Asymmetric Fano resonance and bistability in a two-ring resonator switch

by:

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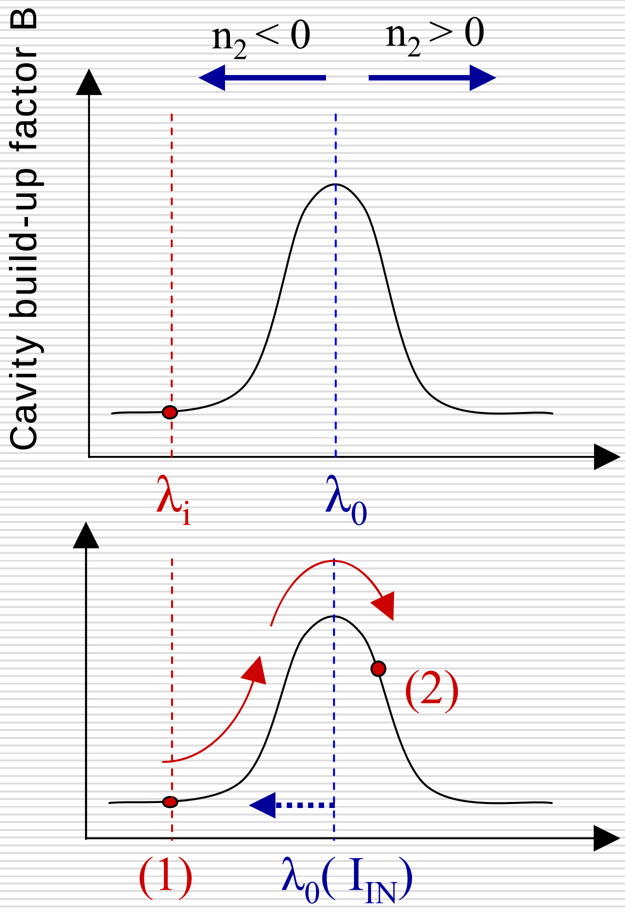
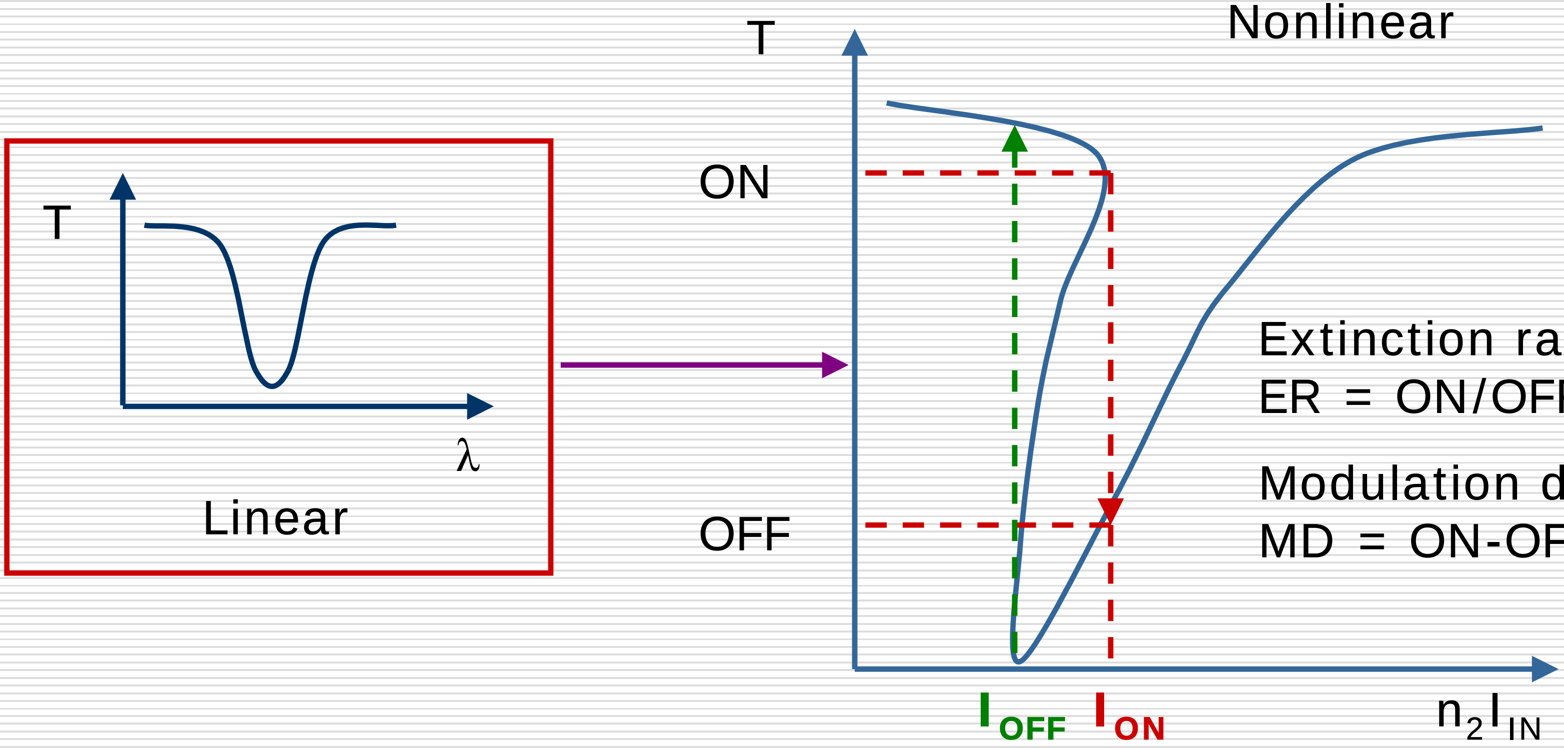
Illustration about bistability



- As I_{IN} ↑, the resonant wavelength λ_0 moves.
- The movement depends on the sign of Kerr nonlinearity n_2.
- For $n_2<0$, it is pulled towards the operating wavelength λ_i.
- As λ_0 moves, the build-up factor increases accordingly.
- The build-up factor B starts to decrease when $\lambda_0 < \lambda_i$.

