MSFC-409-Abstract

Quantum coherence effects in atomic media such as electromagnetically-induced transparency and absorption, lasing without inversion, super-radiance and gain-assisted superluminality have become well-known in atomic physics. But these effects are not unique to atoms, nor are they uniquely quantum in nature, but rather are fundamental to systems of coherently coupled oscillators. In this talk I will review a variety of analogous photonic coherence phenomena that can occur in passive and active coupled optical resonators. Specifically, I will examine the evolution of the response that can occur upon the addition of a second resonator, to a single resonator that is side-coupled to a waveguide, as the coupling is increased, and discuss the conditions for slow and fast light propagation, coupled-resonator-induced transparency and absorption, lasing without gain, and gain-assisted superluminal pulse propagation. Finally, I will discuss the application of these systems to laser stabilization and gyroscopy.

MSFC-409-Presentation

Coherence Phenomena in Coupled Optical Resonators

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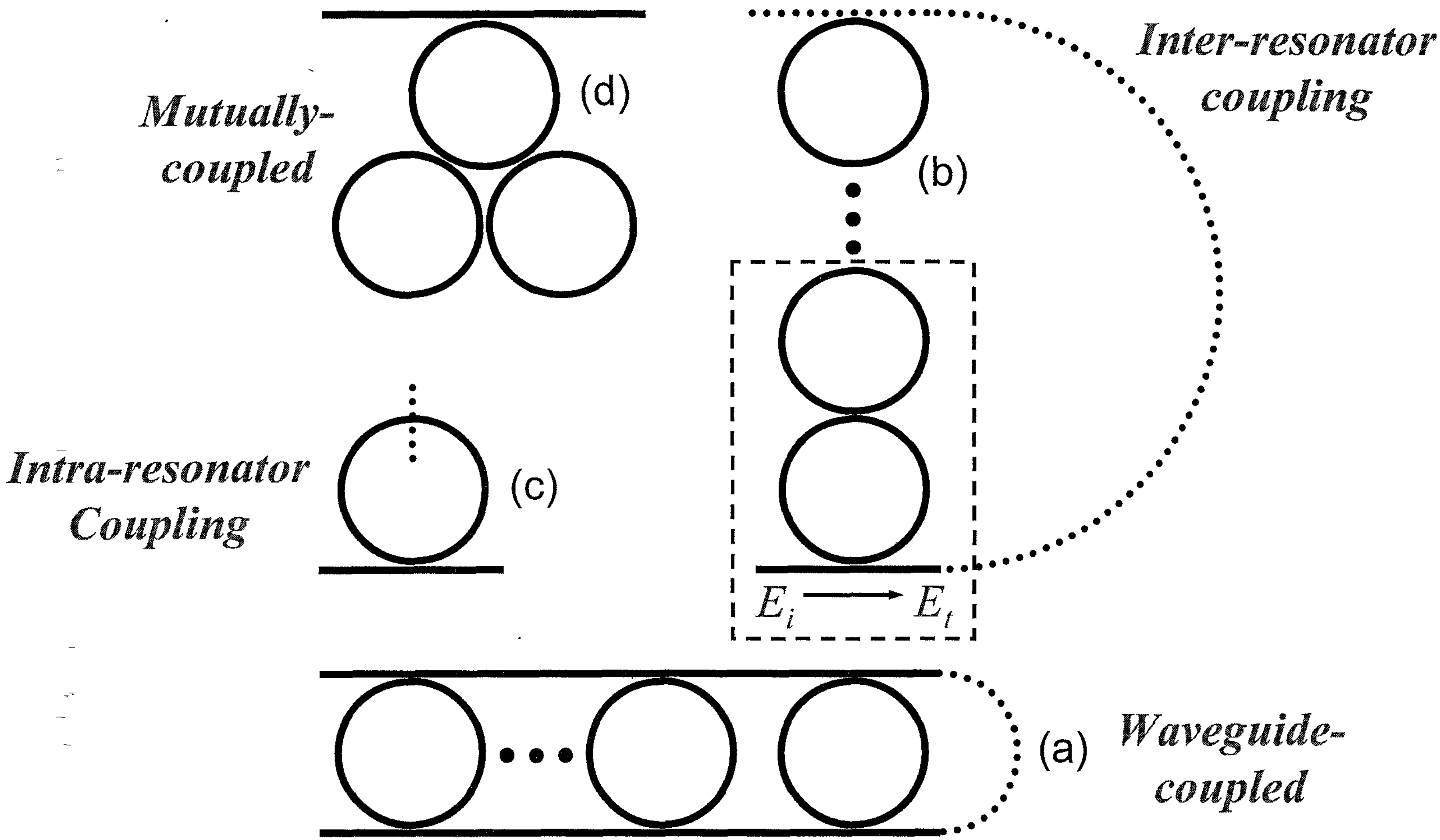
NASA
Marshall Space Flight Center

