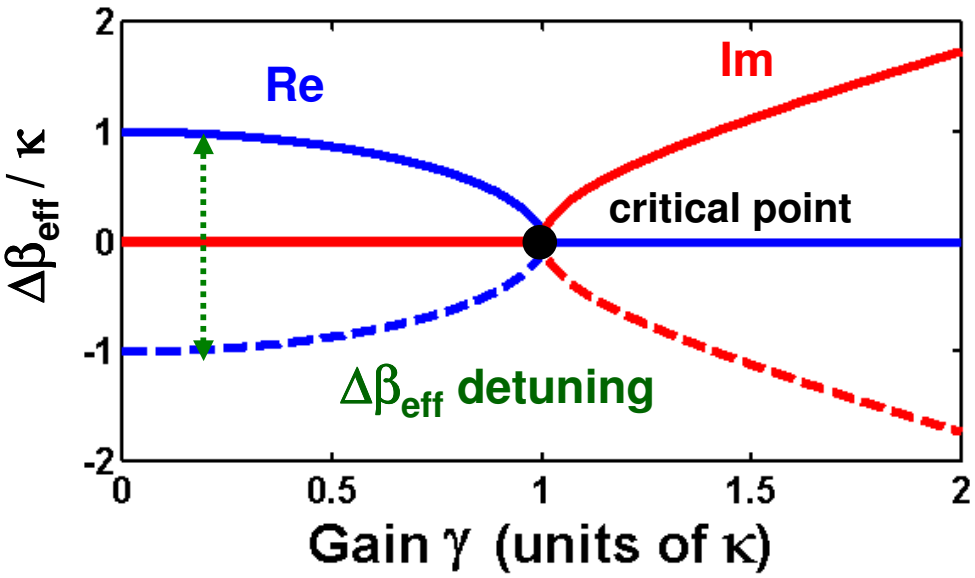

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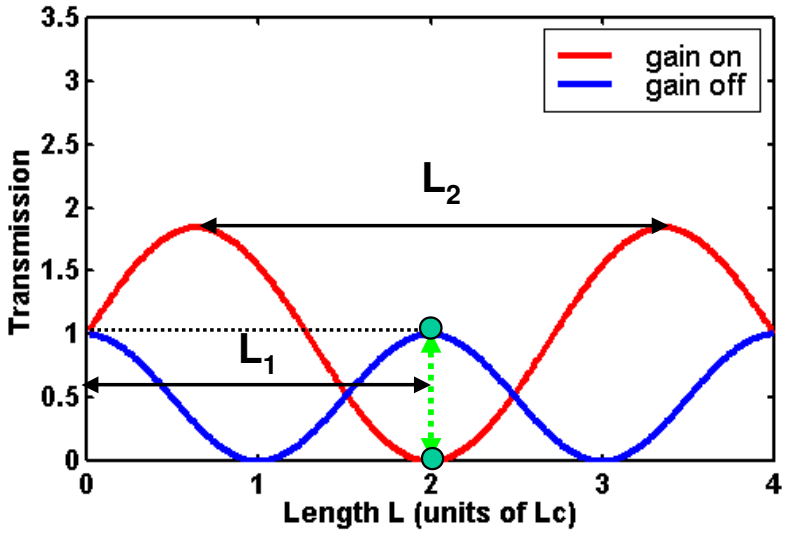
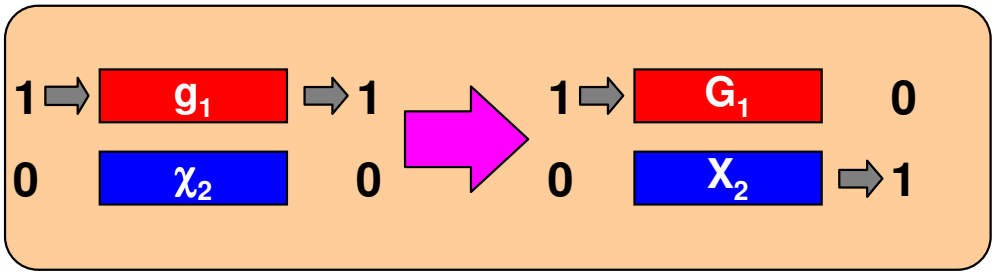
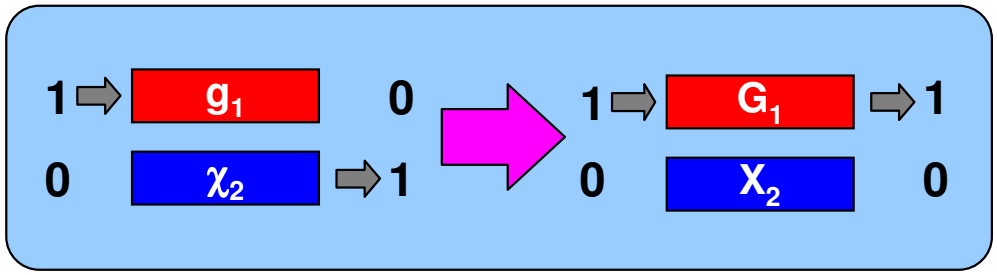


Binary switching operation

Bar -> Cross: T_{11}=1, T_{12}=0 -> T_{11}=0, T_{12}=1

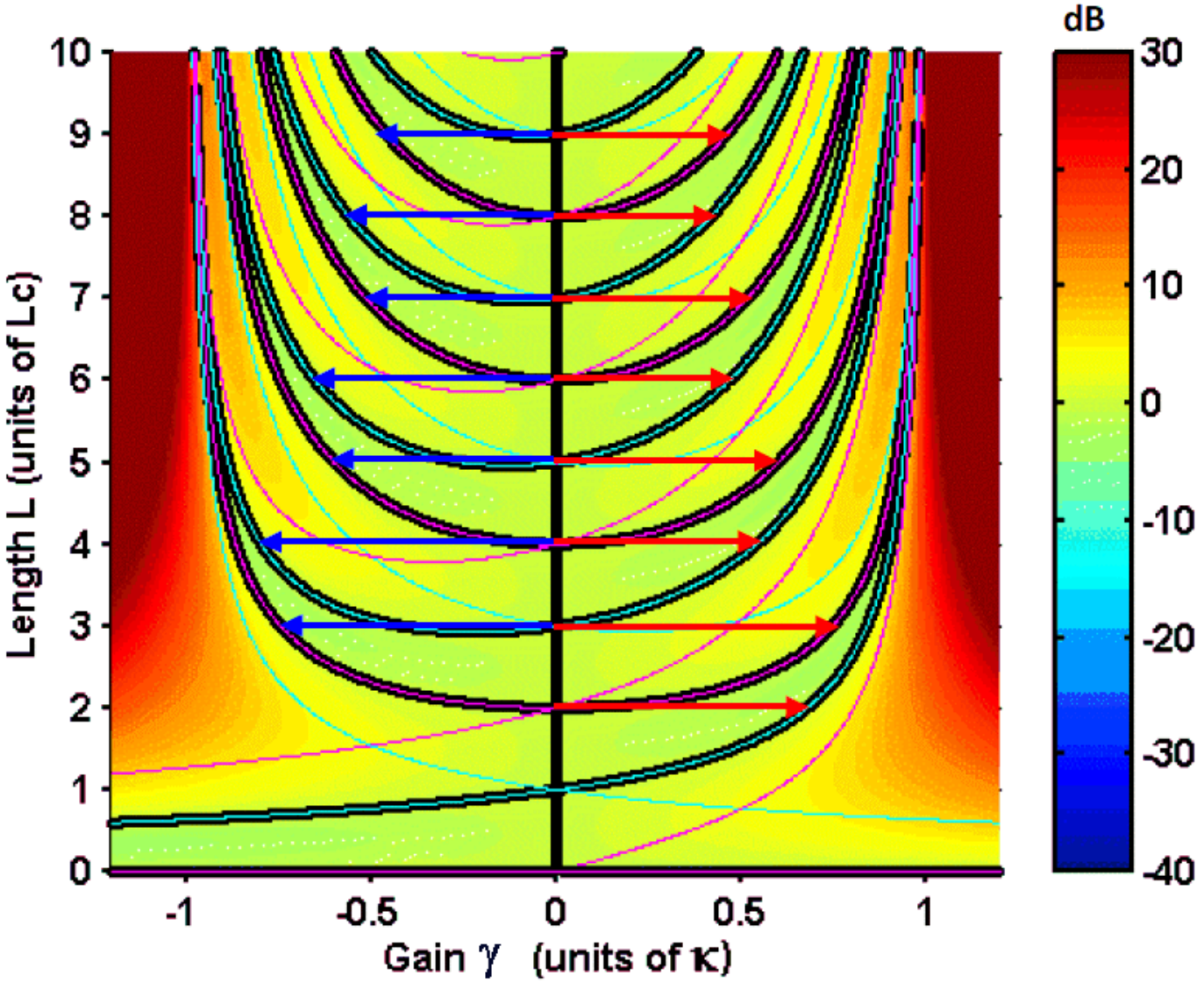


Cross -> Bar: T_{11}=1, T_{12}=0 -> T_{11}=0, T_{12}=1



Can we obtain binary switching in a non conservative layout?

Binary switching in a uniform PT-symmetric coupler



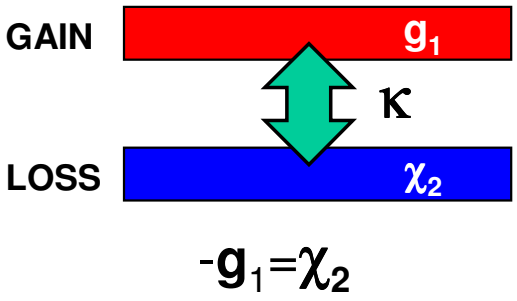
T_{11}= 1 (bar)

T_{12}= 0 (cross)

$T_{11} + T_{12}$= 1 (energy conservative states)

What is the minimal gain × length product for switching?

Control parameter: The imaginary detuning $-\Delta_{im}$



$-g_1=\chi_2$

Detuning

$$\delta=\frac{\beta_1+ig_1-(\beta_2-i\chi_2)}{2}=\frac{\beta_1-\beta_2}{2}+i\Delta_{\text{im}}$$

$$\Delta_{\text{im}}=\frac{g_1+\chi_2}{2}$$

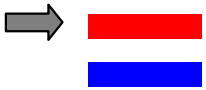
Δ_{im}= **imaginary detuning !**

A. Lupu, H. Benisty. et al, Opt. Exp. 2013

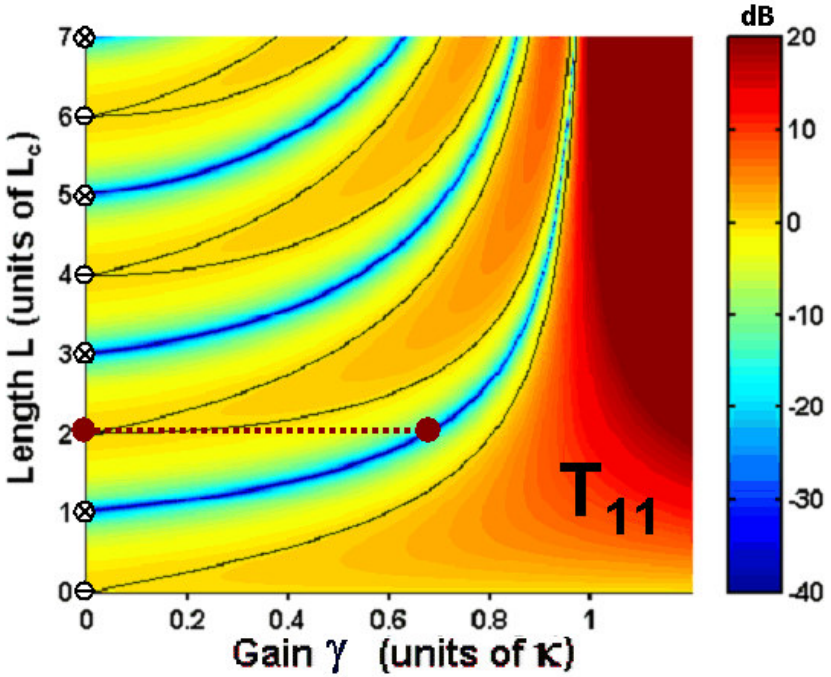
CMT solution

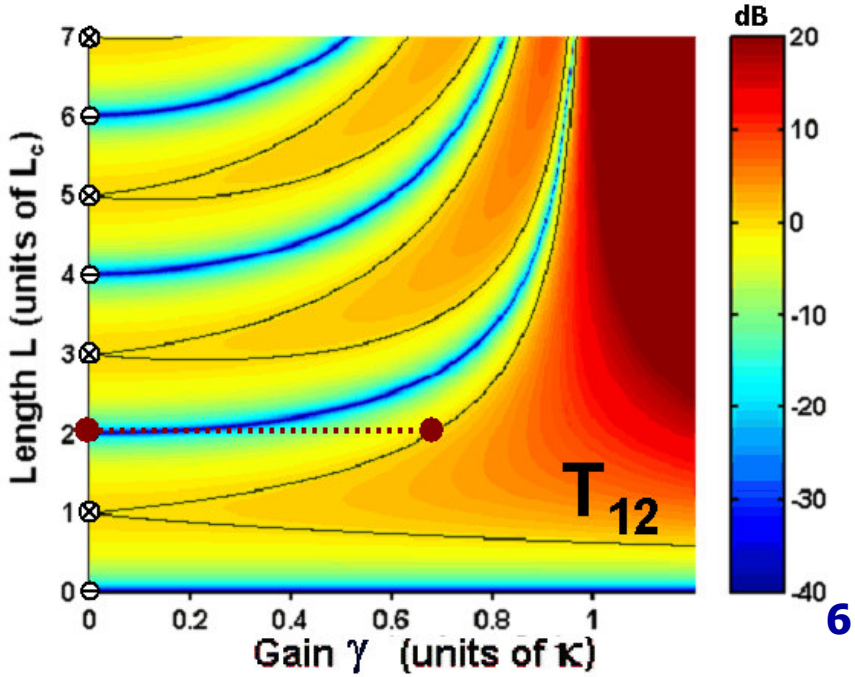
$$\tan\left(\sqrt{\pi^2-\Delta_{\text{im}}^2L^2}\right)=-\sqrt{\frac{\pi^2}{\Delta_{\text{im}}^2L^2}-1}$$

$$\Delta_{\text{im}}L=\frac{g_1+\chi_2}{2}2L_c\approx 0.67\pi \quad \Leftrightarrow \quad 18.6\text{dB}$$