At $n_2 < 0$, the situation in (1) becomes unstable at the increasing B. It would suddenly jump to a stable situation in (2).

Parameters in nonlinear switching

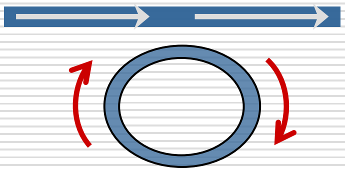


Extinction ratio
ER = ON/OFF

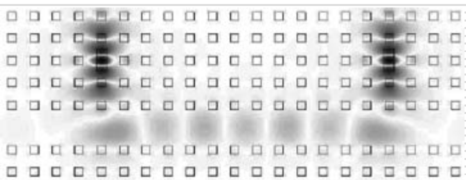
Modulation depth
MD = ON-OFF

Bistability in various configurations

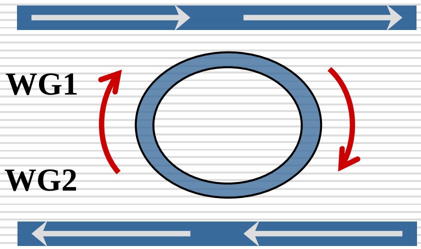
(1)



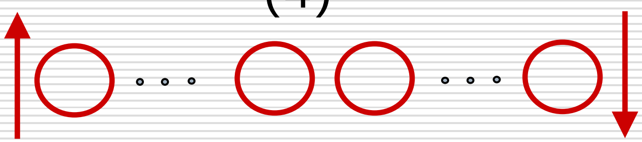
(2)



(3)



(4)



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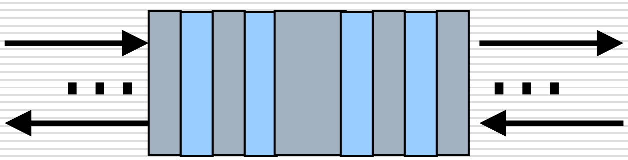
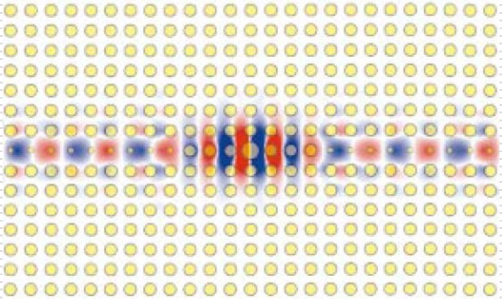
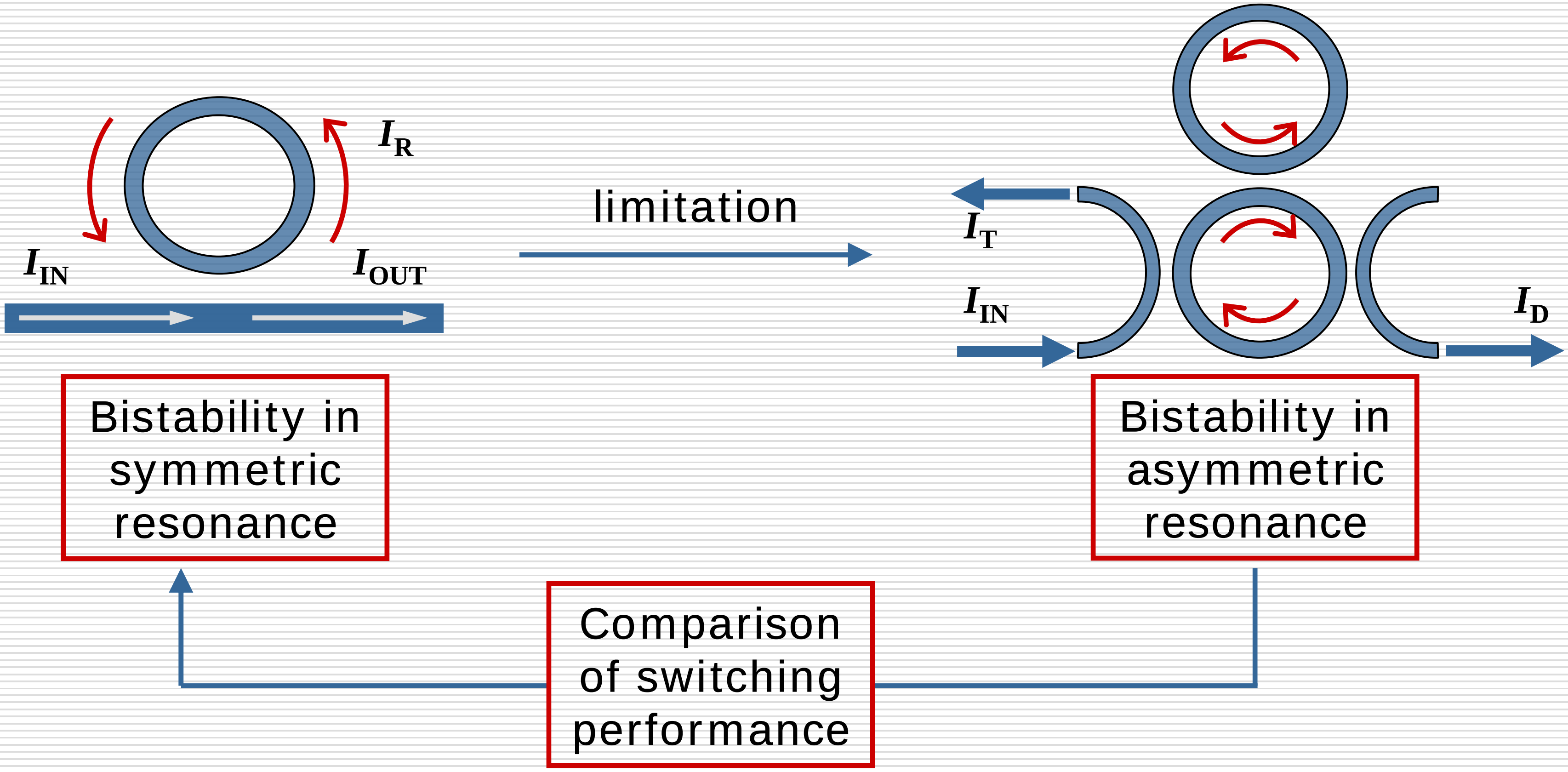


(6)



1. F. Sanchez, Opt. Commun. 142, 211 (1997).
2. B. Maes, et. al.. J. Opt. Soc. Am. B 22(8), 1778-1784 (2005).
3. Y. Dumeige, et. al.. Opt. Commun. 250 (2005) 376-383.
4. Y. Dumeige, et. al.. Phys. Rev. B, 72 066609 (2005).
5. J. Danckaert, et. al., Phys. Rev. B, 44, 15, 8214 (1991).
6. M. Soljačić, et. al., Phys. Rev. B, 66, 055601 (2002).