Outline

- WGM Splitting
- Coherence Effects in Passive Systems
  - Coupled-Resonator-Induced Transparency and Absorption (CRIT and CRIA)
  - Gain-Assisted Superluminality (GAS)
- Coherence Effects in Active Systems
  - Lasing Without Gain (LWG)
  - Reduced lasing thresholds
- Application: laser gyroscopy

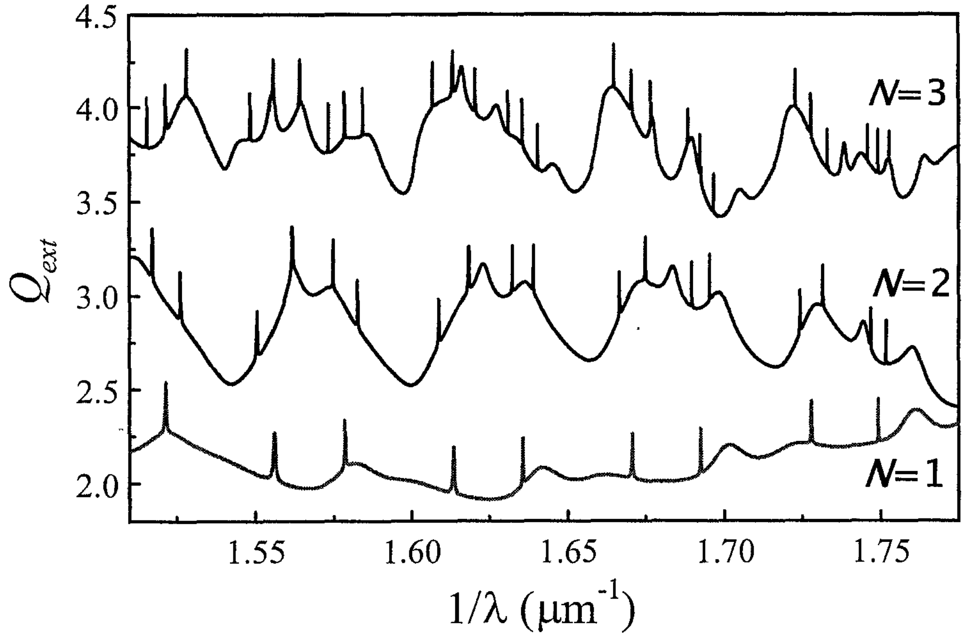
Varieties of Coupled Optical Resonators



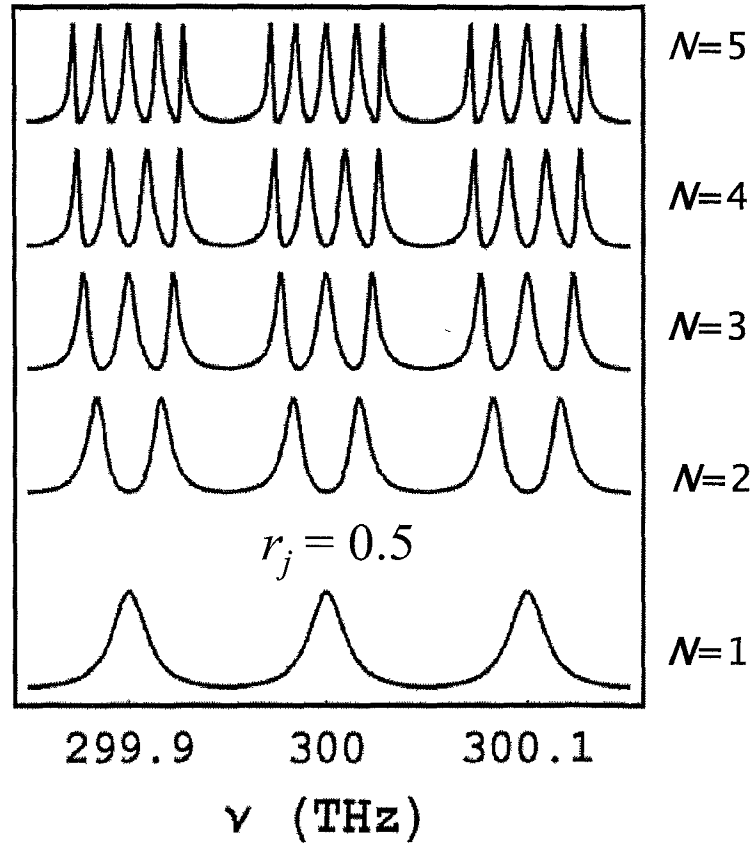
Whispering-Gallery-Mode Splitting

D.D. Smith, H. Chang, K. Fuller, *JOSA B* **20**, 1967 (2003).