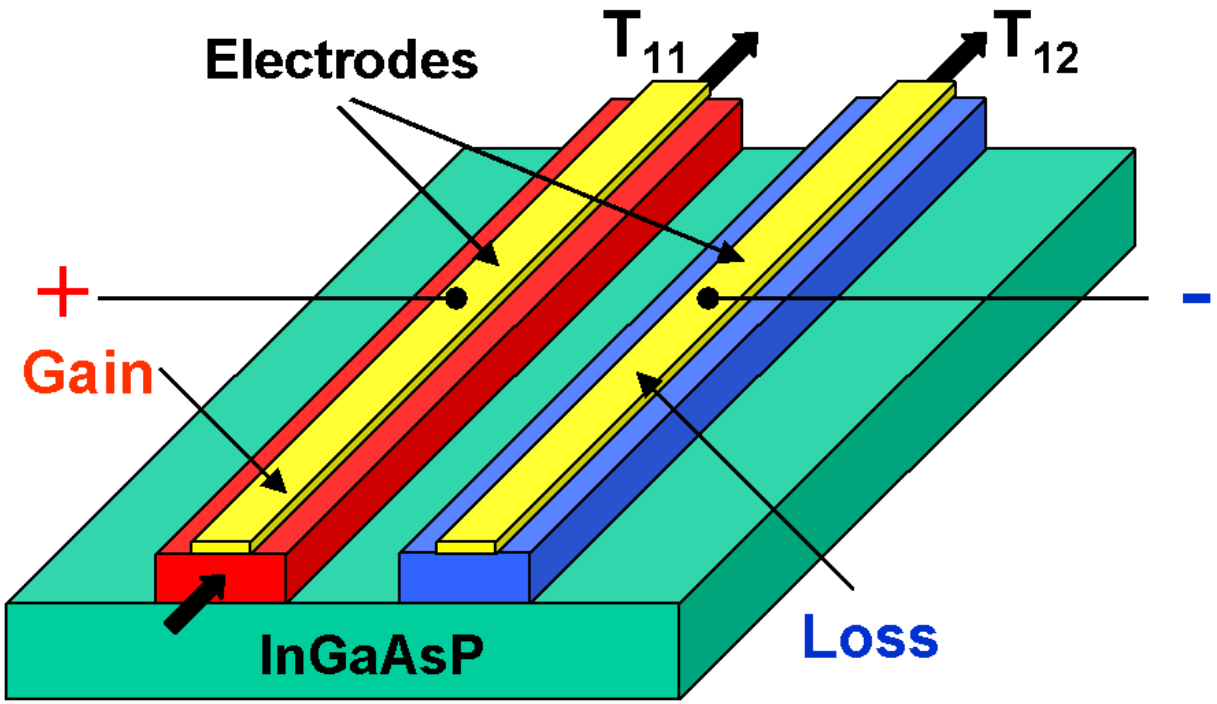
$L=2L_c$



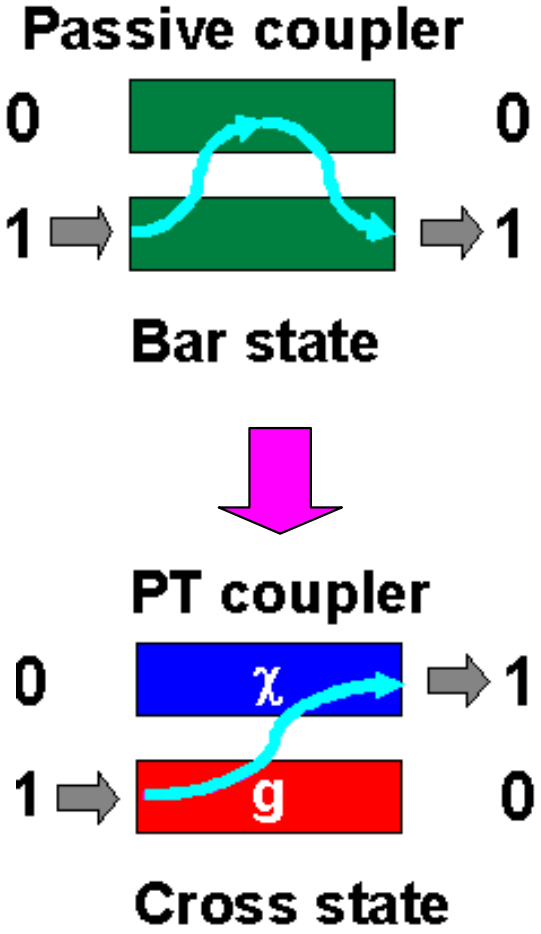


PT-symmetric switch using gain-loss modulation

III-V technology electro-optical switch



Operation principle

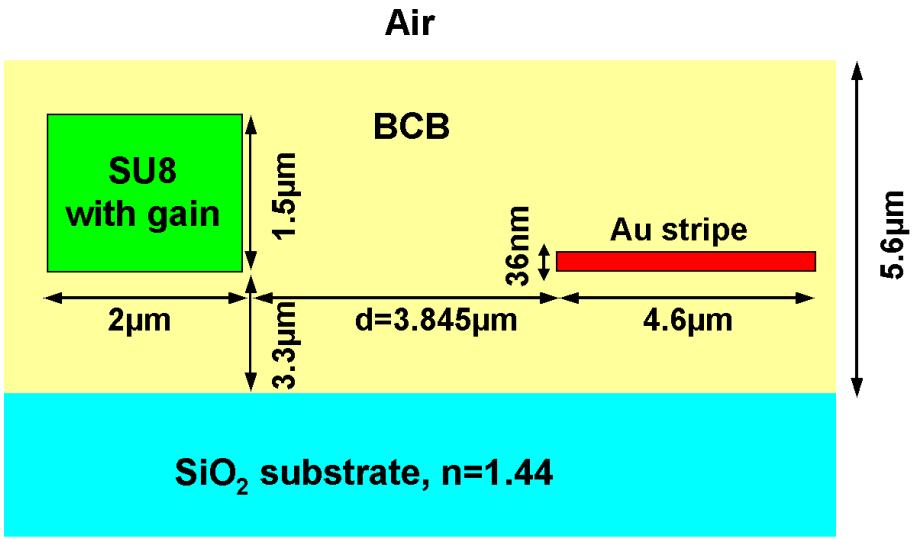


Advantages :

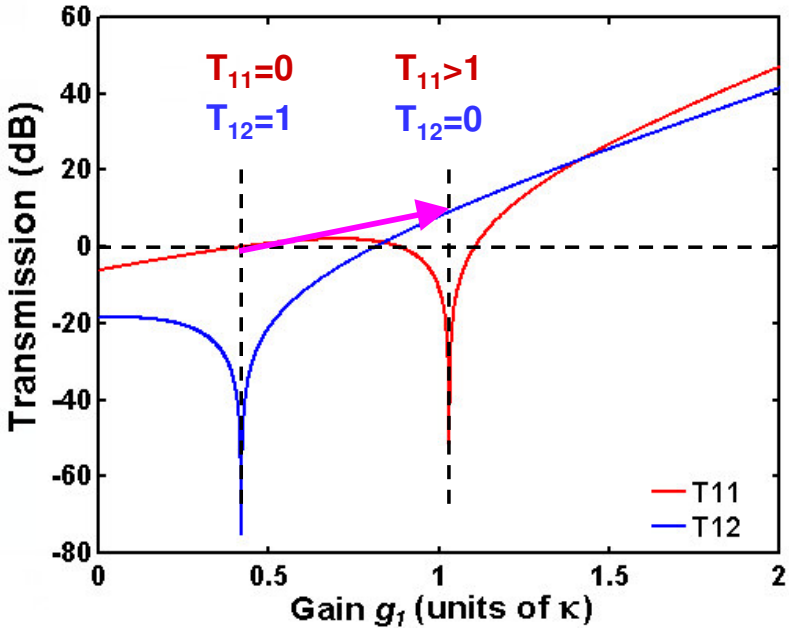
- Compatibility with III-V laser sources fabrication technology
- Emulation of electro-refractive index variation in plasmonics and metameterials

Impact of material limitations: PTSS with fixed losses

Hybrid plasmonic/dielectric PTSS design



Fixed losses switching operation



Impact of material limitations: PTSS with fixed losses

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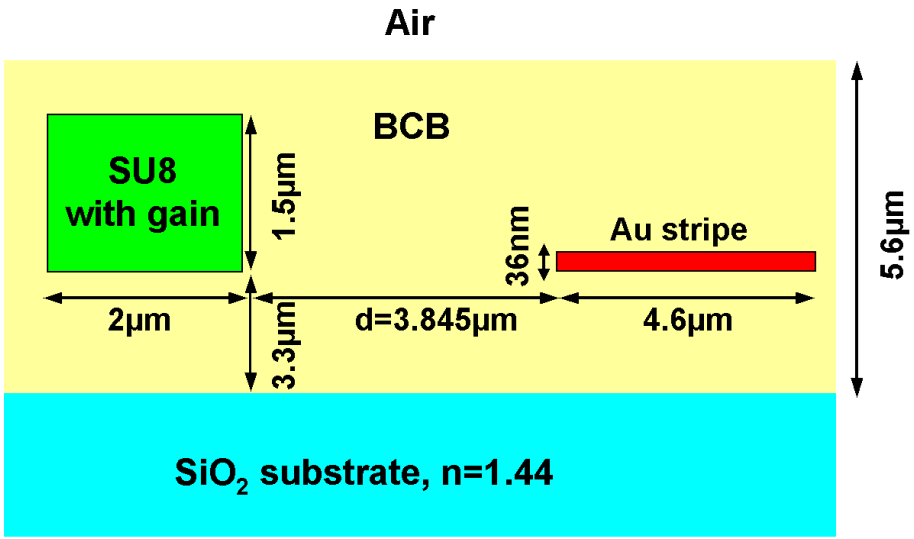

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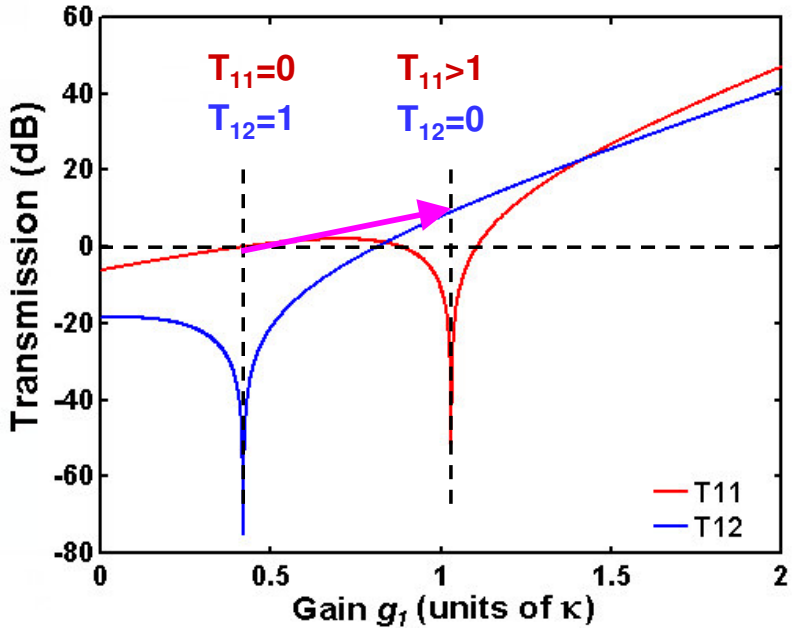


Coupled modes equations

$$i\frac{\partial}{\partial z}\psi = \begin{pmatrix} \beta + ig & \kappa \\ \kappa & \beta - i\chi \end{pmatrix}\psi$$

gain losses

Transfer matrix

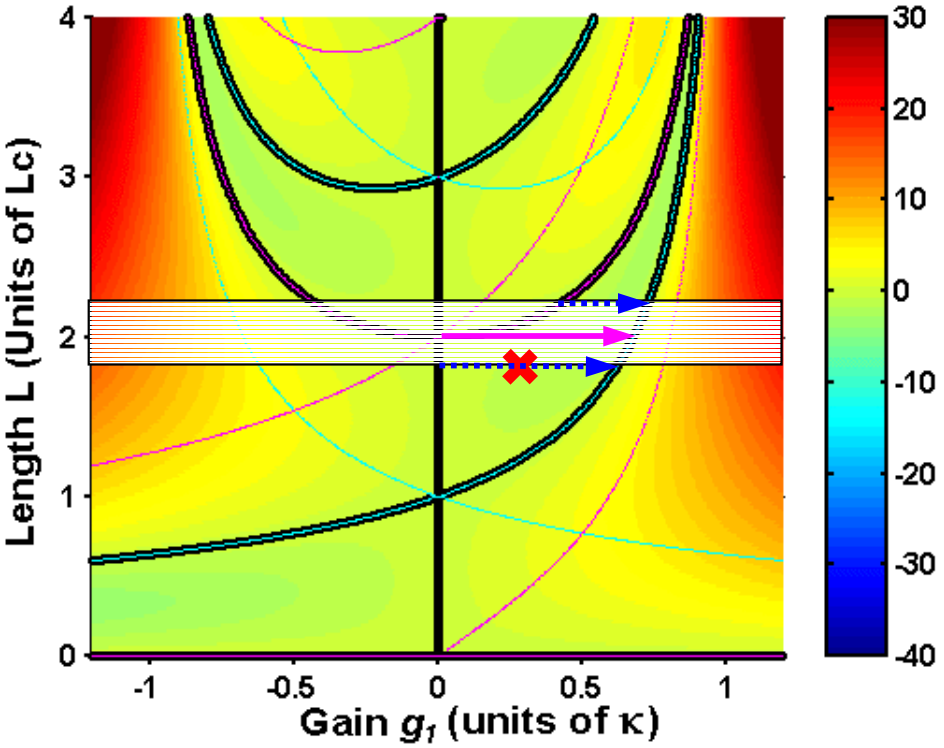
$$M(z) = \begin{pmatrix} \cos(\Omega z) - \frac{i\delta}{\Omega}\sin(\Omega z) & \frac{i\kappa}{\Omega}\sin(\Omega z) \\ \frac{i\kappa}{\Omega}\sin(\Omega z) & \cos(\Omega z) + \frac{i\delta}{\Omega}\sin(\Omega z) \end{pmatrix} \exp\left(\frac{g_1 - \chi_2}{2} z\right)$$

Gauge transformation

Gauge transformation doesn't affect the zeros of PTSS !

Impact of technological imperfections:
deviation from the nominal coupling length

Nominal coupling length $L=2L_c$



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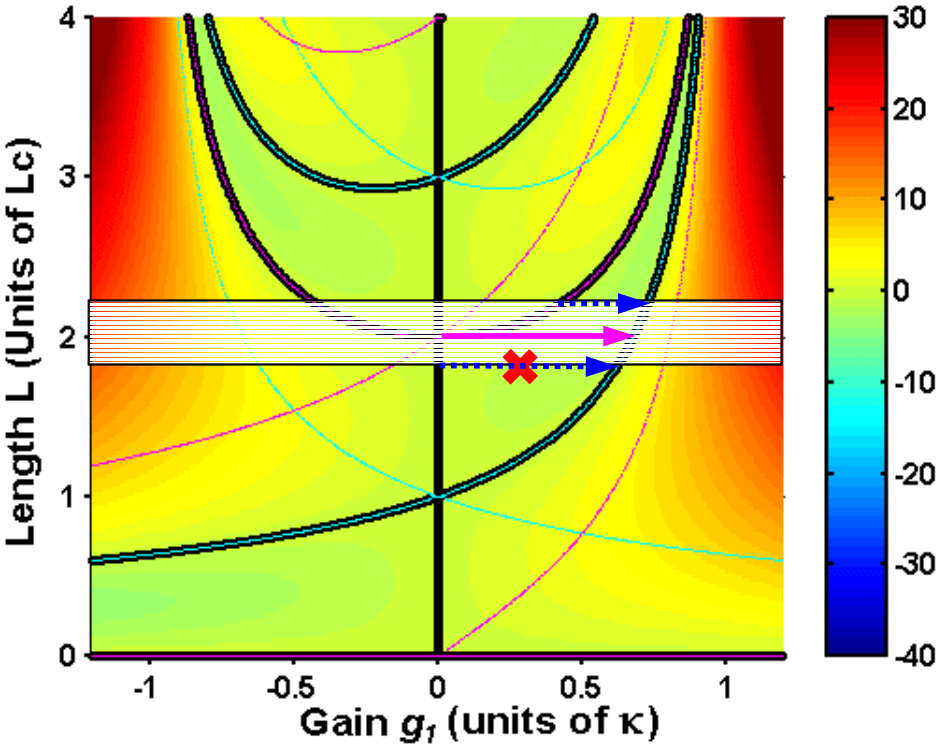
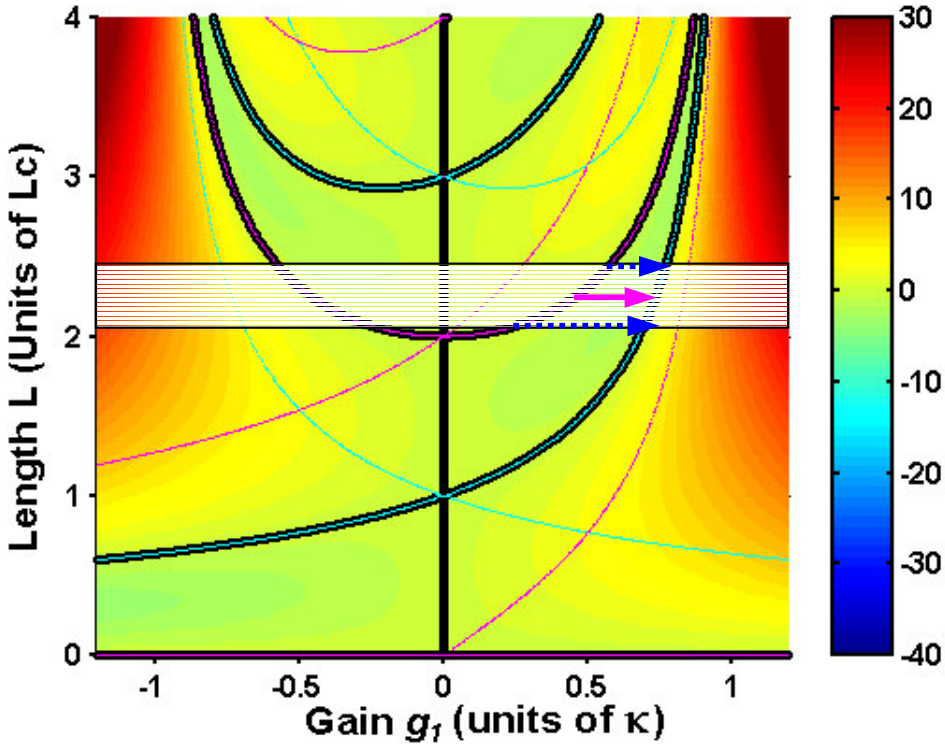
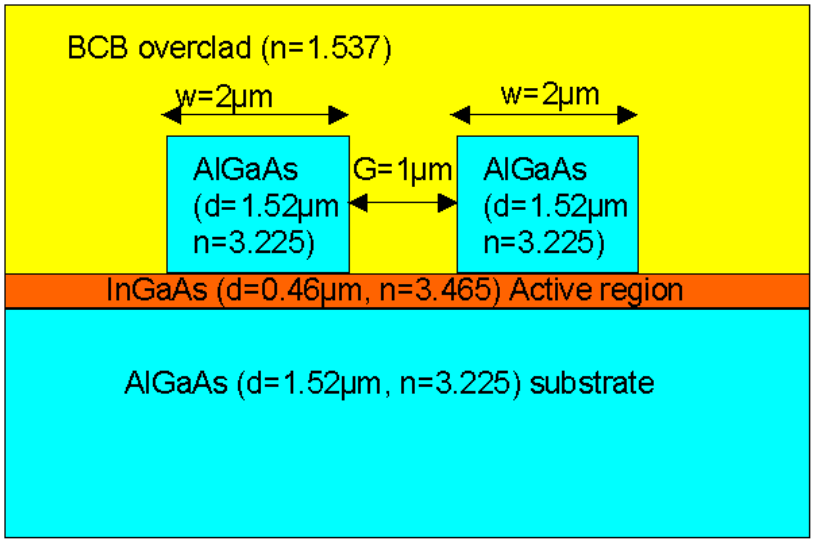