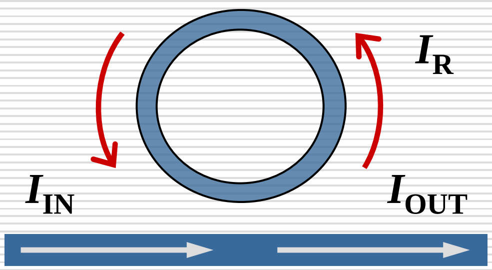
Outline

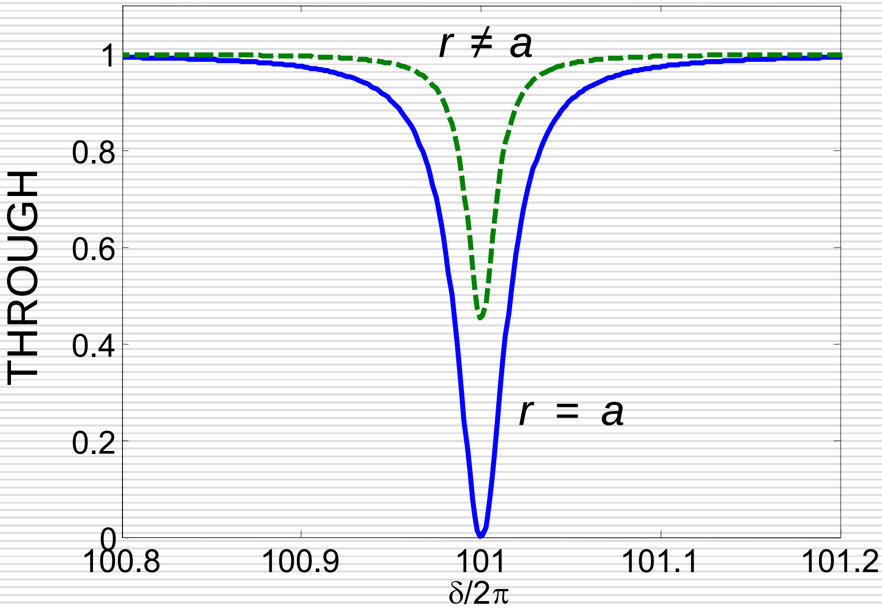


I_R
I_{IN}
I_{OUT}
limitation
I_T
I_{IN}
I_D
Bistability in symmetric resonance
Bistability in asymmetric resonance
Comparison of switching performance

One ring coupled to one bus

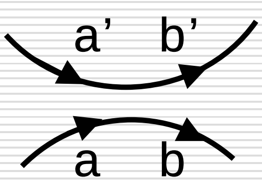
Critical coupling
$r = a$





Assumptions:

- Phase matched and lossless coupling.
- The effective index is constant within narrow range of frequency.



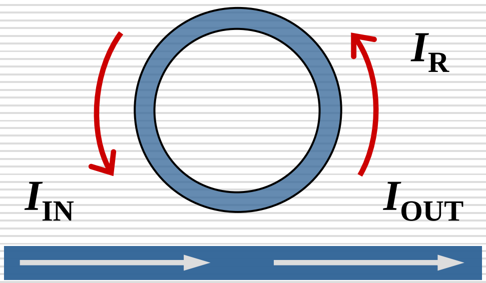
$$\begin{pmatrix} b' \\ b \end{pmatrix} = \begin{pmatrix} r & jt \\ jt & r \end{pmatrix} \begin{pmatrix} a' \\ a \end{pmatrix}$$

$$\delta = (\omega / c) n_{eff} L_C$$

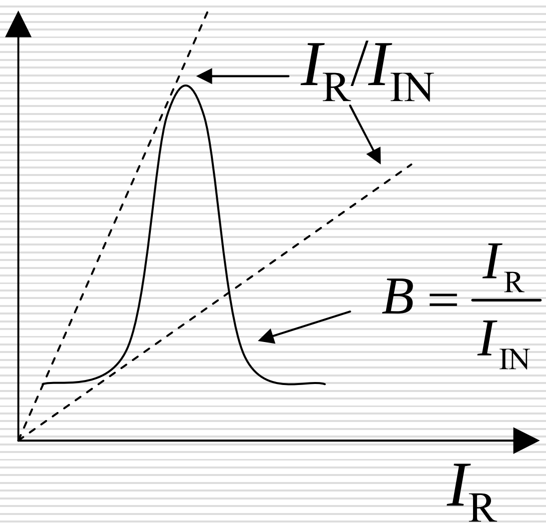
$$L_C = 2\pi R$$

$$r^2 + t^2 = 1$$

Parametric formulation



- The line slope becomes flatter at increasing input intensity I_{IN}.
- Multistability starts to occur when the there are more than one intersections.
- The corresponding I_{IN} and I_{OUT} can be found through I_R.