Mode splitting in μ-particles

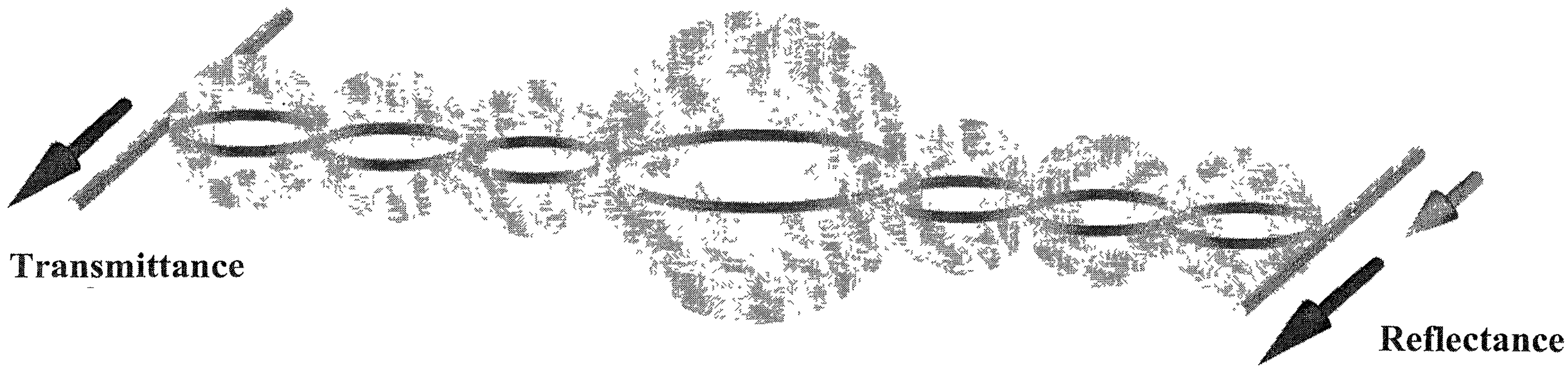


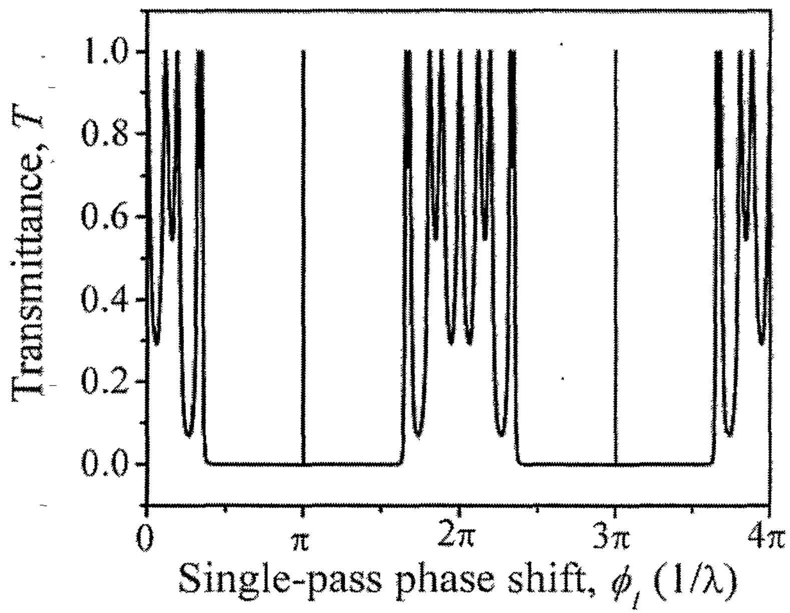
Mode splitting in ring resonators

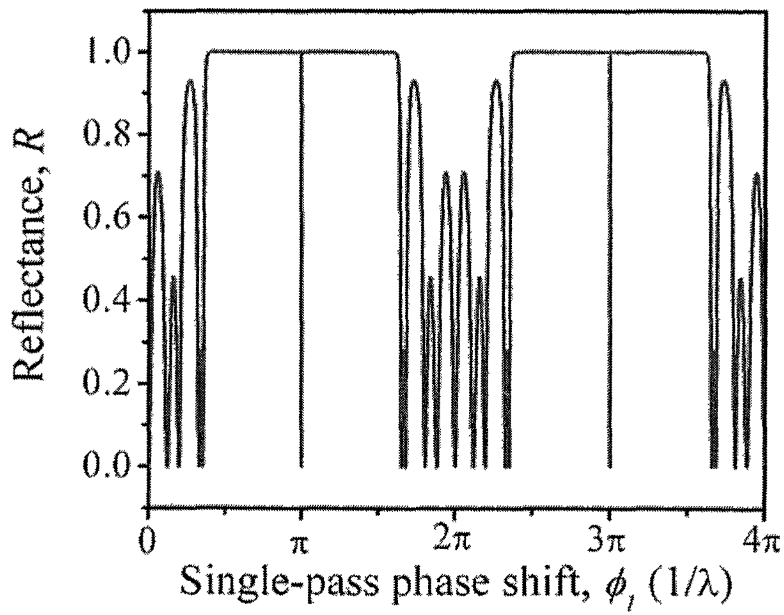


- Consequence of constructive (N odd) or destructive (N even) interference
- *N* resonators yiel

Tight-Binding PBGs in Photonic Molecules







Coupled Resonators = Two Level Atom

Coherent Superposition $|1\rangle$ $|2\rangle$

$$|\psi(t)\rangle = E_1(t)|1\rangle + E_2(t)|2\rangle$$

$$E_{1,2}(t) = a_{1,2}(t)\,\mathrm{e}^{\left[-i\,(\omega_{1,2}\mp\Delta)\,t\right]}$$

Slow-varying amplitudes

Coupled Modes = Schrod. Eqn. in RWA:

$$i\hbar\dot{\alpha}(t) = -\frac{\hbar}{2}\begin{pmatrix} -\tilde{\Delta} & \tilde{\kappa} \\ \tilde{\kappa} & \tilde{\Delta} \end{pmatrix}\alpha(t) = \tilde{H}\alpha(t)$$

Non-Hermitian Hamiltonian

$$\alpha(t) = \left[a_1(t) \quad a_2(t)\right]^{\mathrm{T}}$$ ***Rotating State***

$$\Omega_R \equiv \tilde{\kappa} \qquad \tilde{\Delta} \equiv \tilde{\omega}_1 - \tilde{\omega}_2 = \Delta + i\gamma_{12}/2$$ ***Complex NL Coupling and Detuning***

$$\alpha(t) = \begin{bmatrix} \tilde{\chi}_r & -\tilde{\chi}_i^* \\ \tilde{\chi}_i & \tilde{\chi}_r^* \end{bmatrix}\alpha(0)$$

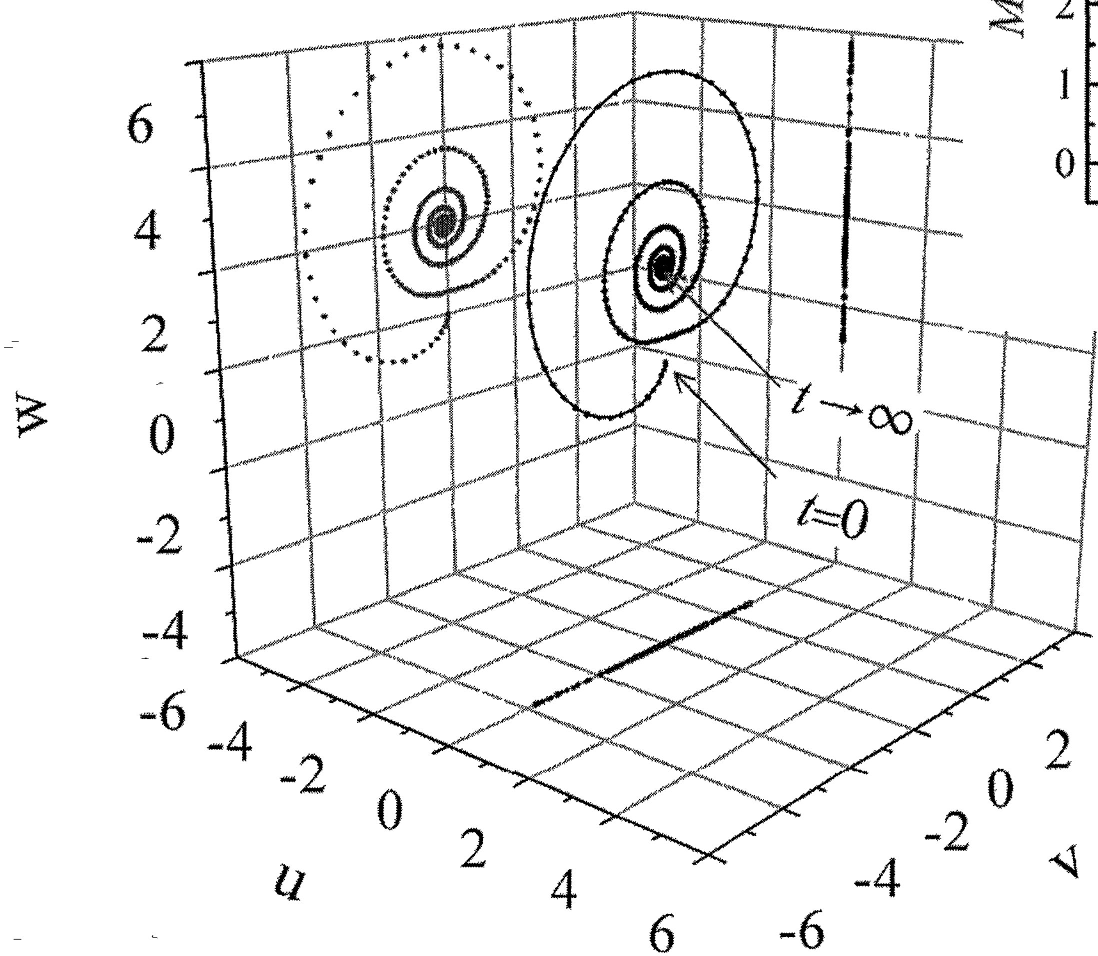
$$\tilde{\chi}_r = \cos\left(\tilde{\Omega}t/2\right) + i\left(\tilde{\Delta}/\tilde{\Omega}\right)\sin\left(\tilde{\Omega}t/2\right)$$