Optimal coupling length $L>2L_c$

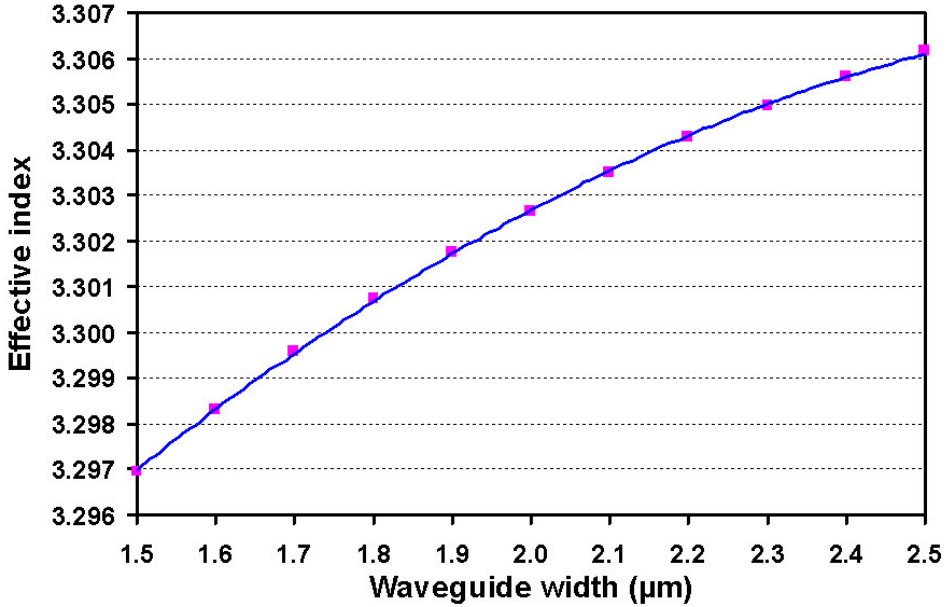


Impact of technological imperfections:
mismatch of PT-symmetric coupler effective index

PTSS design



Effective index variation



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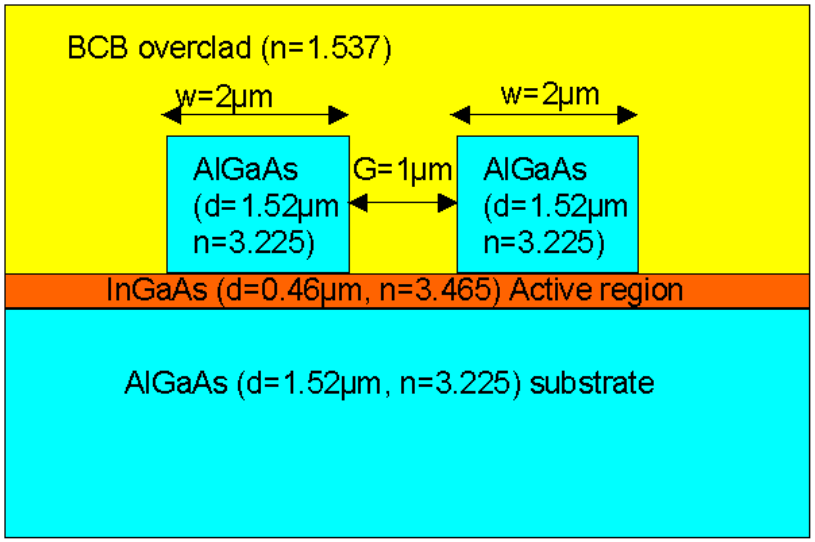

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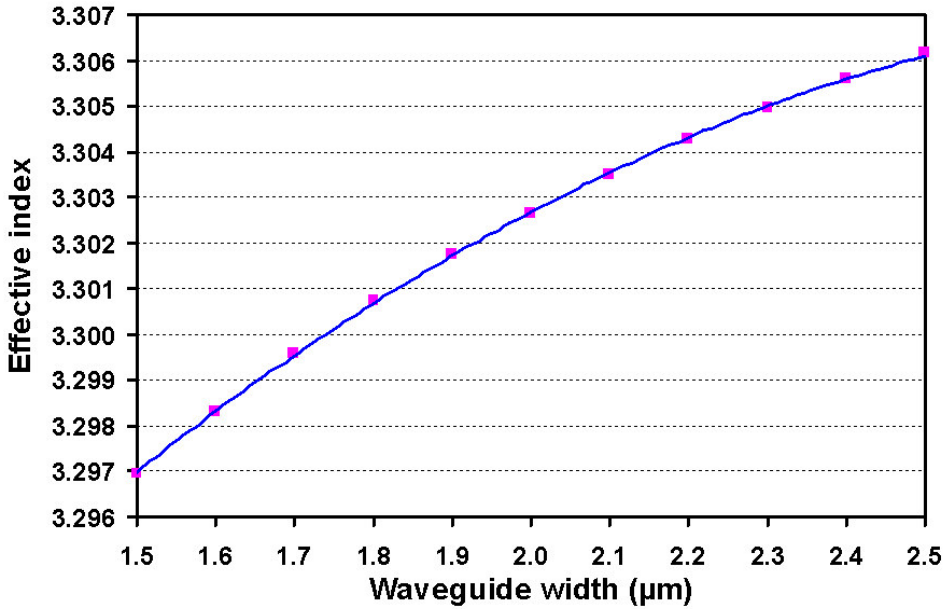
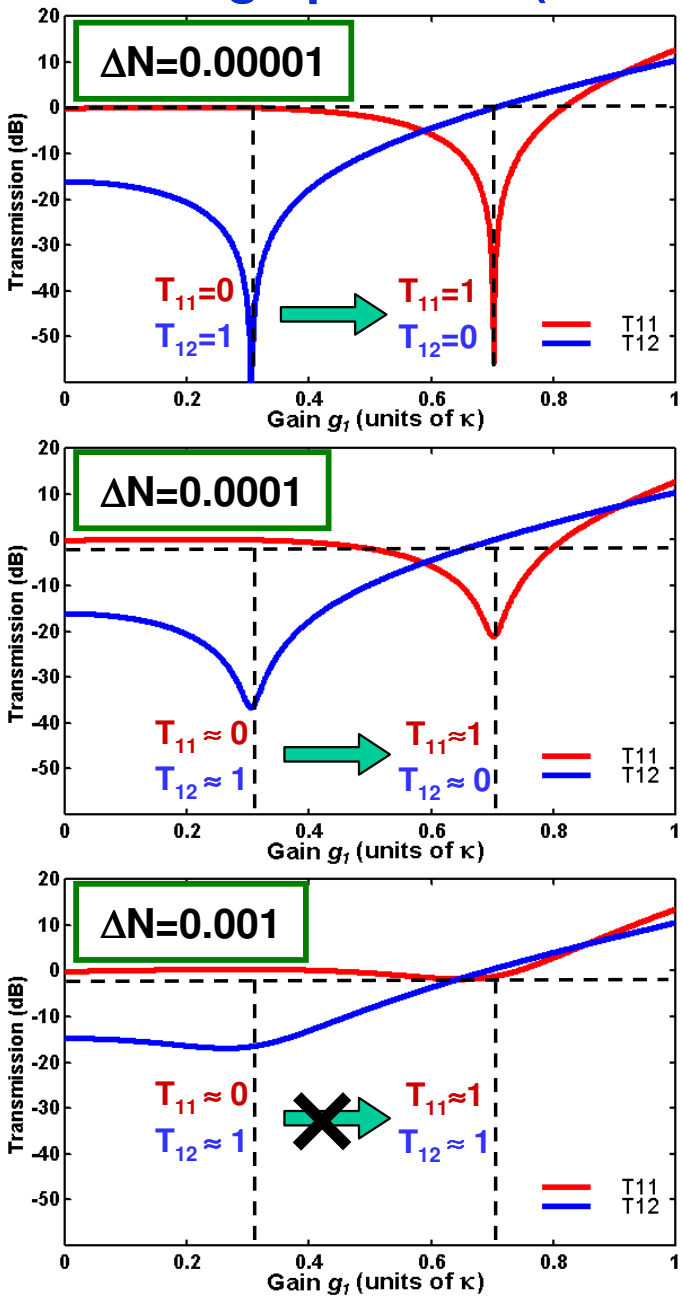
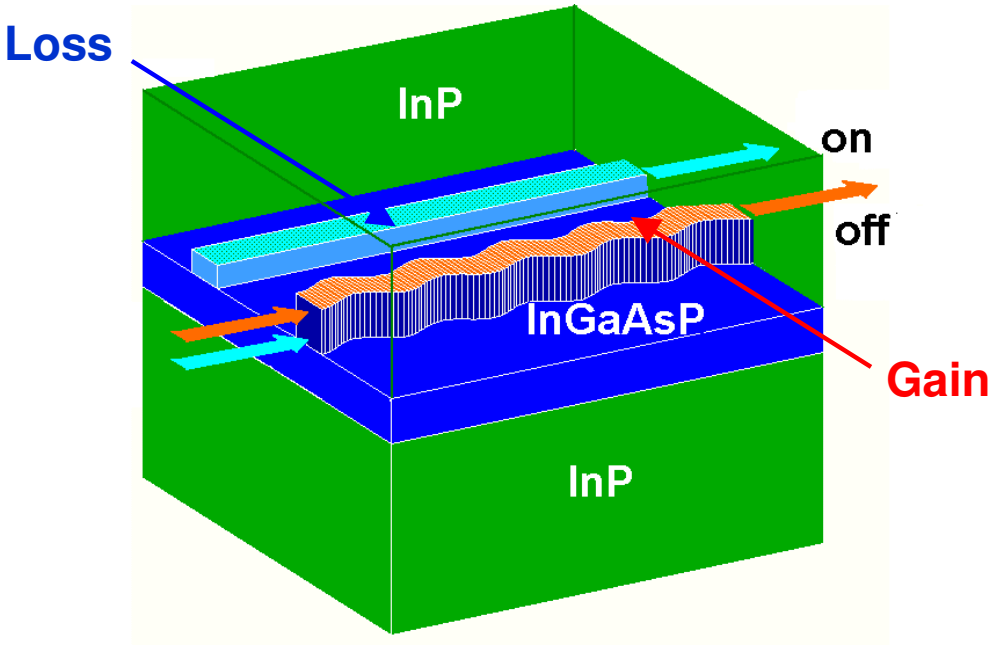


Switching operation ($L=2.1L_c$)

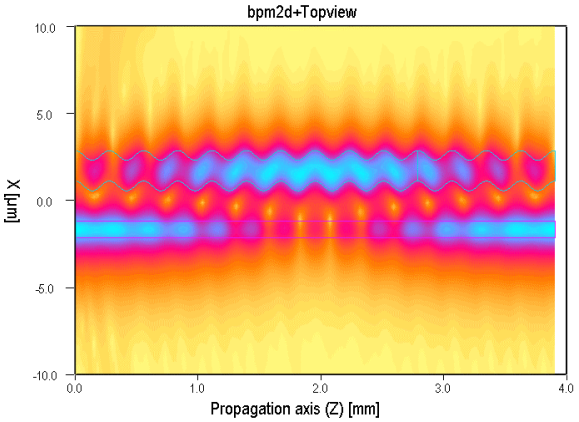


Robust technological design:
grating assisted asymmetric PTSS

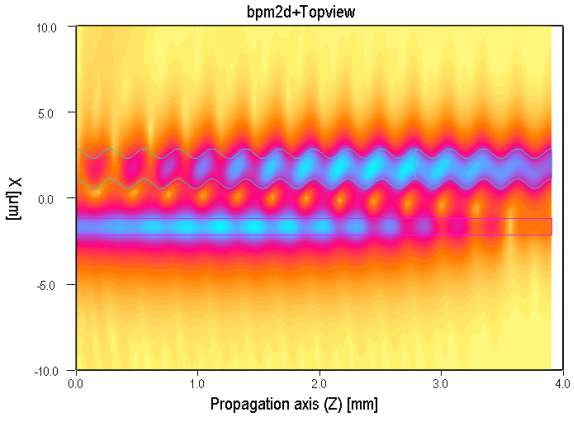
Grating assisted PTSS



PTSS off



PTSS on



Robust technological design:
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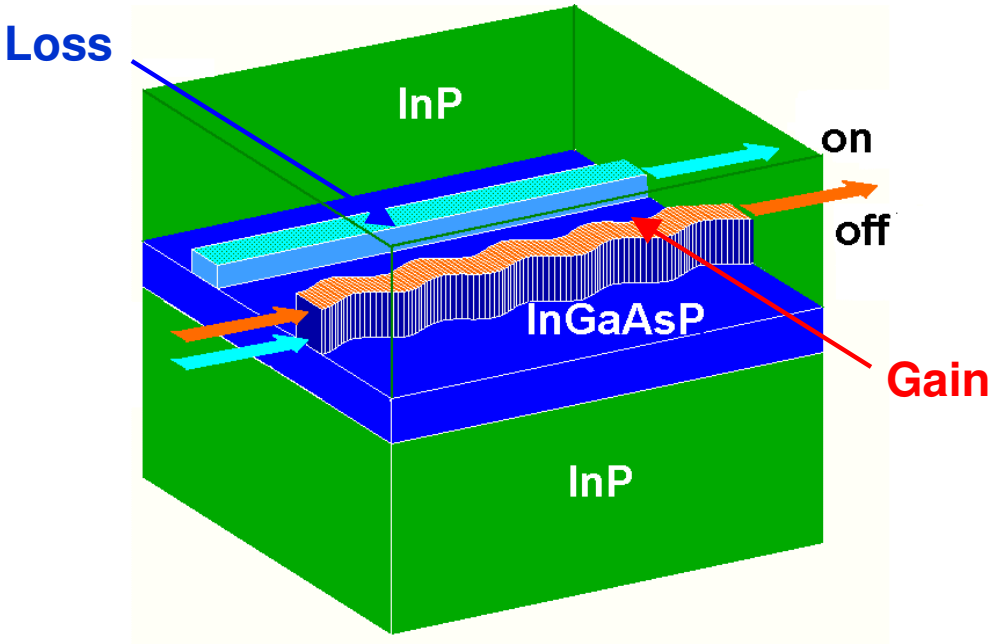
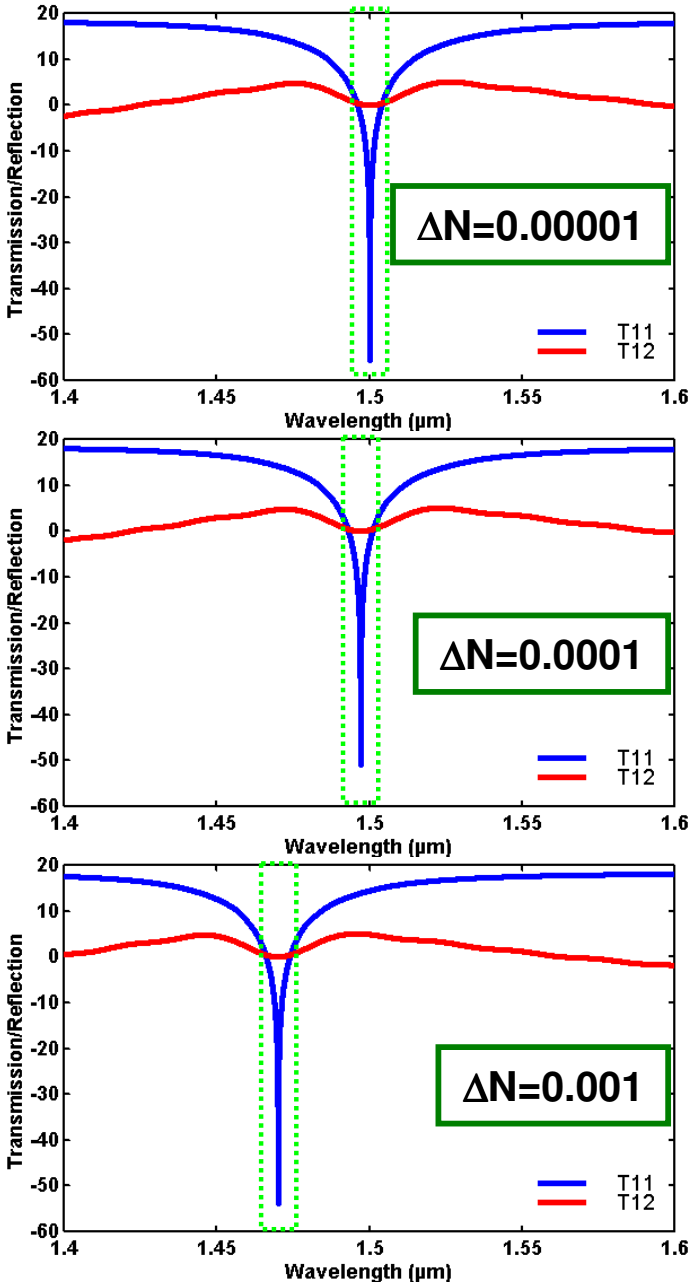
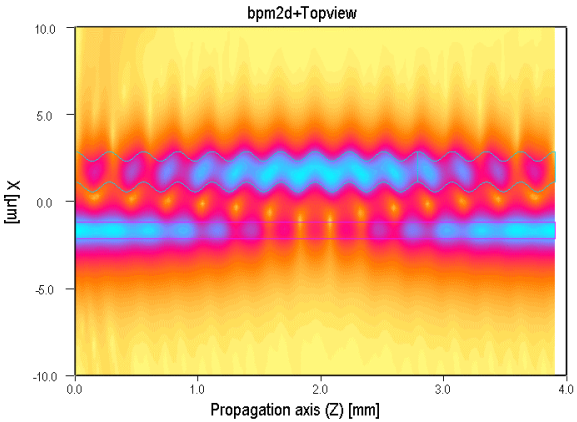