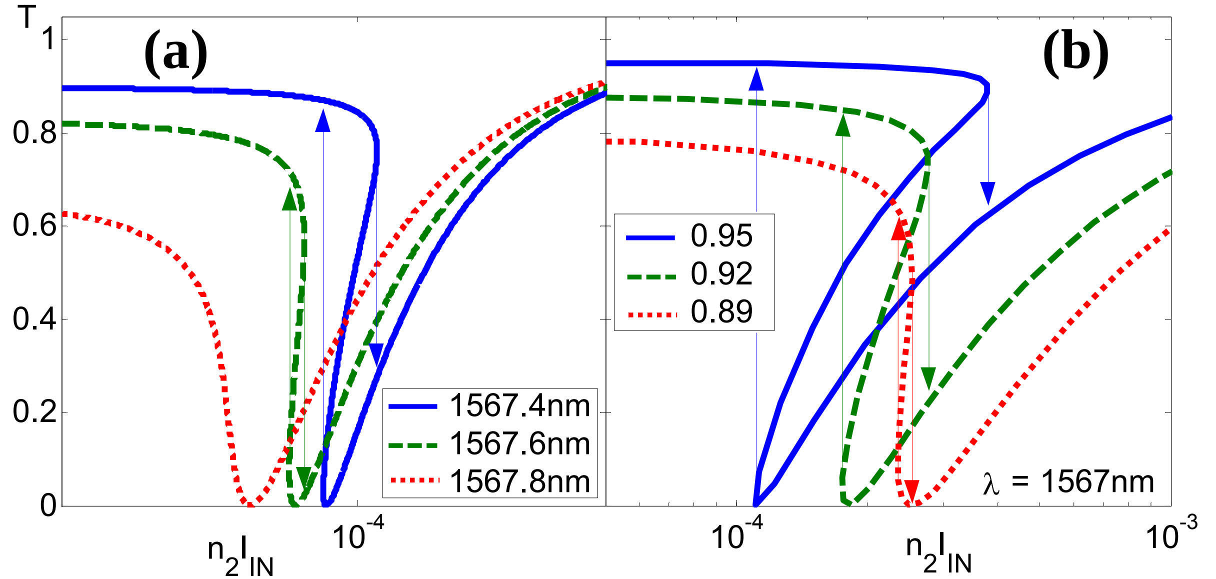
$$B = \frac{I_R}{I_{IN}} = \frac{1 - r^2}{1 - 2ra\cos\delta + r^2 a^2}$$

$$\delta(I_R) = \delta_L + \Delta\delta_{NL}(I_R) = \frac{2\pi L}{\lambda}\left(n_{\text{eff}} + n_2 \eta I_R\right)$$

$$\eta = \frac{1 - \exp(-\alpha L)}{\alpha L}$$

Only Kerr nonlinearity n_2 is assumed to present.

Nonlinear Spectrum



The nonlinear sensitivity is at best in the critical coupling condition.

Initial detuning condition

$$|\omega - \omega_0| \geq \Delta\omega\sqrt{3}/2$$

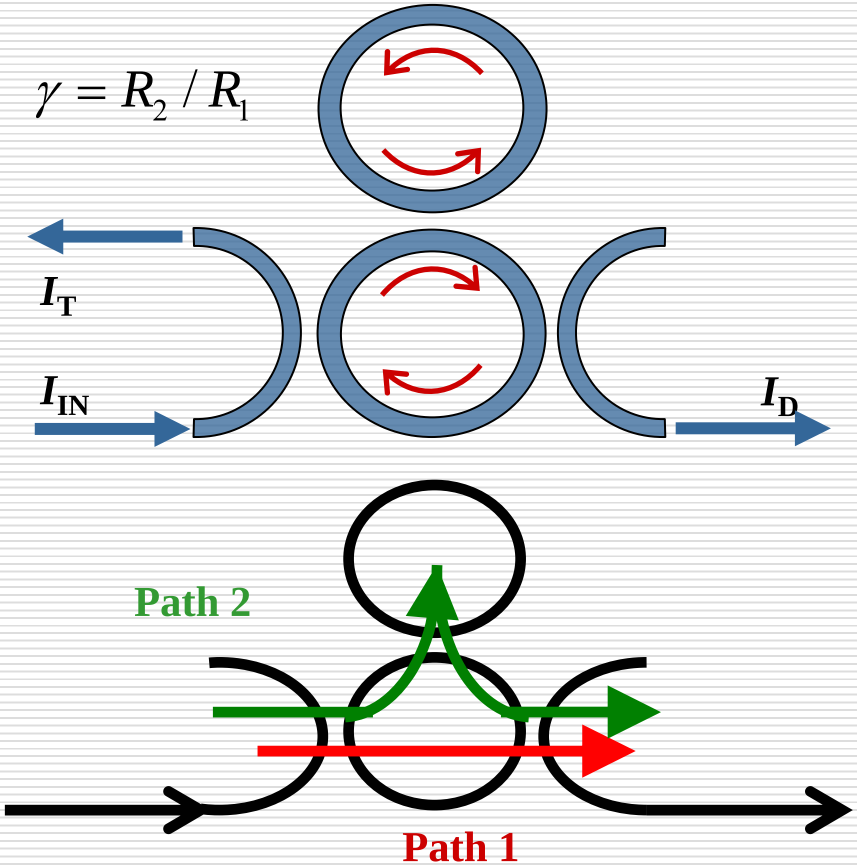
- Different curves in (a) correspond to different initial detuning. Bistability occurs only when detuning is larger than the critical detuning.
- Extinction ratio (ER) increases when detuning is closer to critical detuning.
- Figure (b) shows ER increases when the loss is increased, which broadens the linewidth. This has the same effect as if the detuning is closer to critical detuning. But broader linewidth also increases the input threshold.