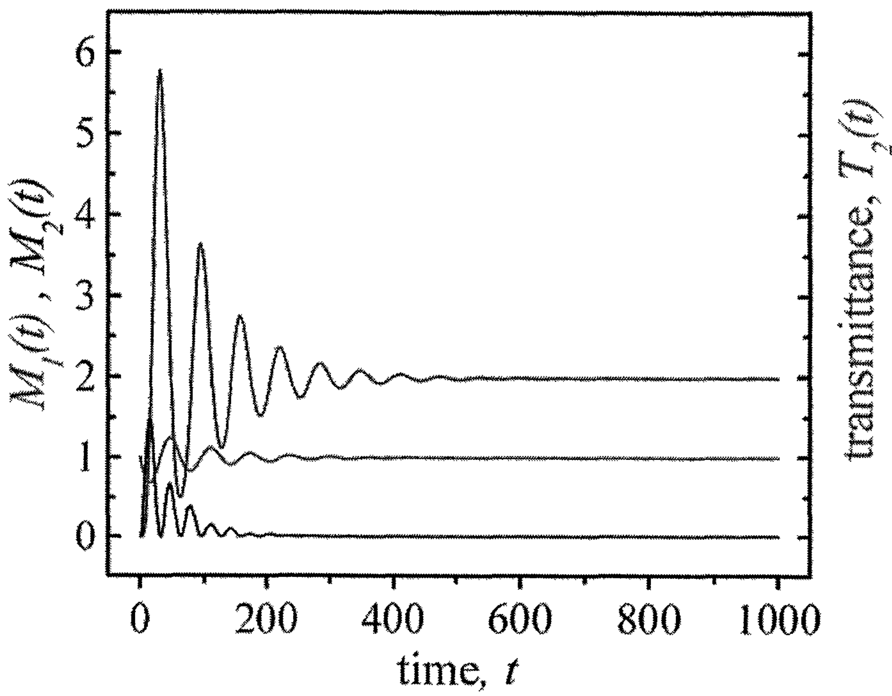
$$\tilde{\chi}_i = i\left(\Omega_R^*/\tilde{\Omega}\right)\sin\left(\tilde{\Omega}t/2\right)$$

$$\tilde{\Omega} \equiv \sqrt{\tilde{\Delta}^2 + |\Omega_R|^2}$$ ***Complex Generalized Rabi Frequency*** → ***Damped Rabi Oscillations!***