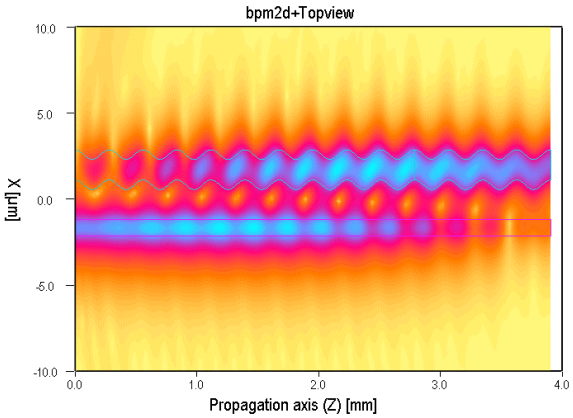
Grating assisted PTSS switching



PTSS off



PTSS on

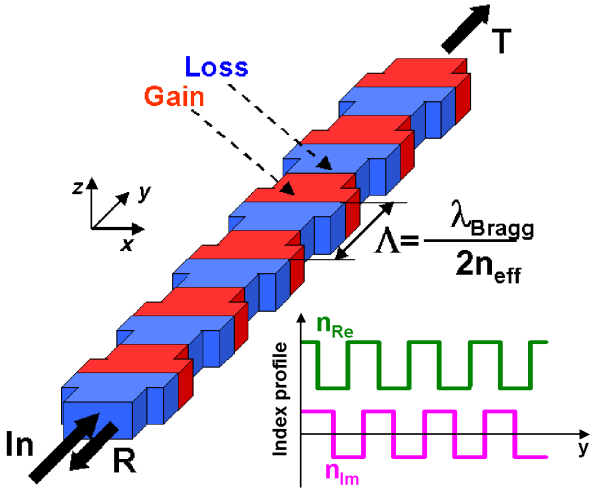


Outline

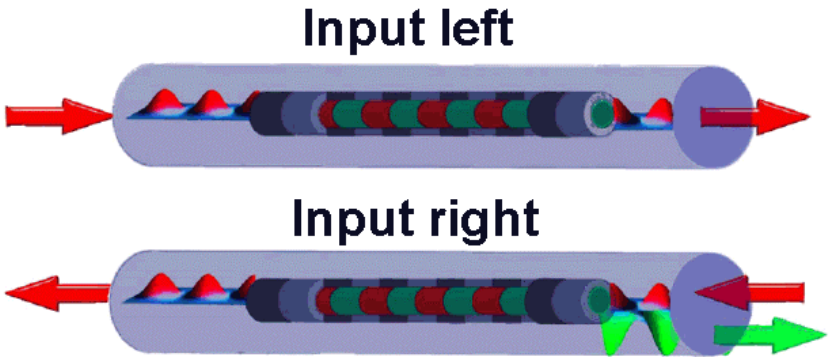
- Using PT-symmetry for switching applications
- **Locally PT-symmetric Bragg gratings**
- PT-symmetry: a new platform for active optical devices
- Summary and conclusions

Non-reciprocal PT-symmetric Bragg type devices

PT-symmetric Bragg grating



Unidirectional reflectivity



Z. Lin et al, Phys. Rev. Lett 106, 213901 (2011)

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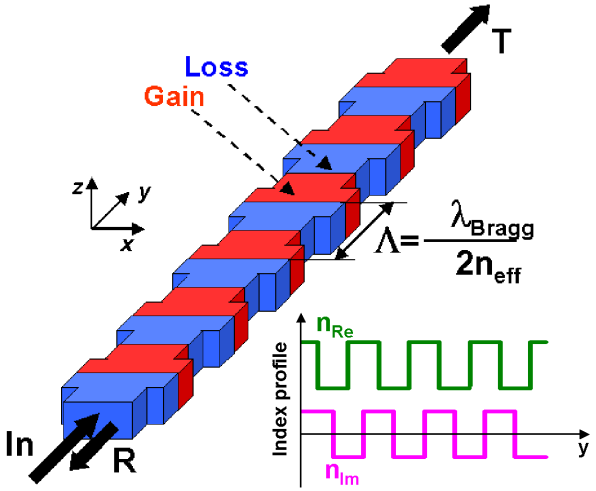

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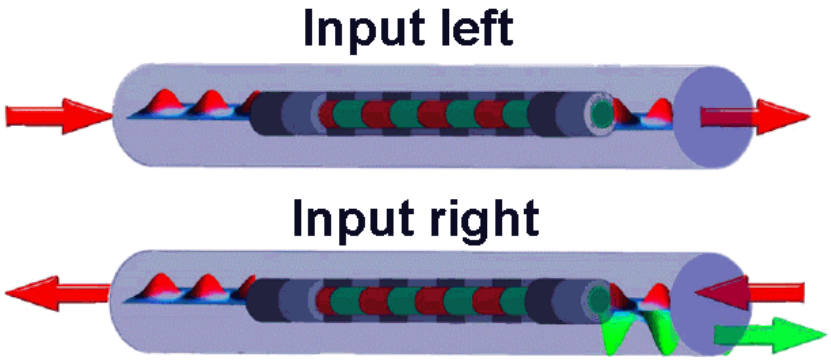
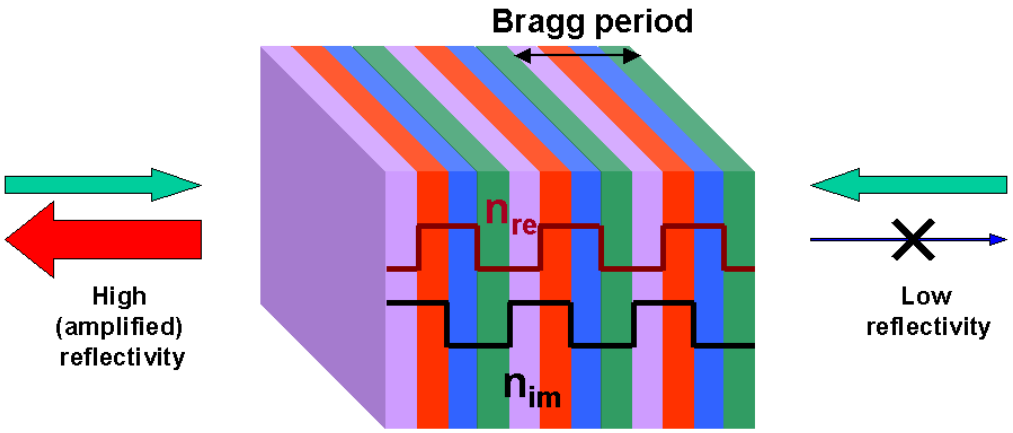


Z. Lin et al, Phys. Rev. Lett 106, 213901 (2011)

PT-symmetric Bragg mirror



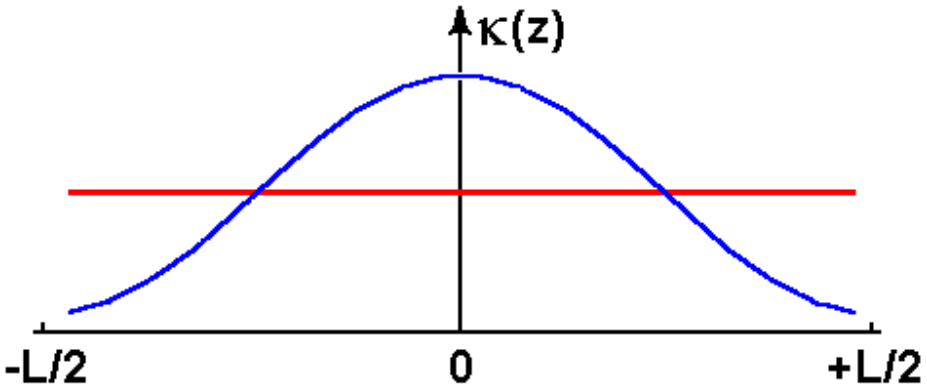
Low reflectivity

High reflectivity

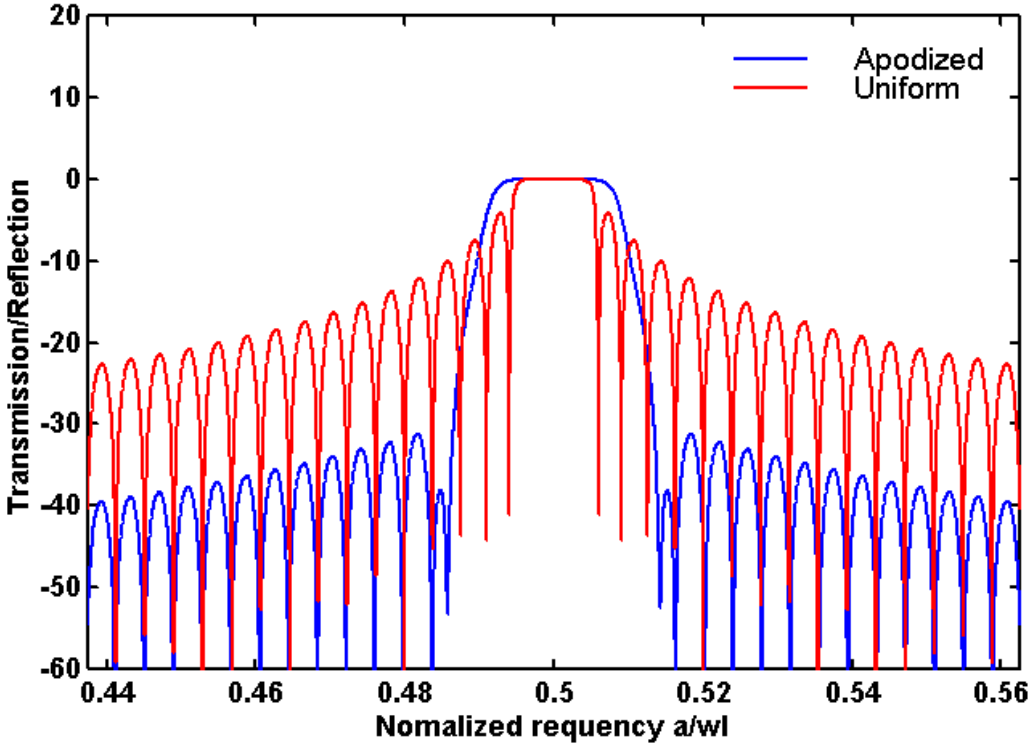
L. Feng et al, Opt. Express 22, 1760–1767 (2014)

Apodization principle: coupling profile tapering

Coupling profile

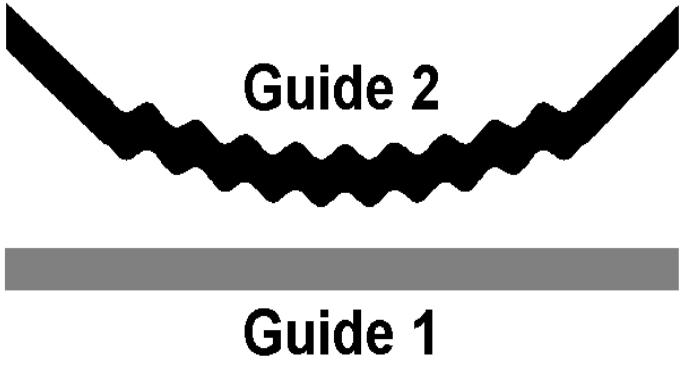


Conventional Bragg grating spectral response

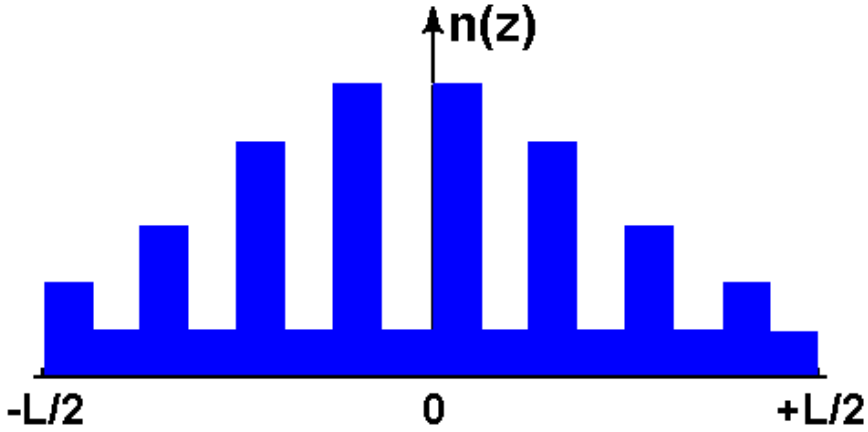


Coupling profile tapering methods

- **Inter-waveguides spacing variation:**
  - co- and contra-directional couplers



- **Refractive index contrast modulation:**
  - photo-imprinted Bragg gratings
  - rugated Bragg mirrors



- **Grating duty ratio variation:**
  - co- and contra-directional couplers
  - surface corrugated Bragg gratings
  - Bragg mirrors

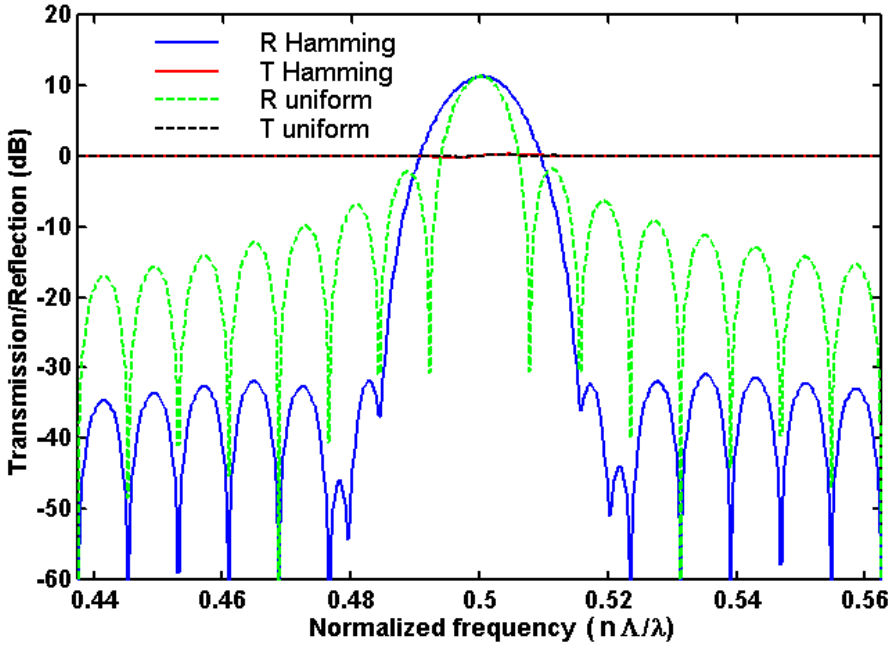
Nonuniform perfectly PT-symmetric Bragg grating

Hamming type apodization of complex index profile

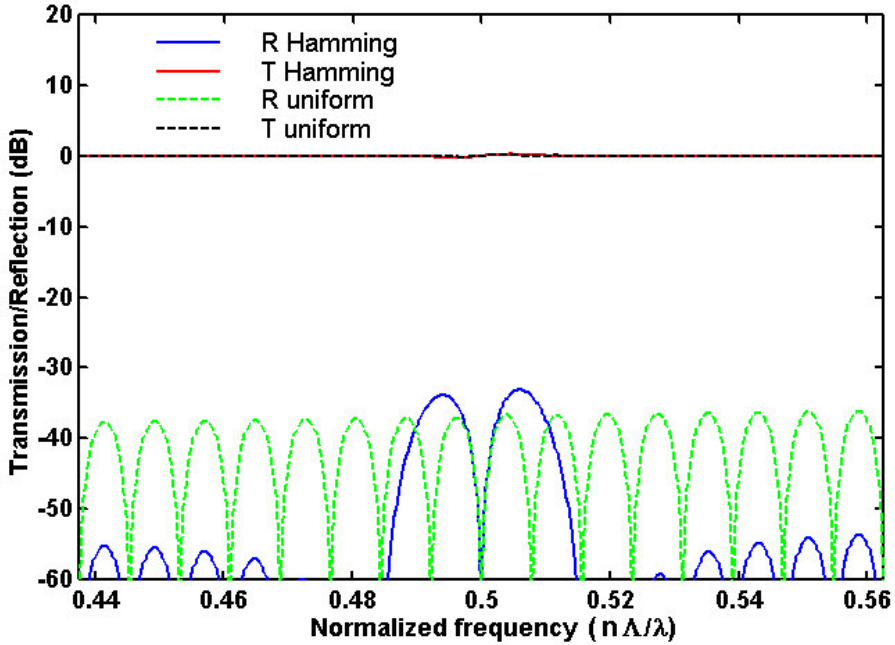
$$n(z) = n_0 + f(z)\Delta n e^{i2\pi z/\Lambda}$$

$$f(z) = 1 + 0.852\cos(2\pi z / L)$$

Front side incidence (high reflection)



Rear side incidence (low reflection)

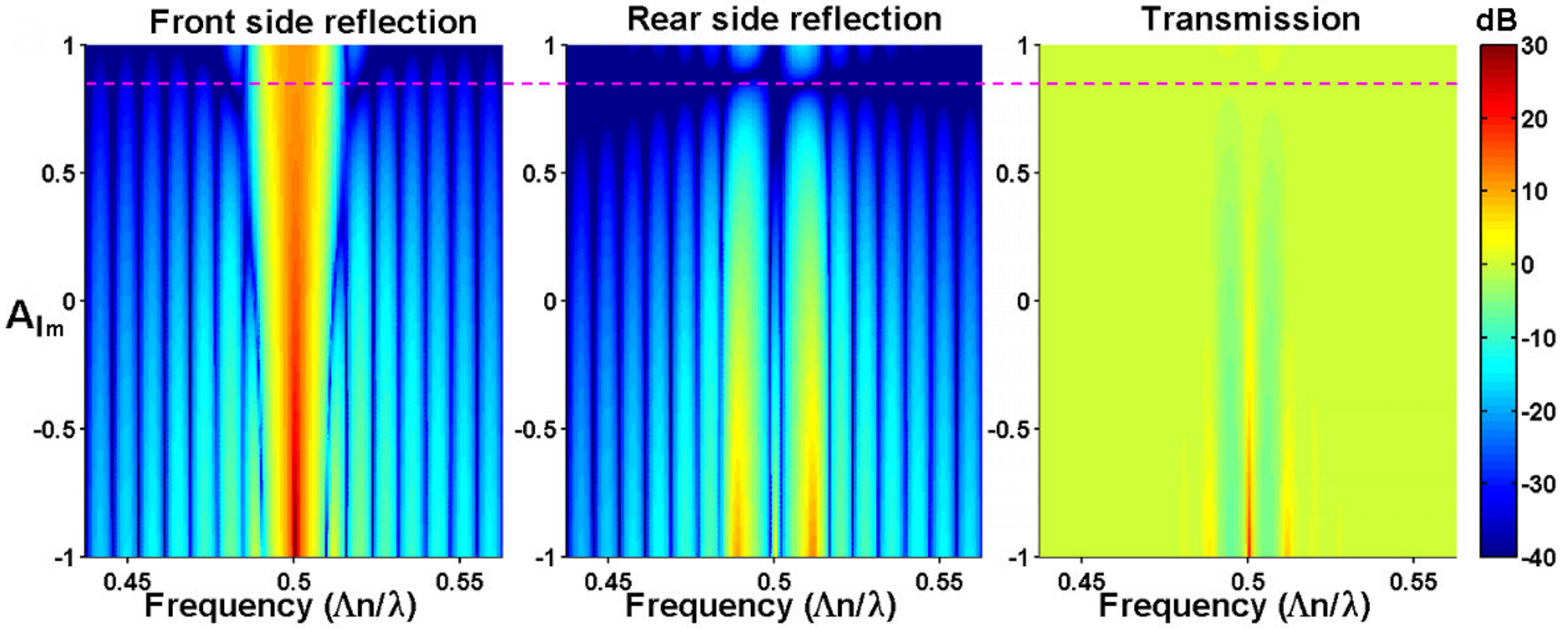


Nonuniform pseudo PT-symmetric Bragg grating

Pseudo PT-symmetric apodization of complex index profile

$$n(z) = n_0 + f(z)\left(A_{\mathrm{Re}} \cos(2\pi z / L) + iA_{\mathrm{Im}} \sin(2\pi z / L)\right)$$