Limitation of symmetric resonance

Difficult to obtain both high ER and large MD

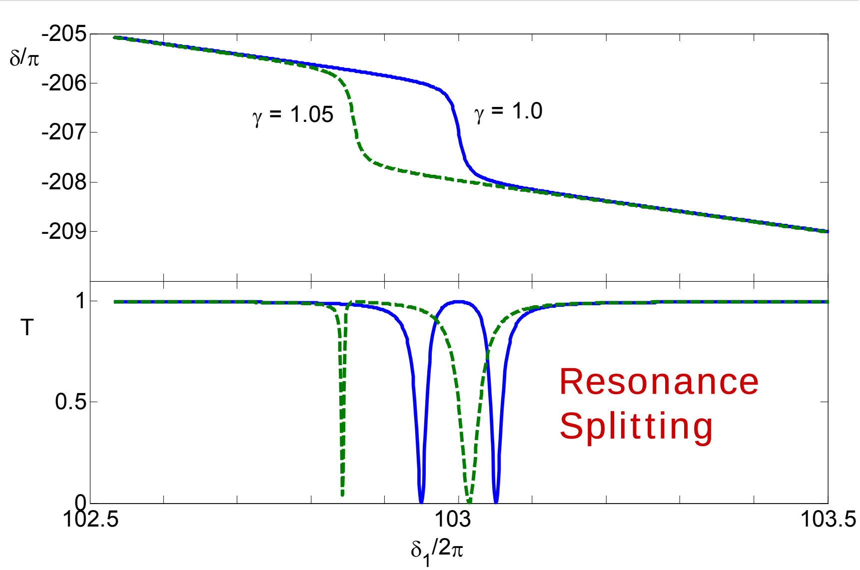
- Generally, high ER can be obtained if we place the operating wavelength very close to critical detuning.
- This makes, in critical coupling condition, the initial amplitude spectrum to be low.
- High ER consequently yields low ‘modulation depth’.

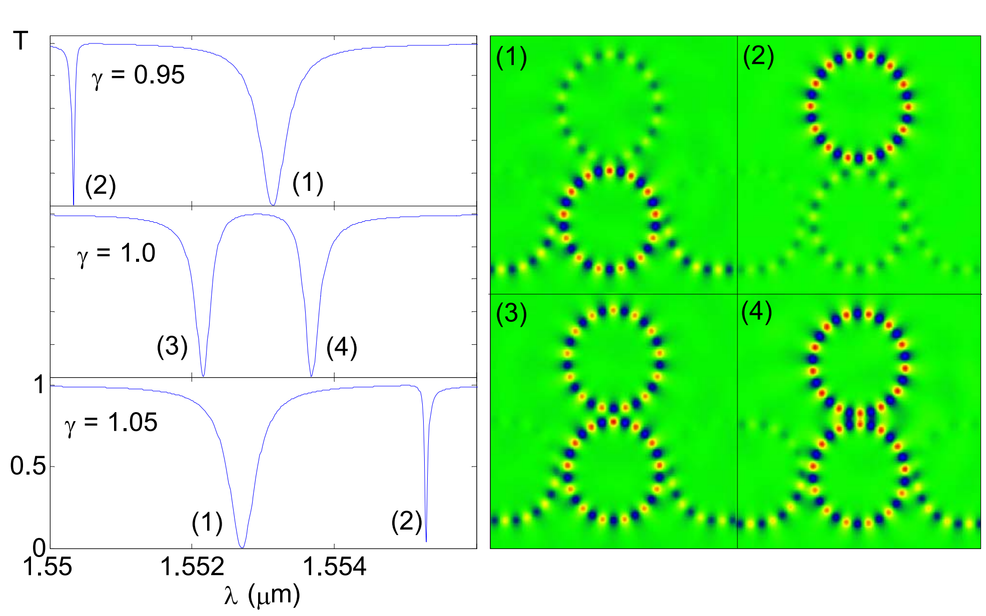
The Two Ring Configuration



- The upper ring provides optical feedback to the bottom ring.
- This induces significant phase perturbation at the vicinity of the upper ring resonance.
- This '**loading effect**' induces a large phase swing, where additional resonance is possible.
- The resonance is mainly due to the interference between the denoted pathways

Linear spectrum

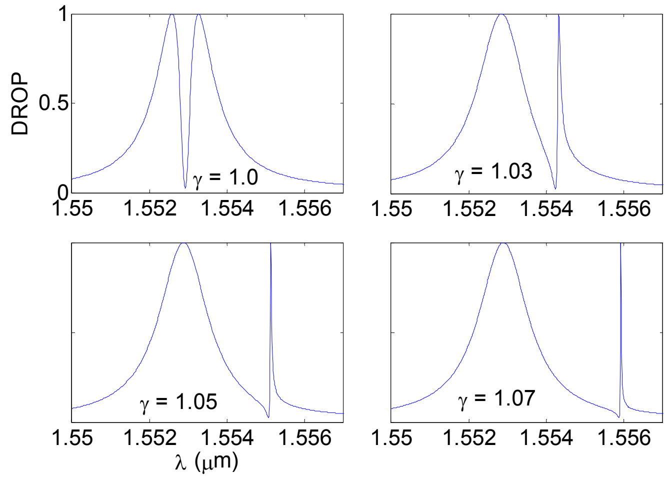


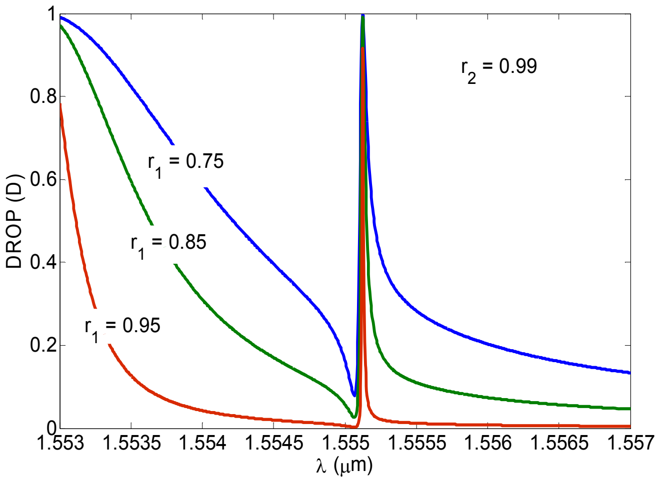


The modified round trip phase

$$\delta = \tan^{-1}\left\{\frac{a_2 \sin(\gamma\delta_1)}{r_2 - a_2\cos(\gamma\delta_1)}\right\} - \tan^{-1}\left\{\frac{a_2 r_2 \sin(\gamma\delta_1)}{1 - a_2 r_2 \cos(\gamma\delta_1)}\right\} - \delta_1$$