If $\gamma_{12} \neq 0 \rightarrow$ H is non-Hermitian, dressed states couple

Rabi Flopping

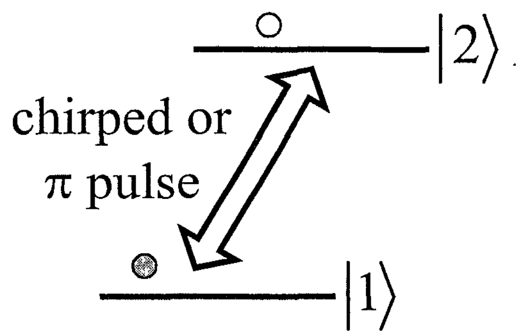


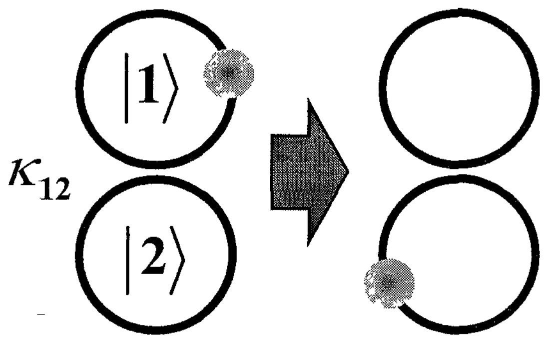


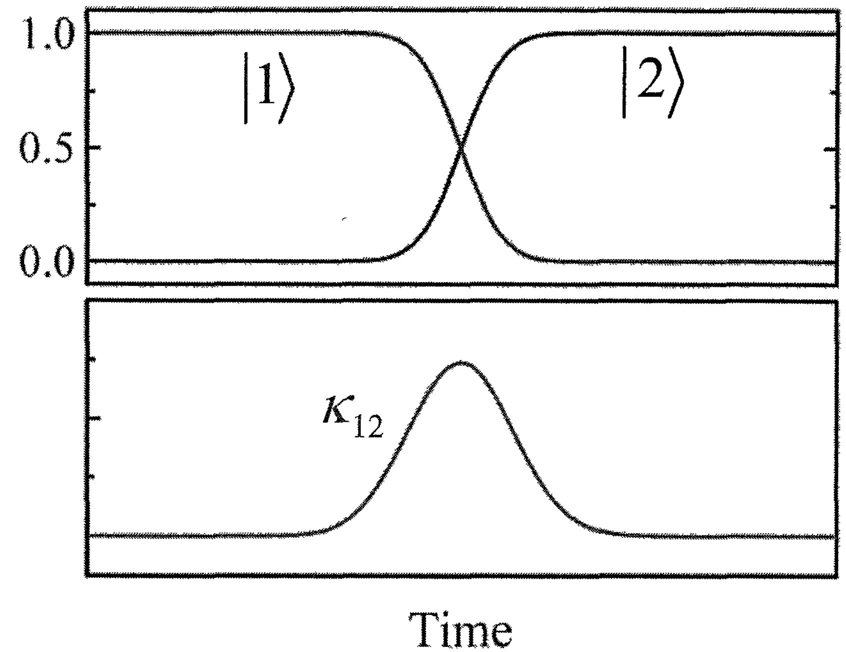
Coupled Resonator Density Matrix:

$$\rho = \begin{pmatrix} E_1 E_1^* & E_1 E_2^* \\ E_2 E_1^* & E_2 E_2^* \end{pmatrix}$$