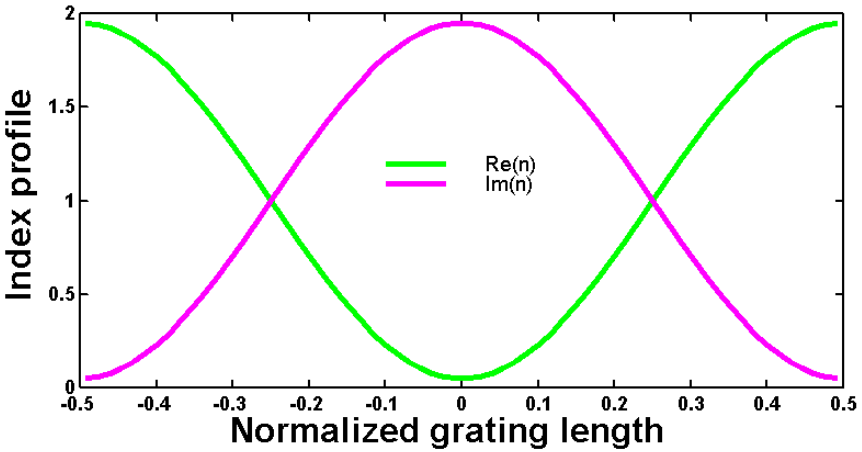
Spectral maps (A_{re}=0.852)

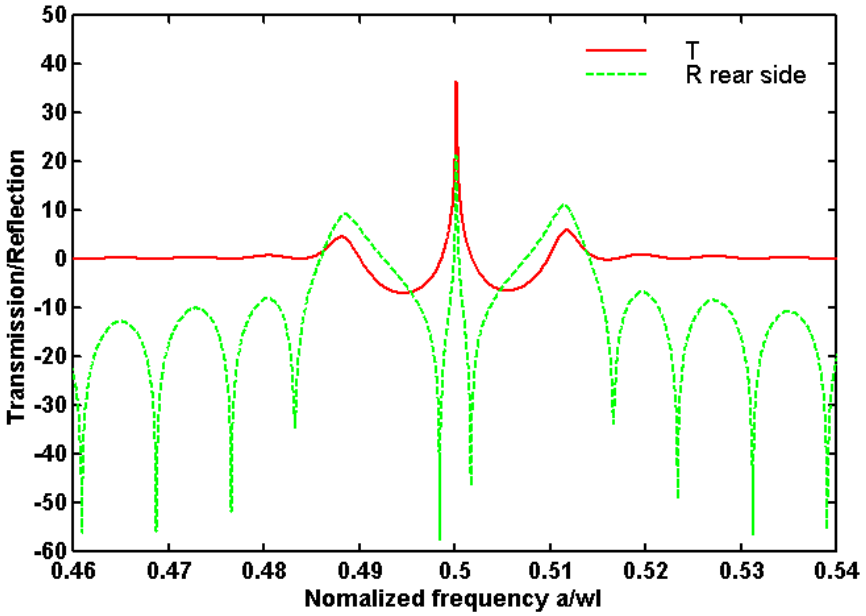


A. Lupu, H. Benisty, A. Lavrinenko, JTSQE 2016

Additional functionalities of locally PT-symmetric Bragg gratings

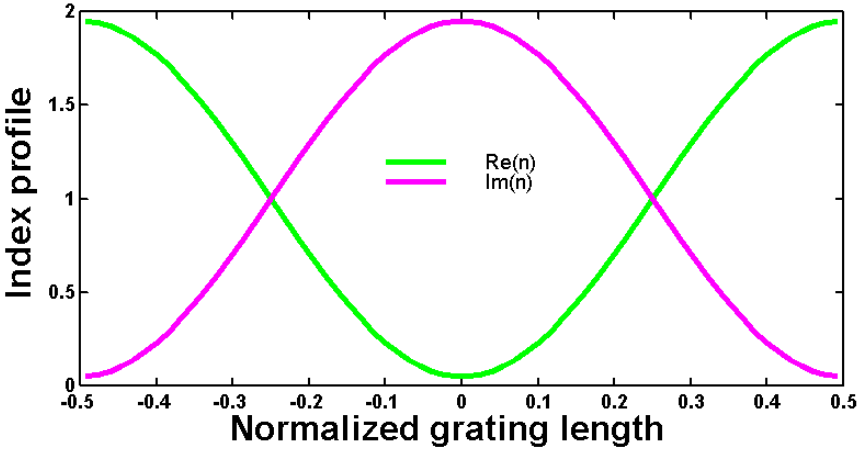
Single mode amplifier (A_{Re}=-0.95; A_{Im}=0.95)

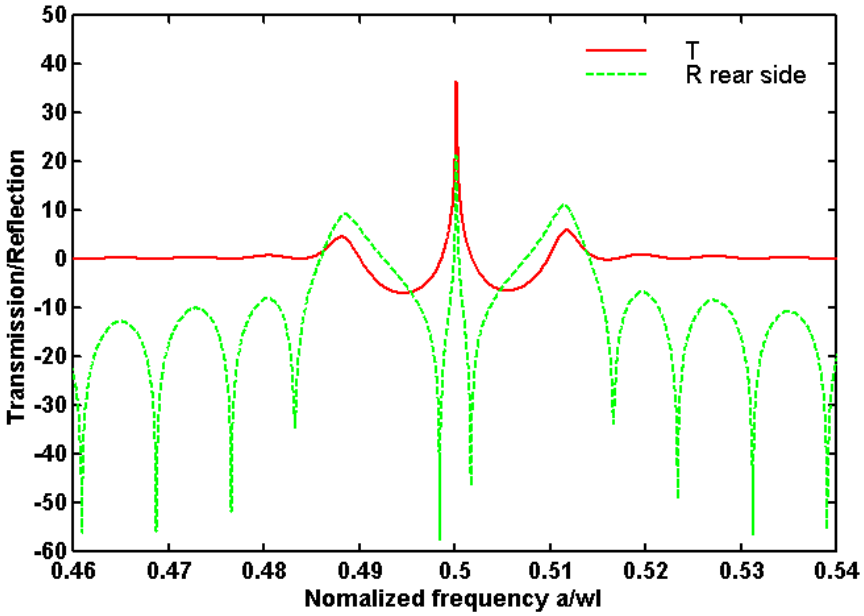




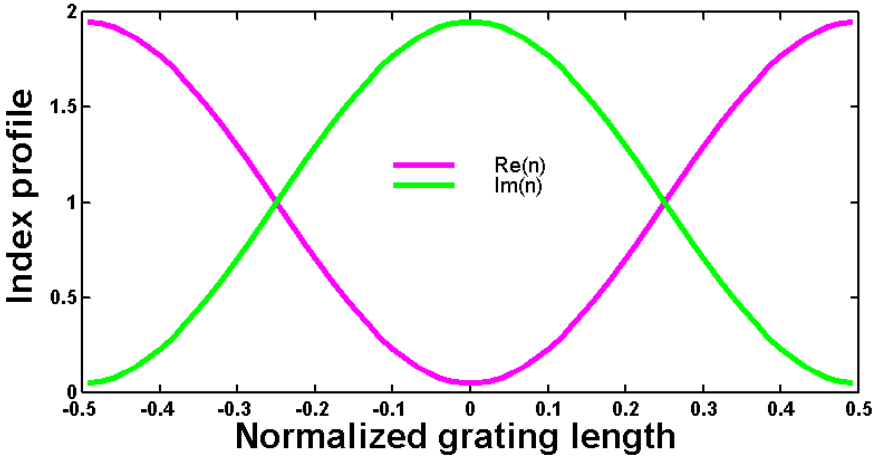
Additional functionalities of locally PT-symmetric Bragg gratings

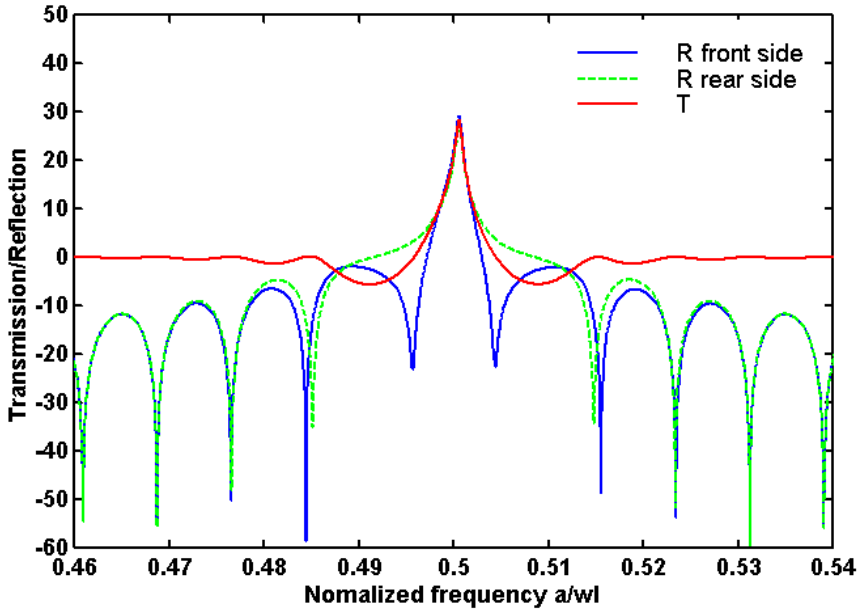
Single mode amplifier (A_{Re}=-0.95; A_{Im}=0.95)





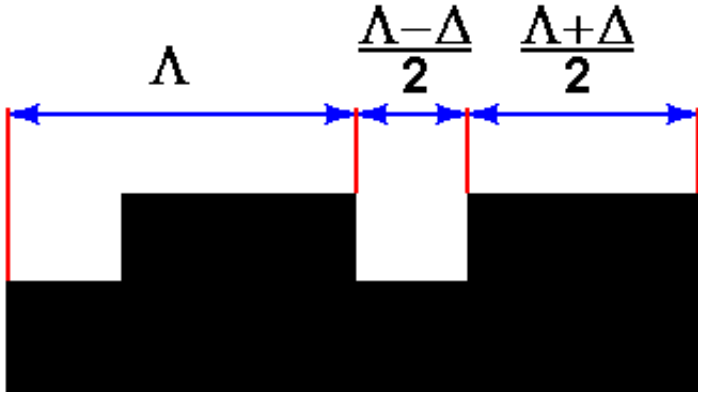
Single mode DFB laser (A_{Re}=0.95; A_{Im}=-0.95)





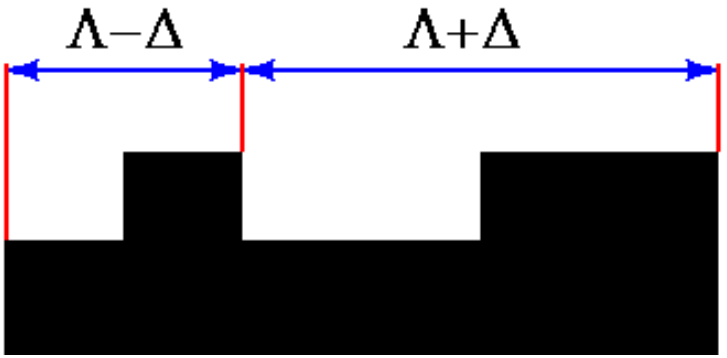
Grating duty cycle modulation methods

Basic Duty Cycle



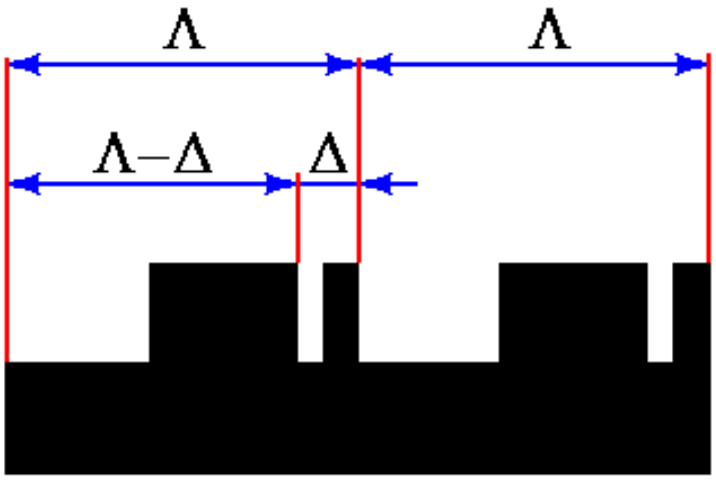
H. Sakata, Opt. Lett., 17, (1992)

Off-Resonance



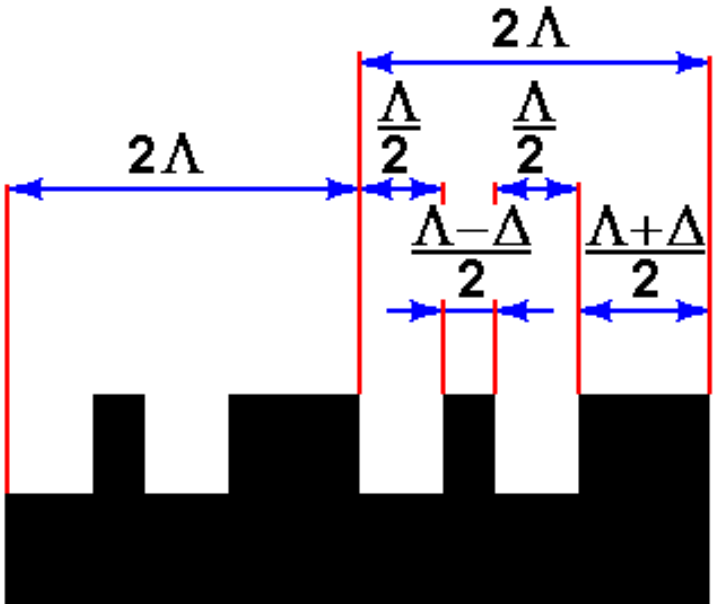
A. Lupu, et al., OFC/IOOC (1999)

Phase Shifted Pair Gratings



D.-B. Kim et al., Photon. Technol. Lett, 10, (1998)