The tuning of Asymmetricity



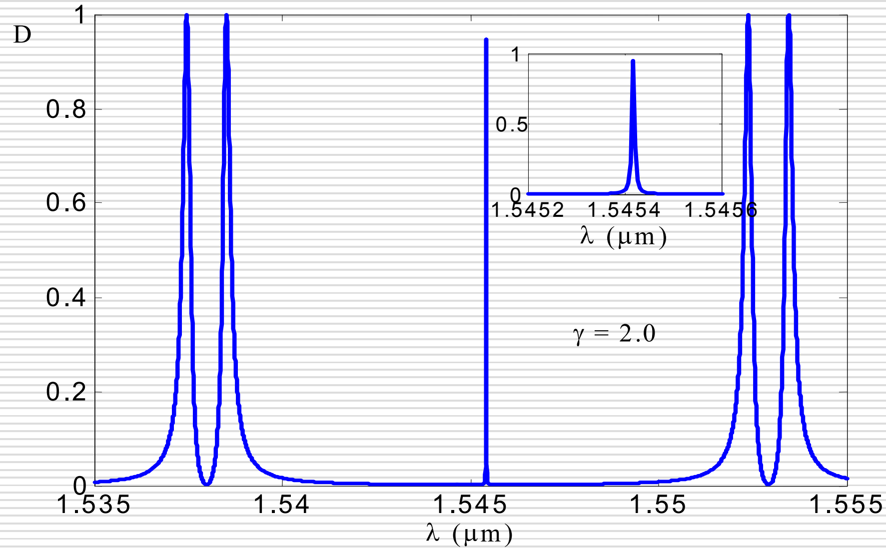


- At $\gamma = 1$, the resonances are split symmetrically. At $\gamma \neq 1$, the resonances are split asymmetrically, giving rise to asymmetric Fano-like resonance.
- The Fano resonance becomes narrower as it detunes farther from the bottom ring resonance.
- The asymmetricity can be tailored upon changing the 'envelope' from the bottom ring spectrum as denoted by changing r_1.

Linewidth 'shrinking'

•A Vernier effect at integer γ makes resonance splitting around the bottom ring resonance.

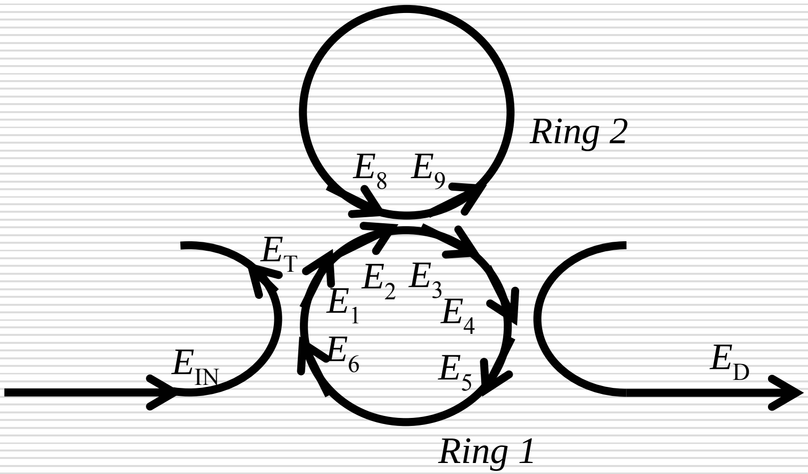
• At the upper ring resonance (just right in the middle), the symmetric Fano-like resonance arises, with the linewidth 'shrunk' by the build-up factor B_2 in the upper ring, relative to the bottom ring resonance linewidth.



$$D = |d|^2 \cong \frac{(1-r_1^2)^2}{(1-r_1^2)^2 + r_1^4(1+\gamma B_2)^2\theta^2},$$

$$\text{with } \theta_{\text{FWHM}} = \frac{2(1-r_1^2)}{r_1^2(1+\gamma B_2)}$$

Nonlinear Spectrum
(parametric formulation)