Coherent Photon Transfer in Coupled Resonators

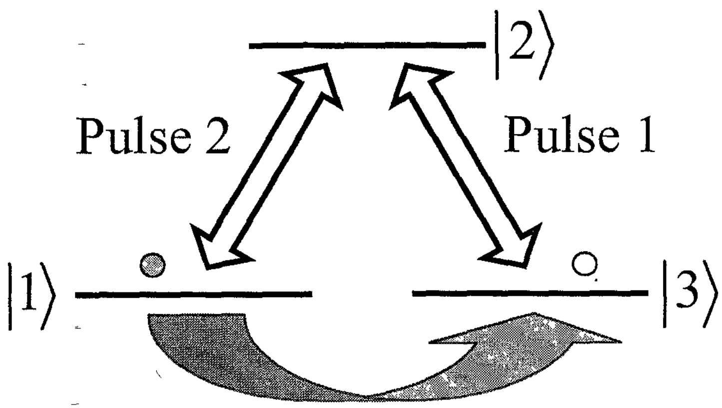


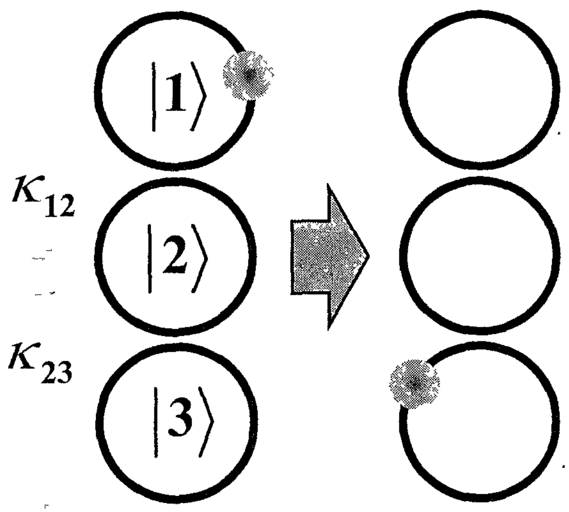


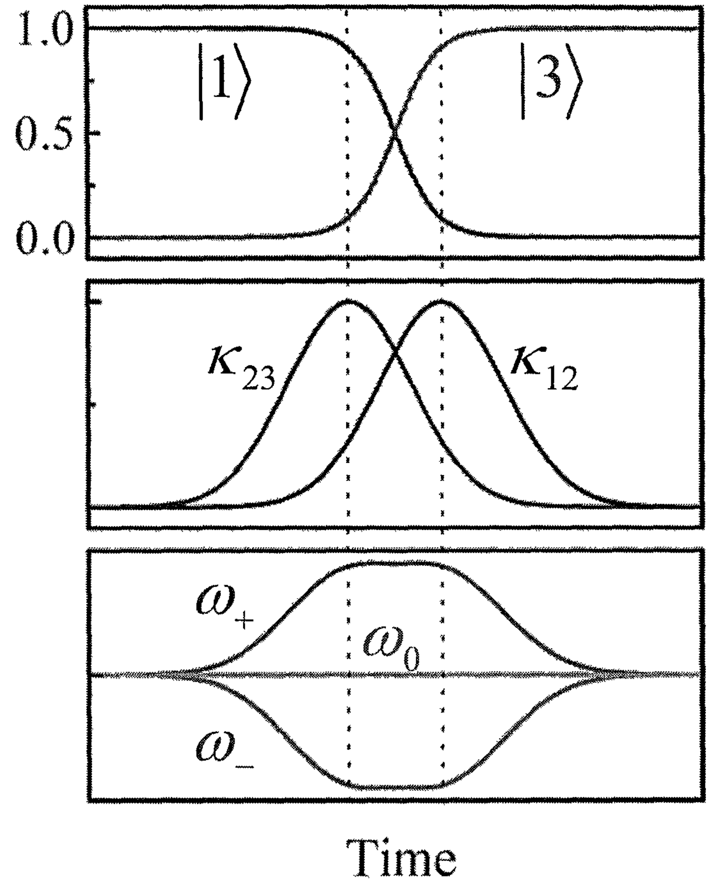


- ***Only coherent excitation yields full transfer***
- ***Sensitive to pulse area and frequency***
- ***Adiabatic transfer independent of pulse area but requires long slow chirp***

Stimulated Raman Adiabatic Passage (STIRAP)