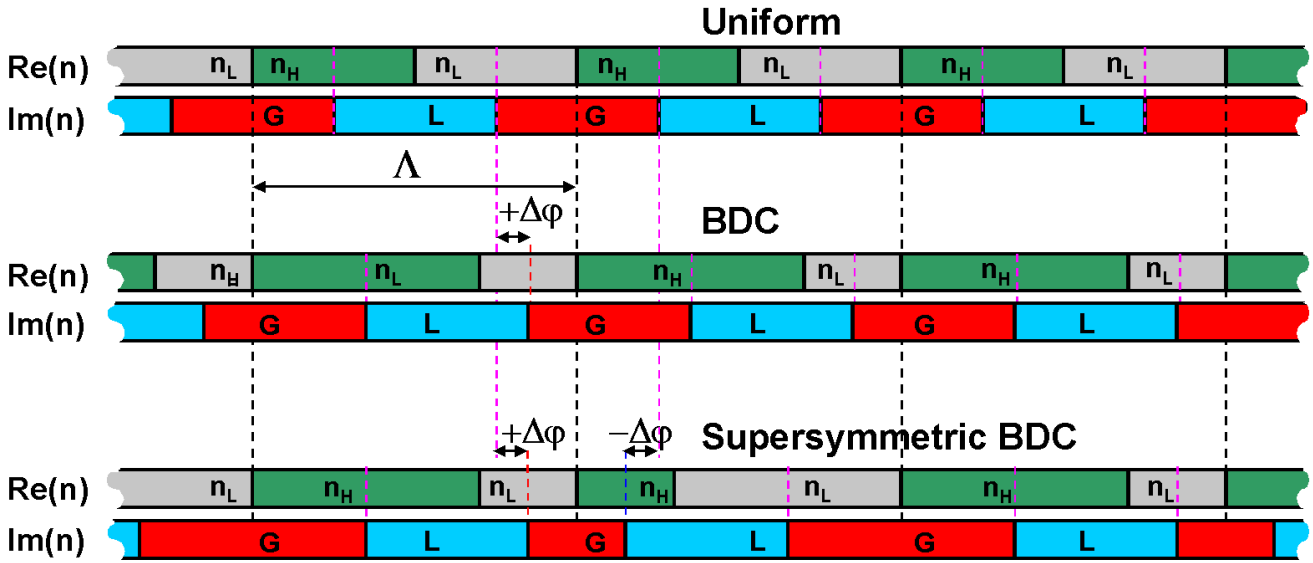
Concatenated Gratings



D. Wiesmann et al., Photon. Technol. Lett., 12, (2000)

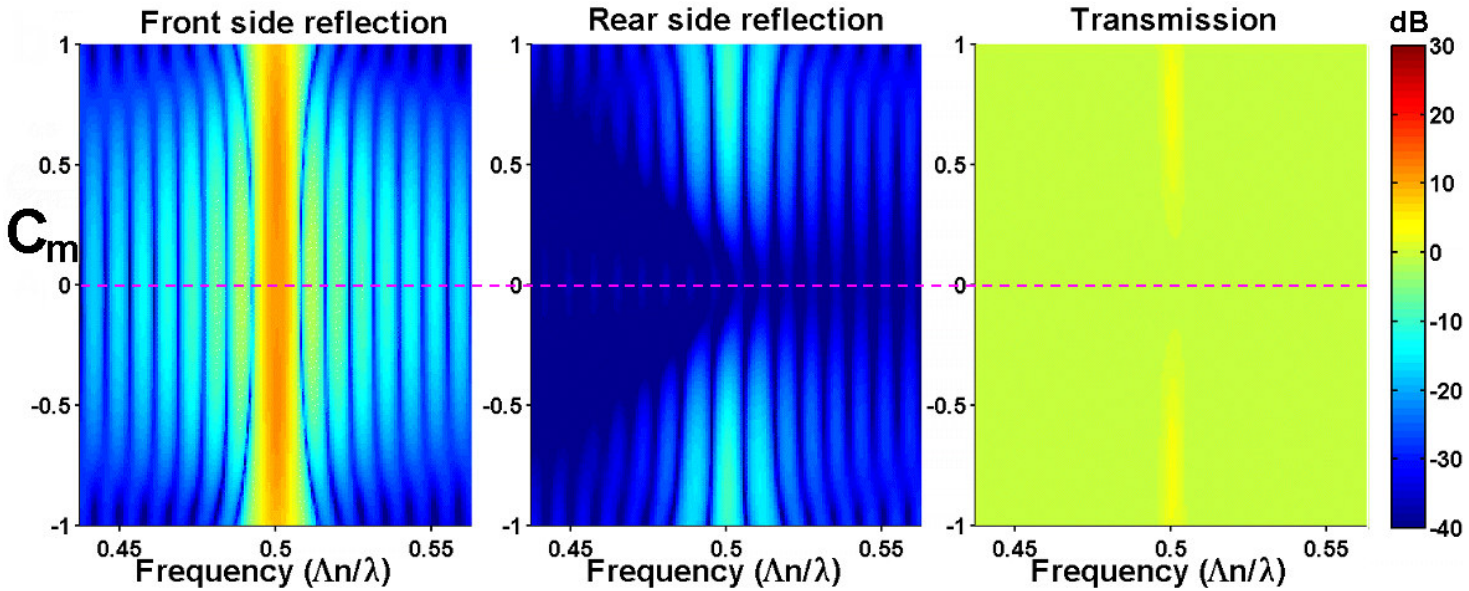
Duty cycle modulated binary PT-symmetric gratings

Duty cycle modulation schemes



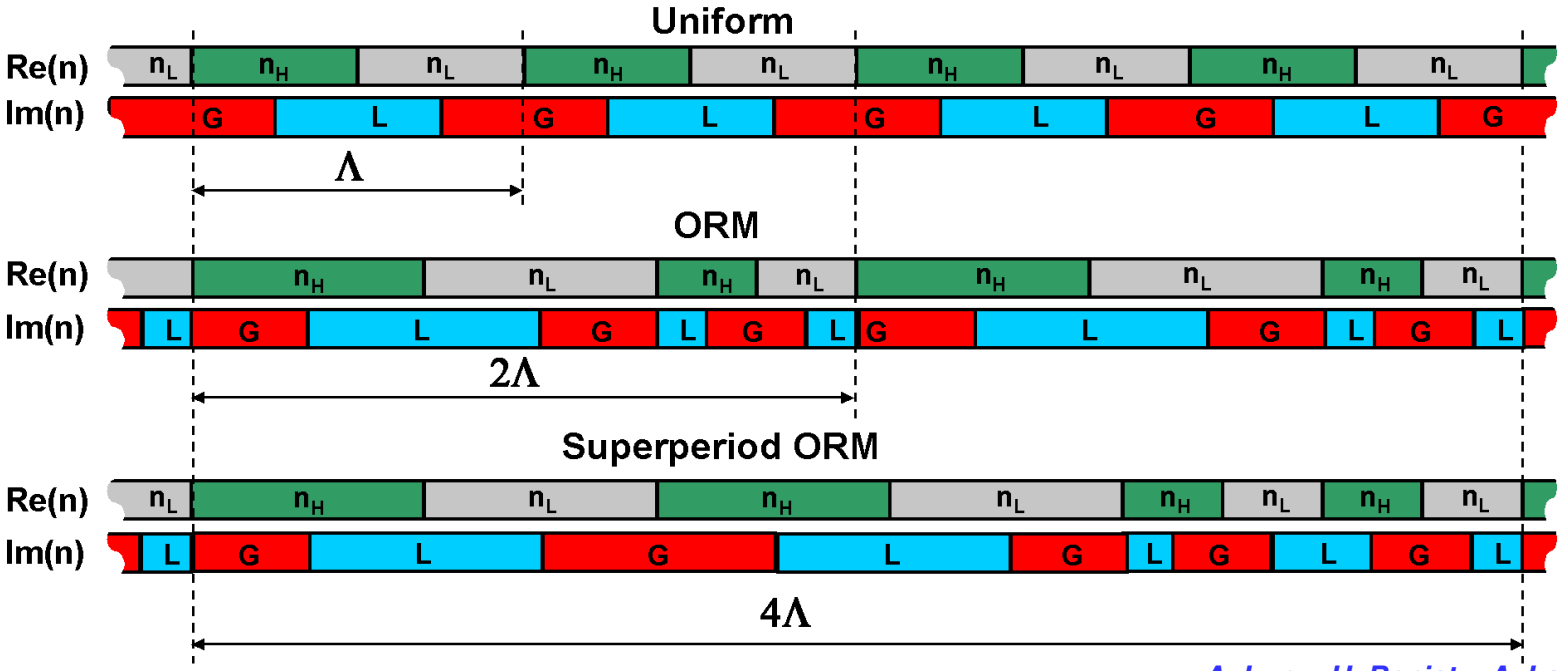
A. Lupu, H. Benisty, A. Lavrinenko, JTSQE 2016

Spectral maps (supersymmetric BDC)



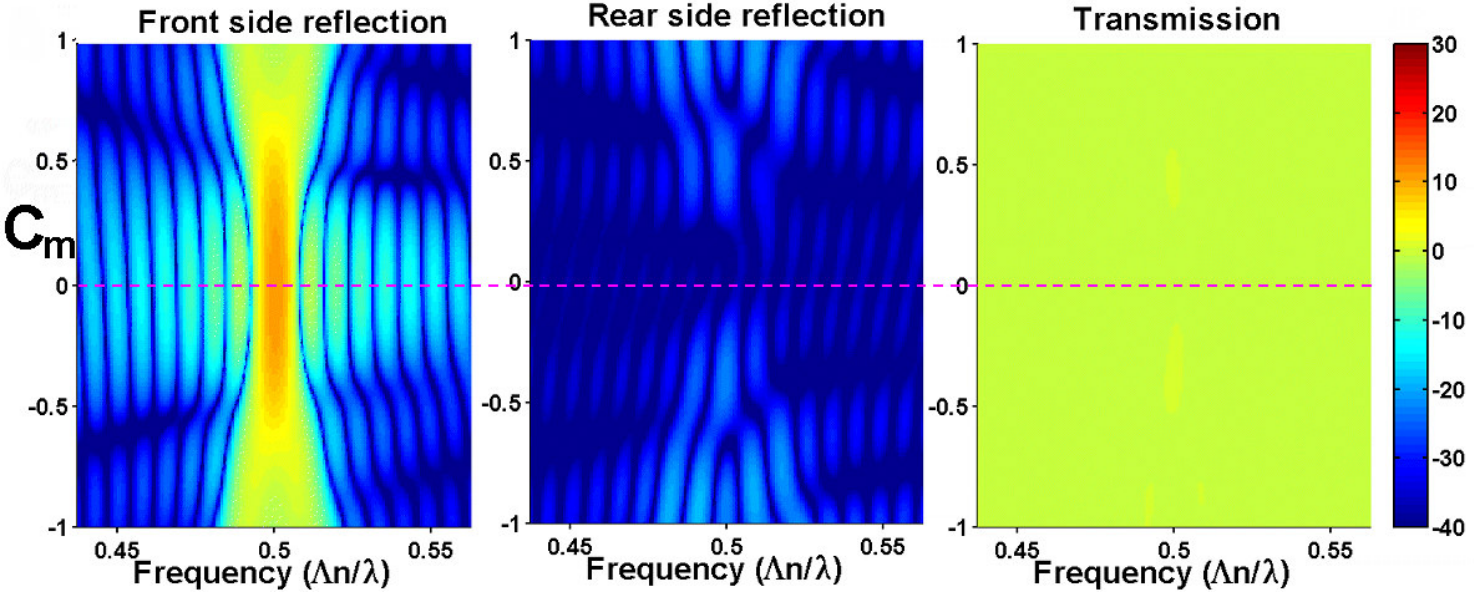
Period modulated binary PT-symmetric gratings

Grating period modulation schemes



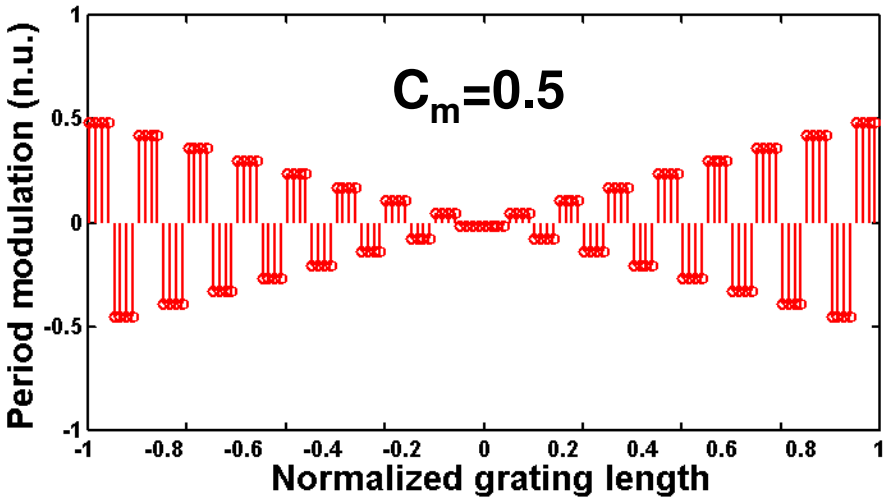
A. Lupu, H. Benisty, A. Lavrinenko, JTSQE 2016

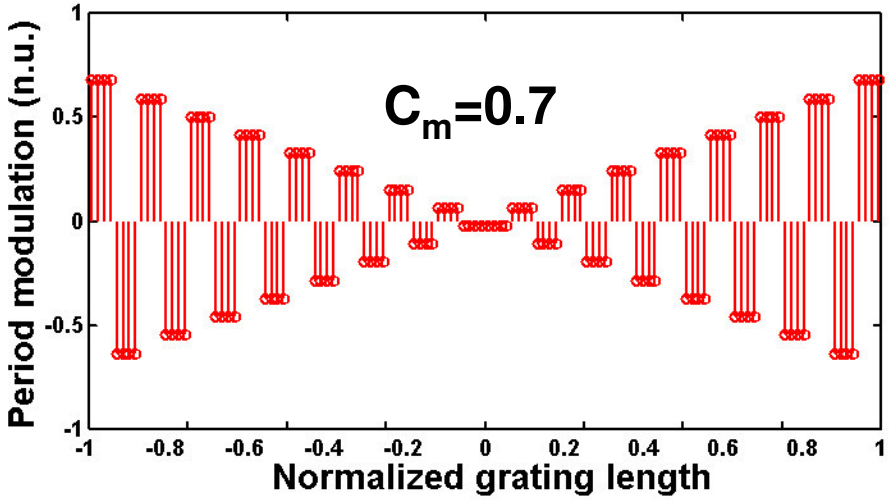
Spectral maps (superperiod ORM)



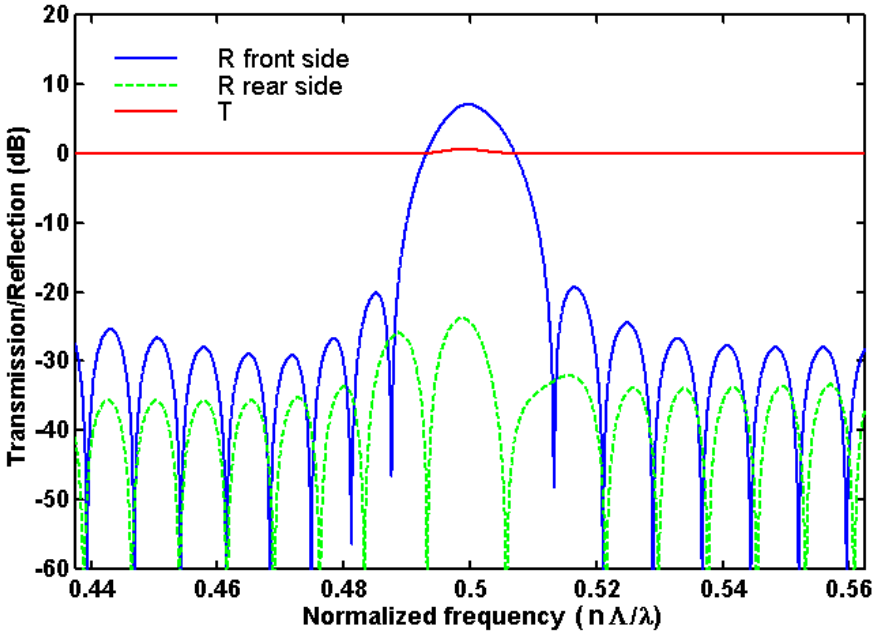
Tailoring spectral properties of locally Parity-Time symmetric Bragg gratings