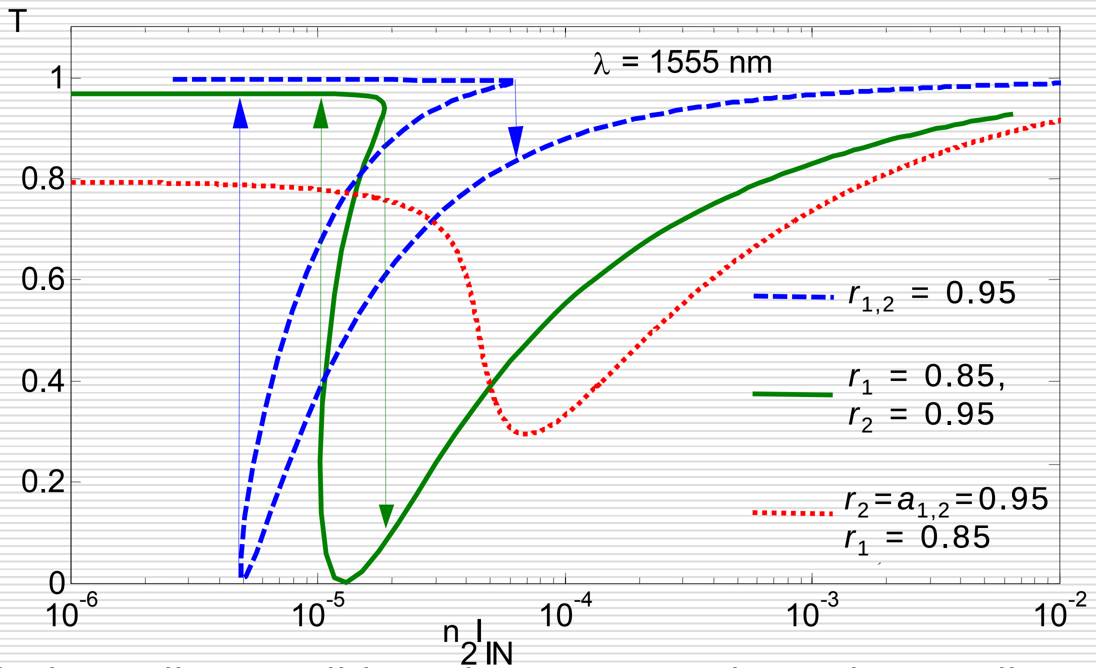
Set of equations

$$E_D = it_1 T_2 a_1^{1/2}\exp(i\gamma_{NL}^{14}\,|E_1|^2)\exp(-i\delta_1/2)E_1$$
$$E_T = [1 - a_1 T_2\exp(-i\delta_1)\exp(i\gamma_{NL}^{16}\,|E_1|^2)](r_1/it_1)E_1$$
$$E_{IN} = [1 - a_1 r_1^2 T_2\exp(-i\delta_1)\exp(i\gamma_{NL}^{16}\,|E_1|^2)](r_1/it_1)E_1$$
$$E_3 = [r_2 - a_2\exp(-i\delta_2)\exp(i\gamma_{NL}^{98}\,|E_9|^2)]E_9/it_2$$
$$E_2 = [1 - a_2 r_2\exp(-i\delta_2)\exp(i\gamma_{NL}^{98}\,|E_9|^2)]E_9/it_2$$
$$|E_2|^2\ a_1^{-1/2} = |E_1|^2,\ T_2 = E_3/E_2,\ \ a_{1,2} = \exp(-\alpha_{1,2}L_{1,2})$$
$$\gamma_{NL}^{ij} = k_0 n_{\text{eff}} n_2 c\varepsilon_o[1-\exp(-\alpha L_{ij})]/(2\alpha)$$

- For convenience, the E_9 is chosen as the parametric field.
- The loading effect is denoted by the T_2 in the set of equations.
- The $n_2 < 0$, R ~ 15 μm (*)

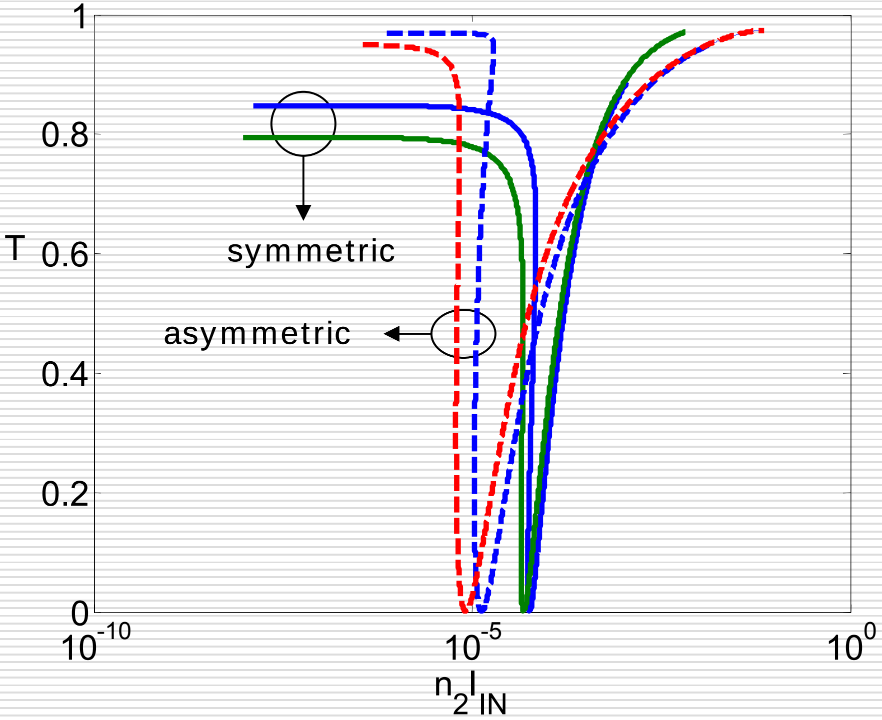
(*) We followed the n_2 and dimensions used in Y. Dumeige, et. al., Opt. Commun. 250 (2005) 376-383

Nonlinear Through (T) Output for different asymmetrical resonances



- In the critical coupling condition, the resonant absorption totally quenches the interference between the two pathways, thus degrading the nonlinear response.
- At non-critical coupling, the intensity build-up is faster as it increases but slower as it decreases.
- Therefore, the ER is significantly improved in a more asymmetric case.

Comparison between the two configurations (with the same optical bandwidth)



- Both configurations exhibit **~0.1nm** (10GHz) optical bandwidth, with ER > 10dB.
- Observably, the asymmetric resonance has 'wider critical detuning' as compared to the symmetric one.
- The asymmetric case has more modulation depth.
- If the relatively high MD is maintained, the input threshold for asymmetric case is one order lower.

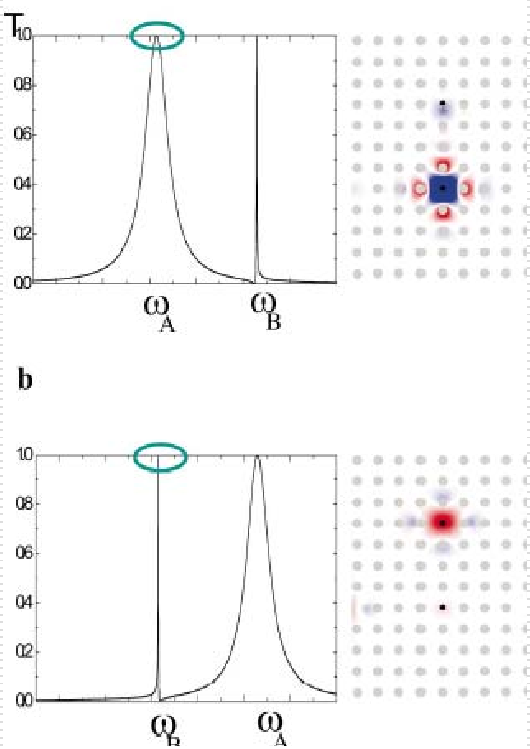
Conclusions

- Introducing asymmetricity increases the extinction ratio and modulation depth at the same time.
- To achieve a desired optical switching bandwidth, a compromise with the input threshold is necessary.
- Critical coupling degrades the switching performance by quenching the inter-pathways interference.
- The two-ring configuration can be used to generate ultra-narrow resonances.