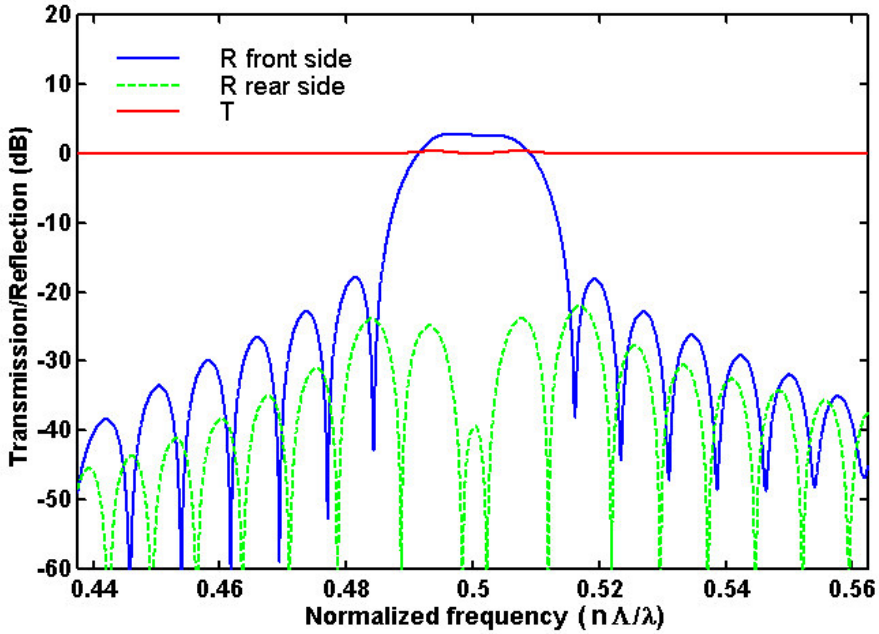
Grating period modulation





Spectral response

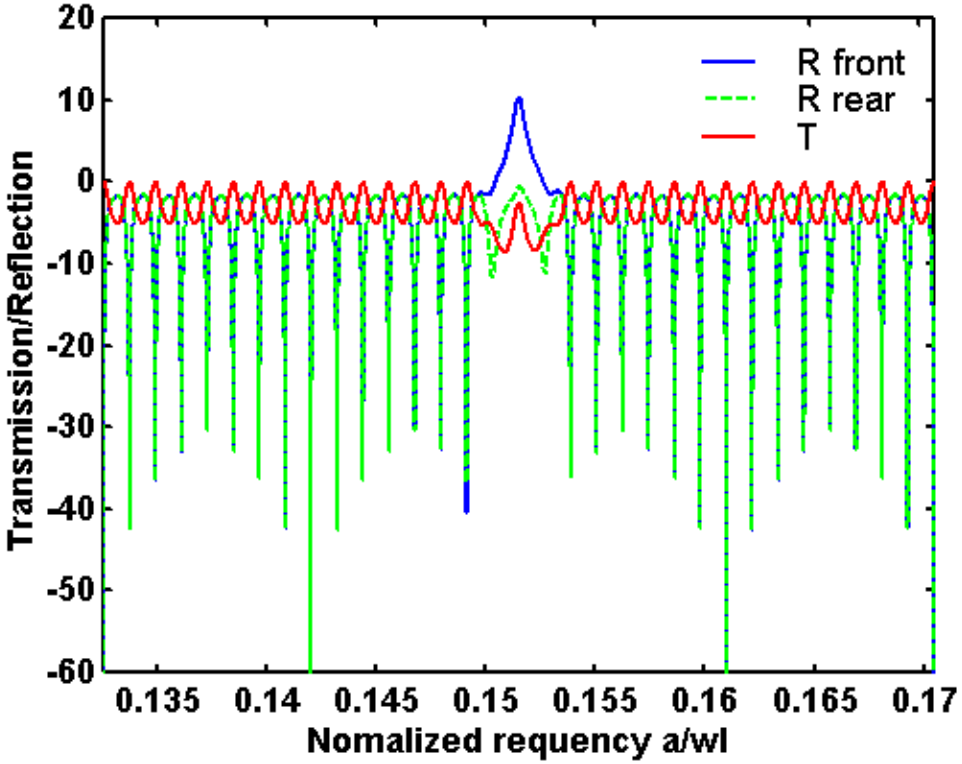




Impact of PT-symmetric grating impedance mismatch with external media

Hamming type apodization of complex index profile

No antireflection coating



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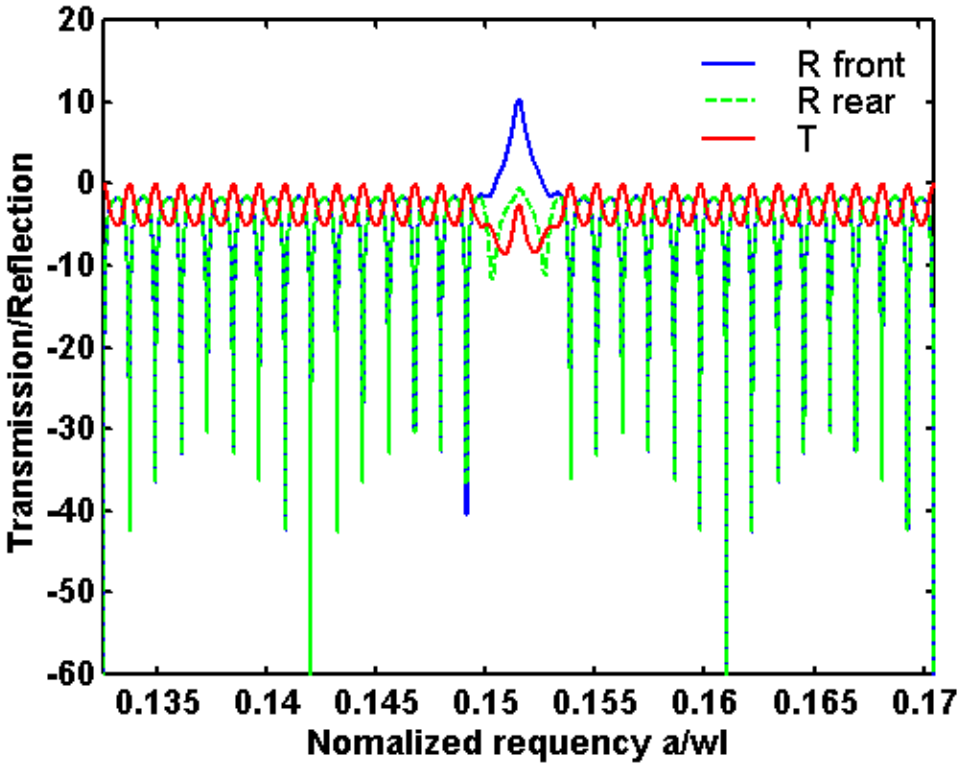
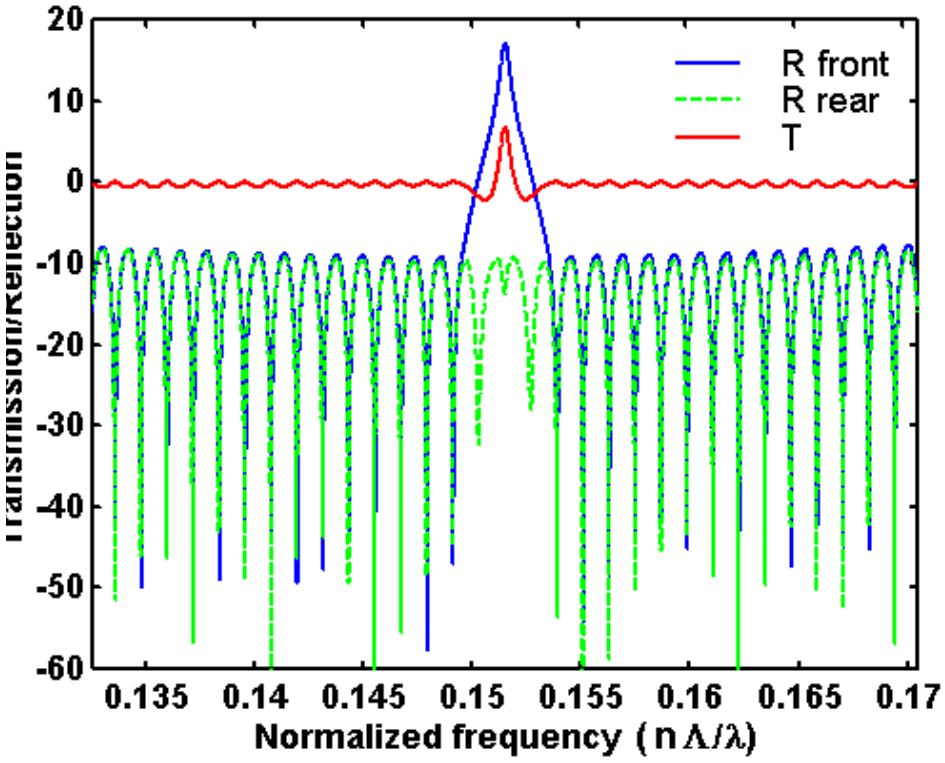


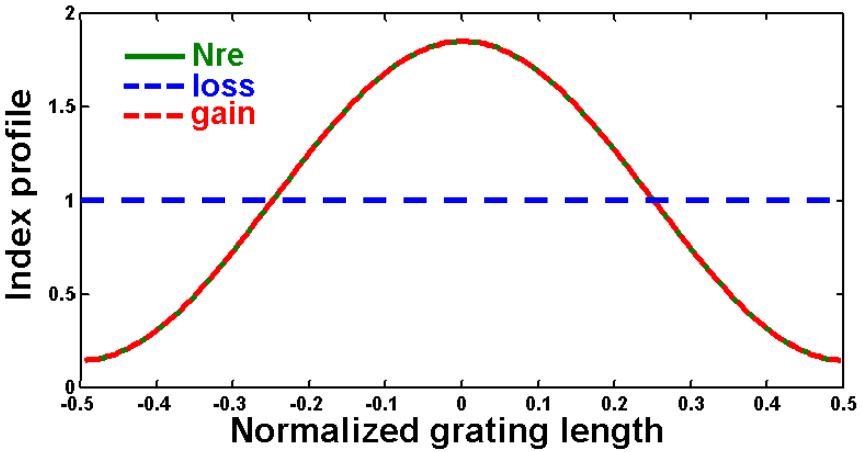
Antireflection coating



Toward active tailoring of the spectral response

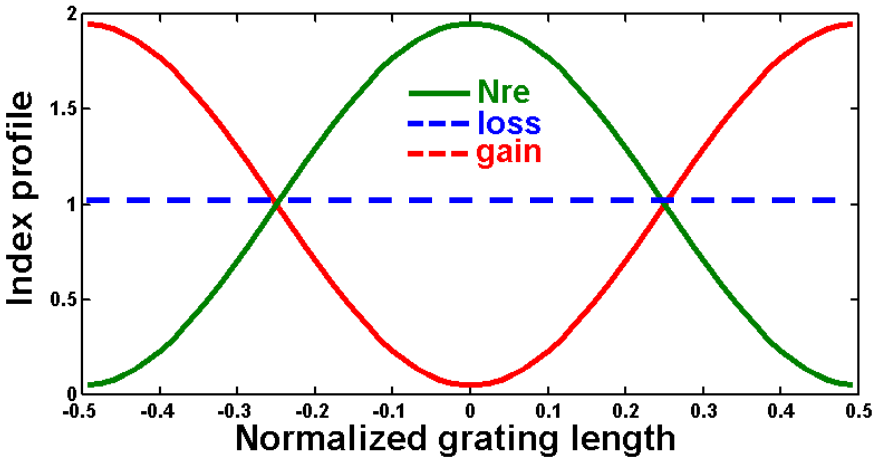
Complex index modulation

A_{Re}=-0.85; A_{loss}=0; A_{gain}=0.85



Complex index modulation

A_{Re}=-0.85; A_{loss}=0; A_{gain}=-0.85



Toward active tailoring of the spectral response

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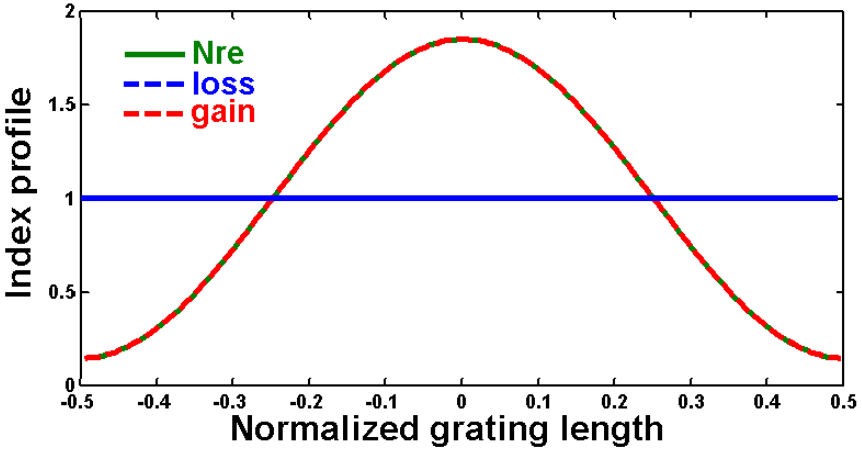
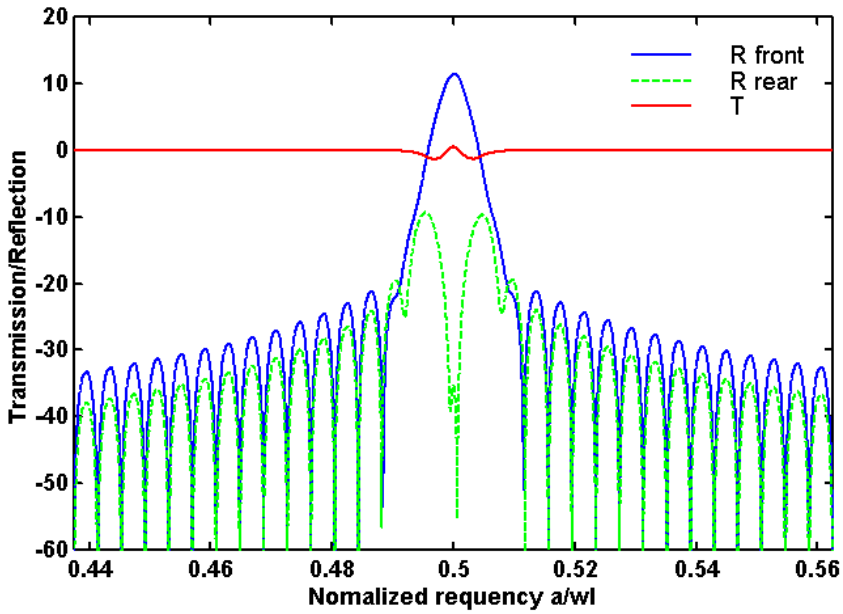
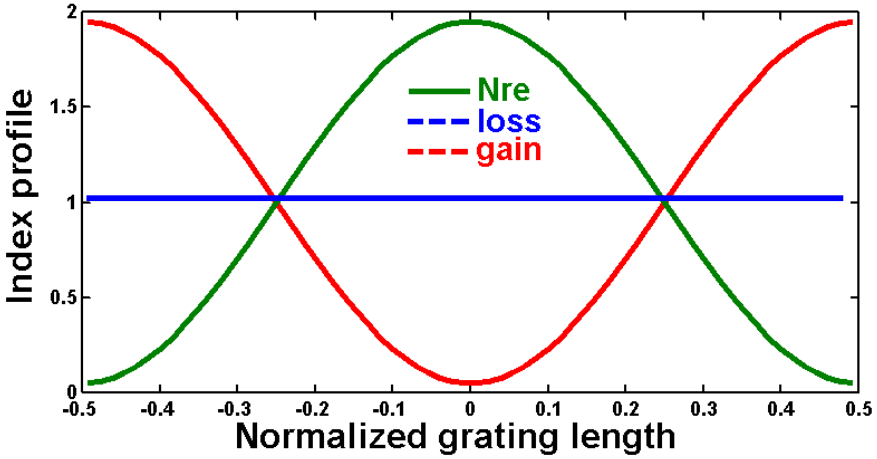
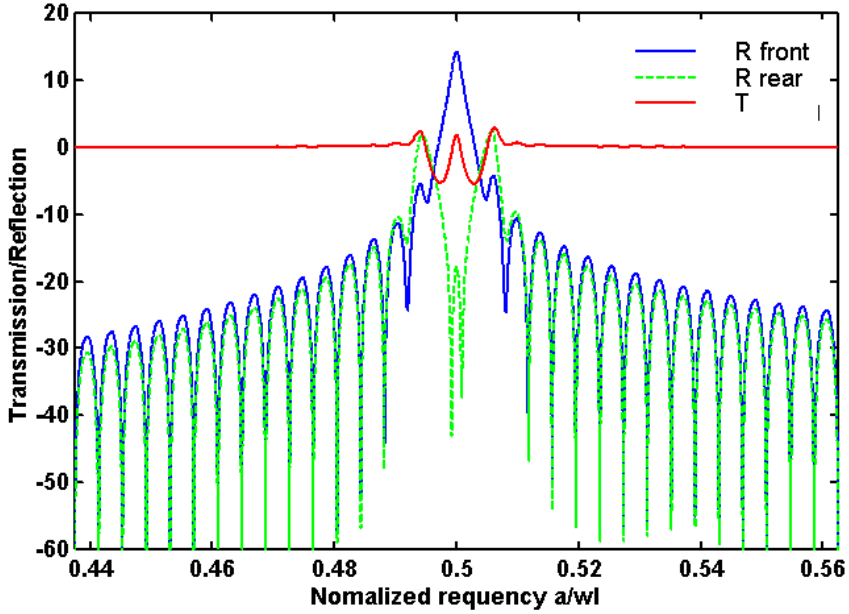




Complex index modulation

A_{Re}=-0.85; A_{loss}=0; A_{gain}=-0.85



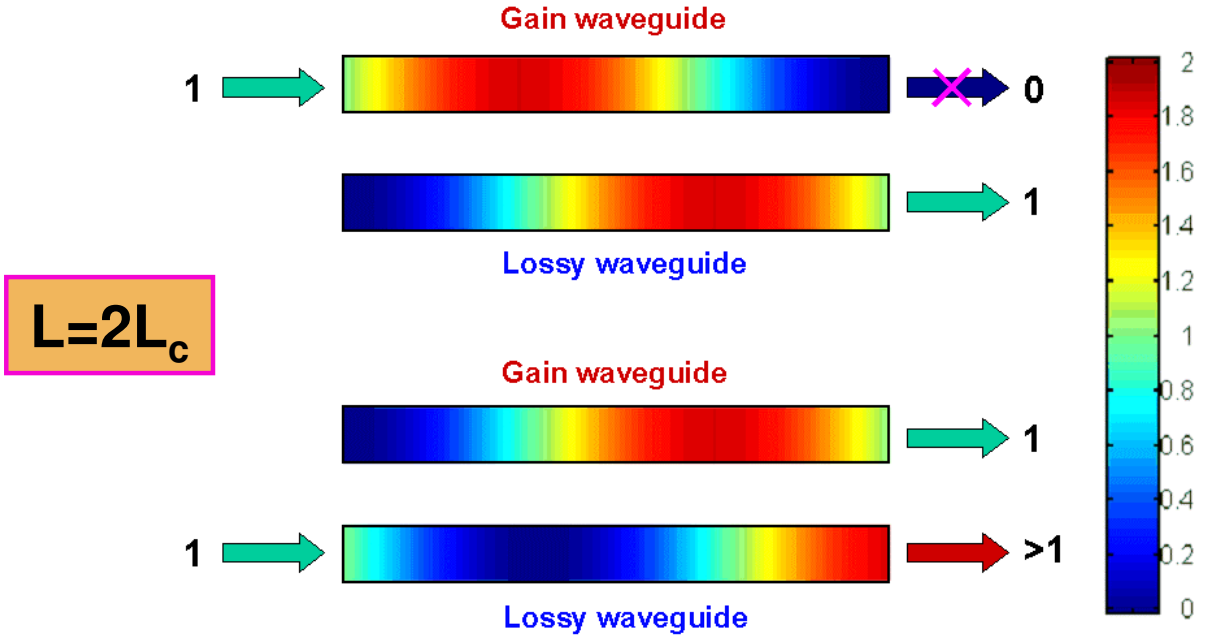


Outline

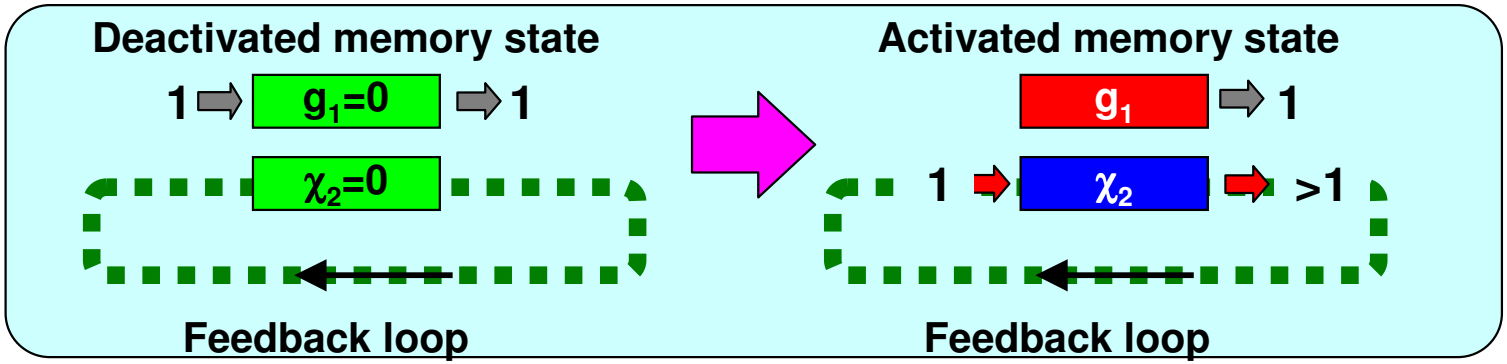
- Using PT-symmetry for switching applications
- Locally PT-symmetric Bragg gratings
- **PT-symmetry: a new platform for active optical devices**
- Summary and conclusions

PT-symmetric spatial non-reciprocity: toward buffer memory applications

Coupler non-reciprocity



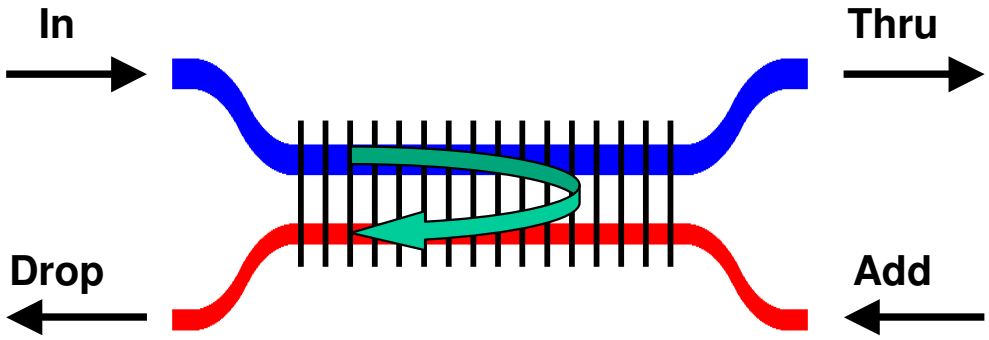
Buffer memory application



See also: M. Kulishov, et al, "Trapping light in a ring resonator using a grating assisted coupler with asymmetric transmission," Opt. Express 13, 3567 (2005)

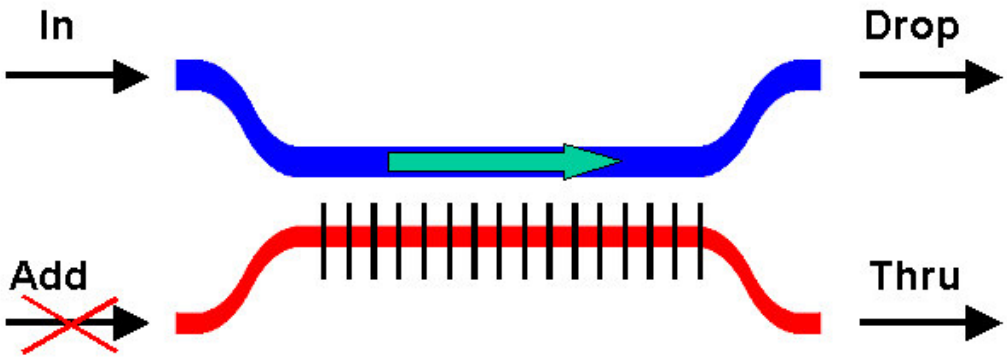
4 ports Bragg grating optical add-drop demultiplexers overview

Contra-directional



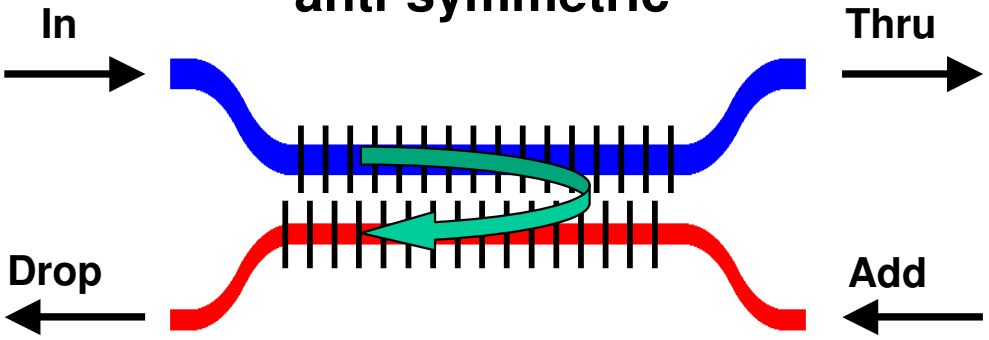
C. Elachi, C. Yeh, Opt. Comm. 7, 201 (1973)

Frustrated coupling



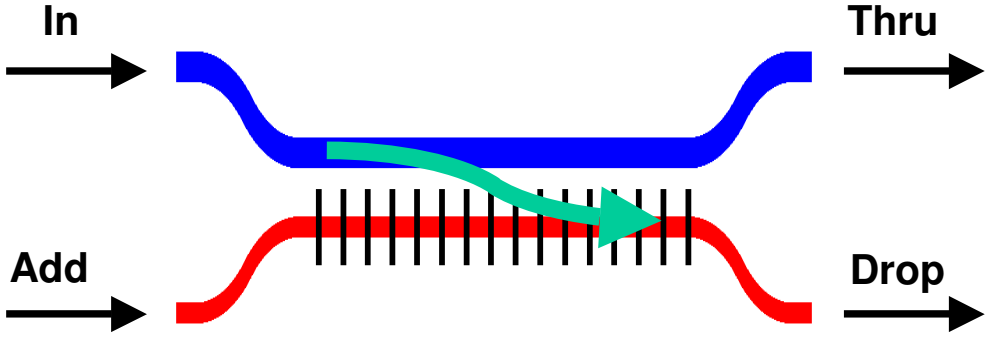
J.-L. Archambault et al, Opt. Lett. 19,180 (1994)

Contra-directional anti-symmetric



Perrone et al, J. Lightwave Technol. 19, 1943 (2001)

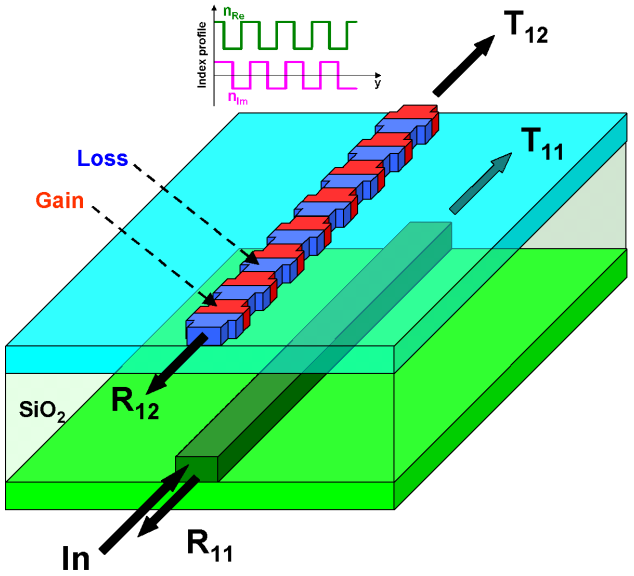
Co-directional



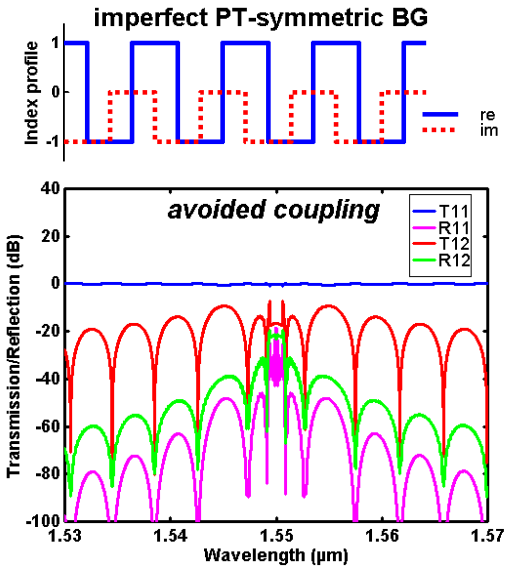
A. Ankiewicz et al, 31, 2151 (1997)
K. Muhieddine et al, Opt. Express 18, 23183 (2010)
A. Lupu et al, Opt. Express 19, 1246 (2011)

PT-symmetric tunable add-drop

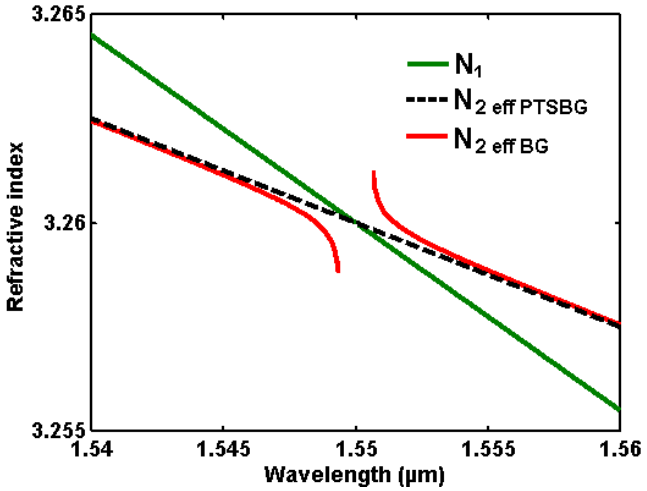
Vertical PTSBG directional coupler



Gain off state

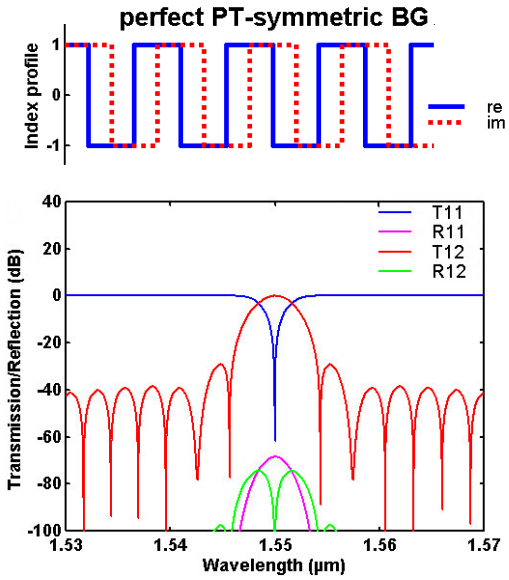


Switch operation principle



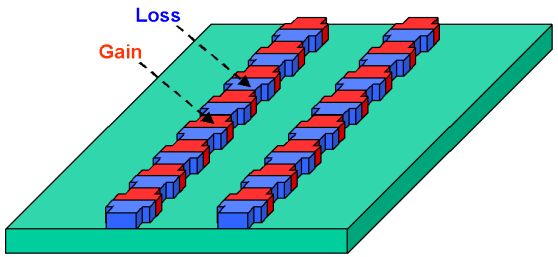
A. Lupu, H. Benisty, et al., PNFA 2014

Gain on state

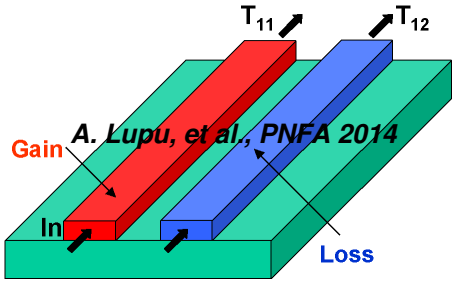


PT-symmetric functional devices

Coherent perfect absorber



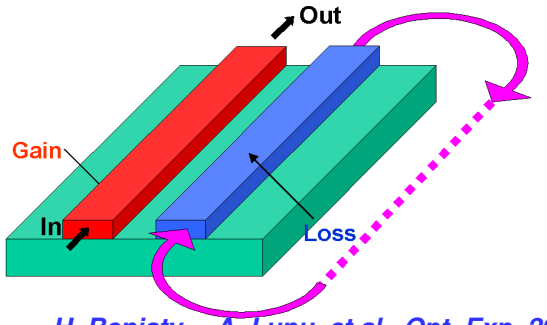
PT-symmetric switch



A. Lupu, et al., PNFA 2014

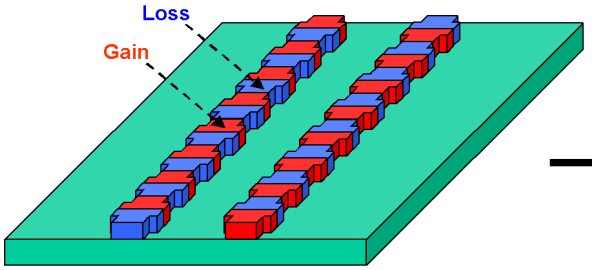
A. Lupu, H. Benisty. et al, Opt. Exp. 2013

Buffer memory



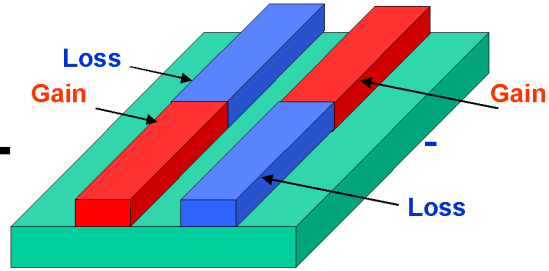
H. Benisty… A. Lupu, et al., Opt. Exp. 2011

A new platform for active optical devices

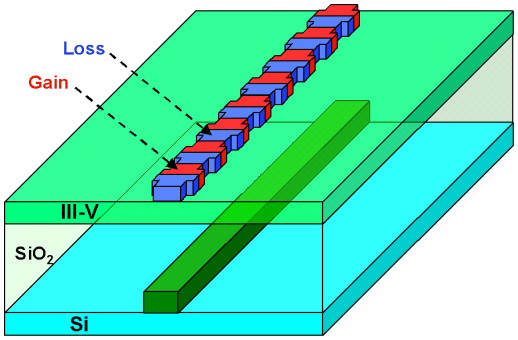


Single mode amplifier

A. Lupu, H. Benisty, A. Lavrinenko, JTSQE 2016



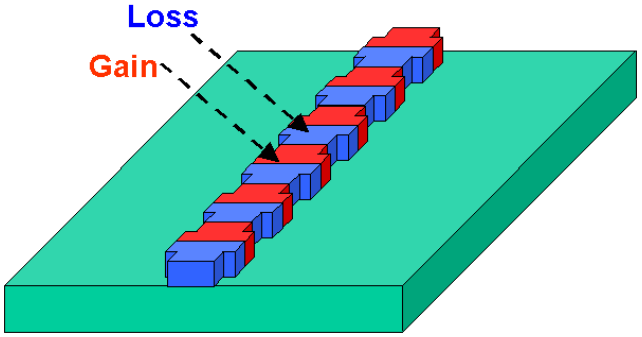
Binary phase modulator (0=>π)



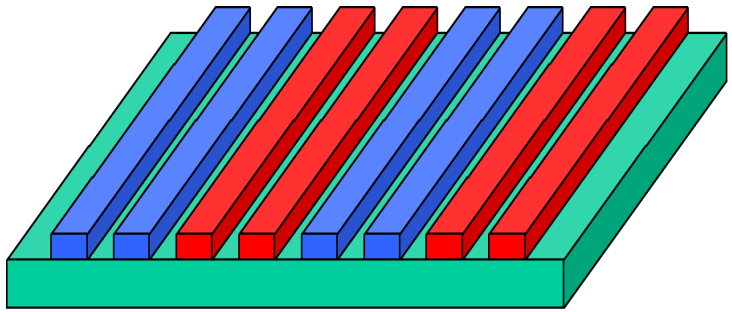
In

Tunable add-drop

A. Lupu, H. Benisty, et al., PNFA 2014



Unidirectional DFB laser

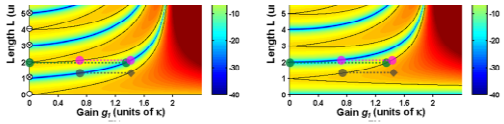


Reconfigurable spatial DMUX

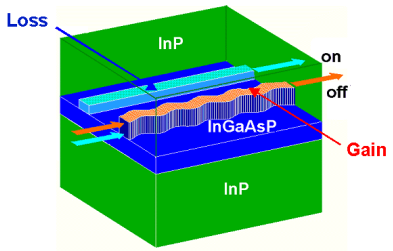
H. Benisty, A. Lupu, A. Degiron, Phys Rev. A 91, 053825 (2015)

Summary and conclusions

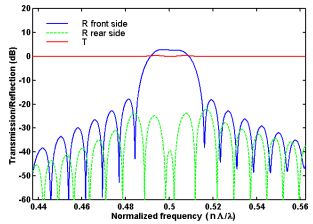
- **Perfect Bar and Cross switch states in a non-conservative layout**



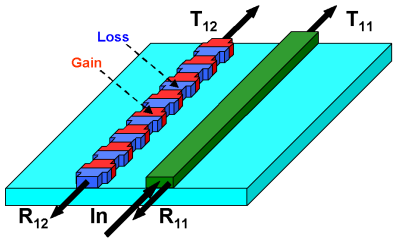
- **Impact of material and technological imperfections**



- **Tailoring spectral properties PT-symmetric Bragg gratings**



- **Proposal of a new platform for active optical devices**




Mind the gap!
Theory
Experiment