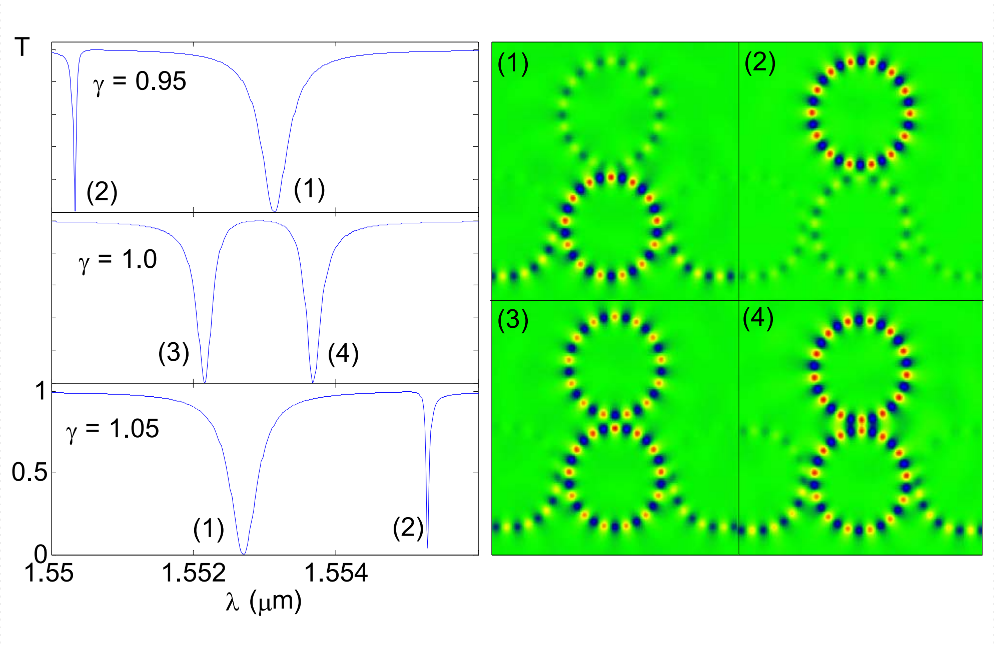
THANK YOU

Q&A

Verification with coupled mode theory from other works

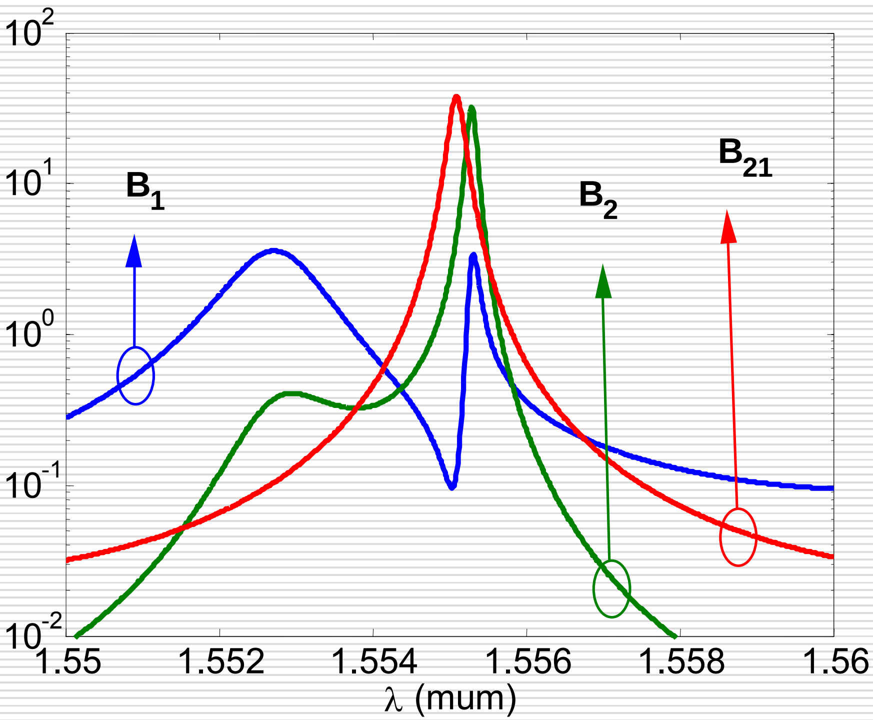


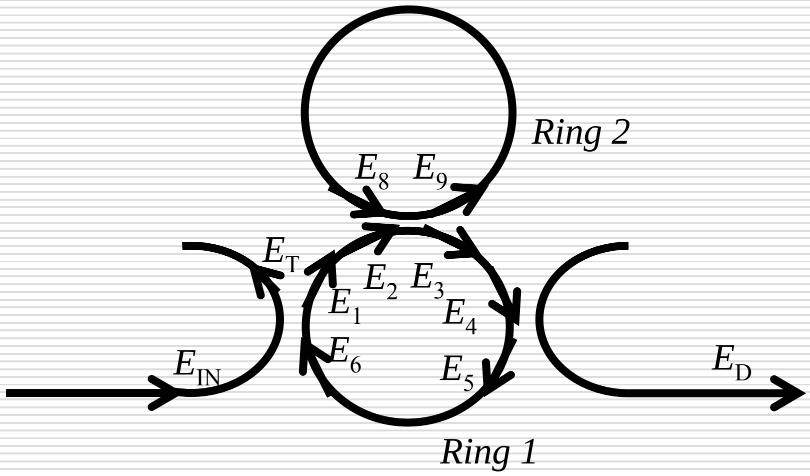
From Yanik et. al. (CMT)



Transfer matrix

Build-up factor in the respective rings





$$FE_{21} = \frac{E_9}{E_2} = \frac{it_2}{1 - a_2 r_2 \exp(-i\delta_2)}$$

$$FE_1 = \frac{E_1}{E_{IN}} = \frac{it_1 / r_1}{1 - a_1 r_1^2 T_2 \exp(-i\delta_1)}$$

$$FE_2 = \left(\frac{E_9}{E_2}\right)\left(\frac{E_2}{E_{IN}}\right) = a_1^{1/4} \exp(-i\delta_1/4)\left(FE_{21}\right)\left(FE_1\right)$$

Build-up slope in the upper rings