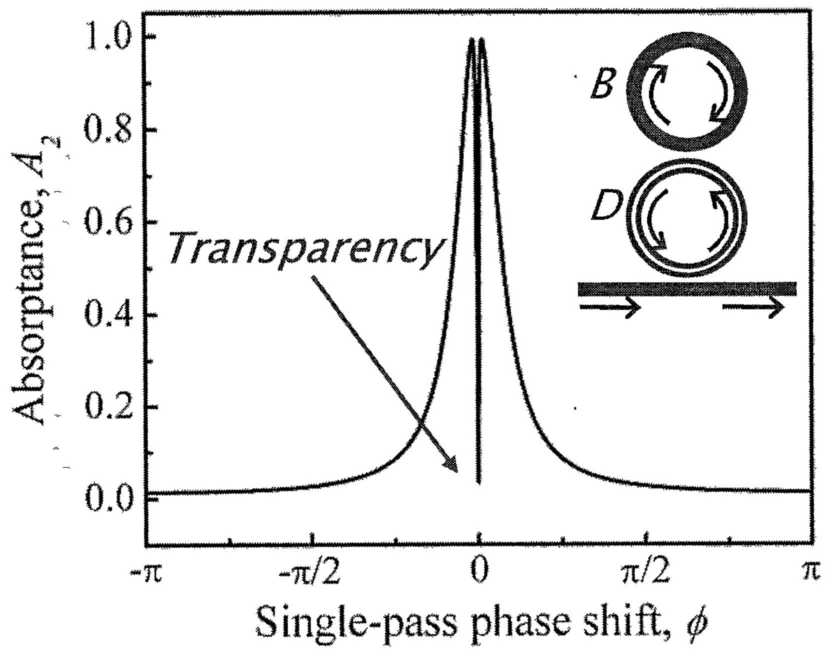


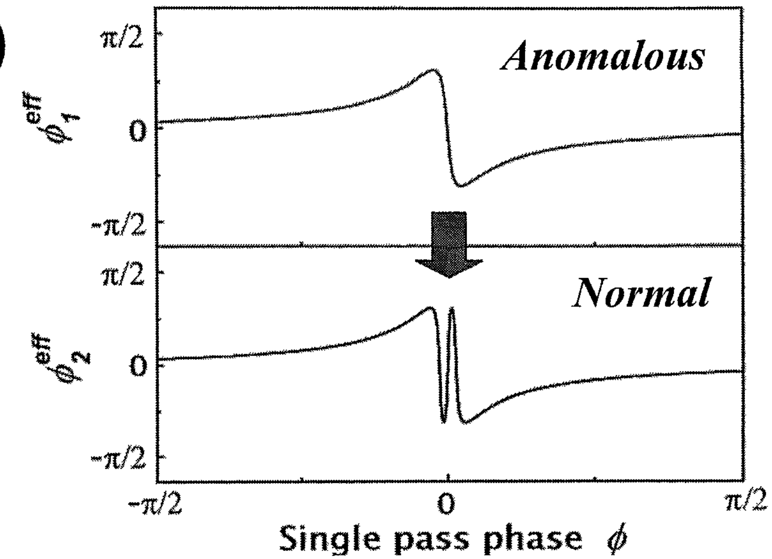




- ***Counterintuitive pulse sequence***
- ***Insensitive to pulse area – rapid transfer***
- ***Requires 2 but not 1 photon resonance***

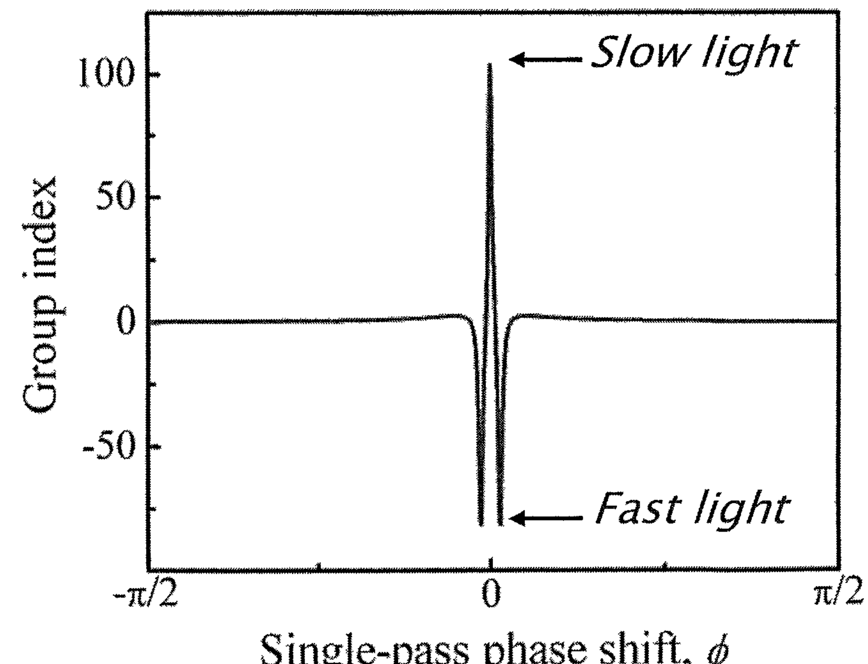
Coupled-Resonator-Induced Transparency (CRIT)





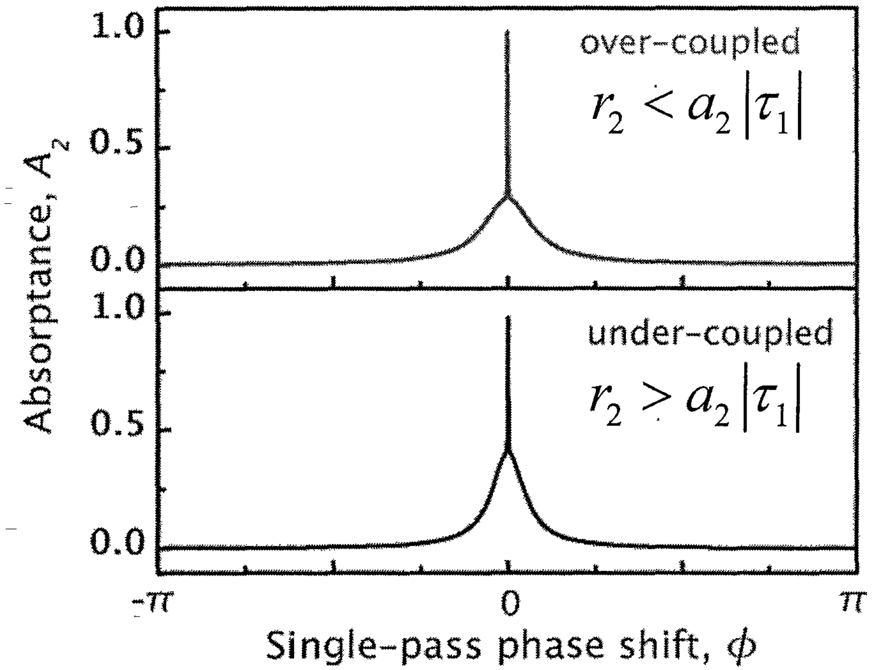
- *Photon Trapping!*
- *Slow light with no absorption!*

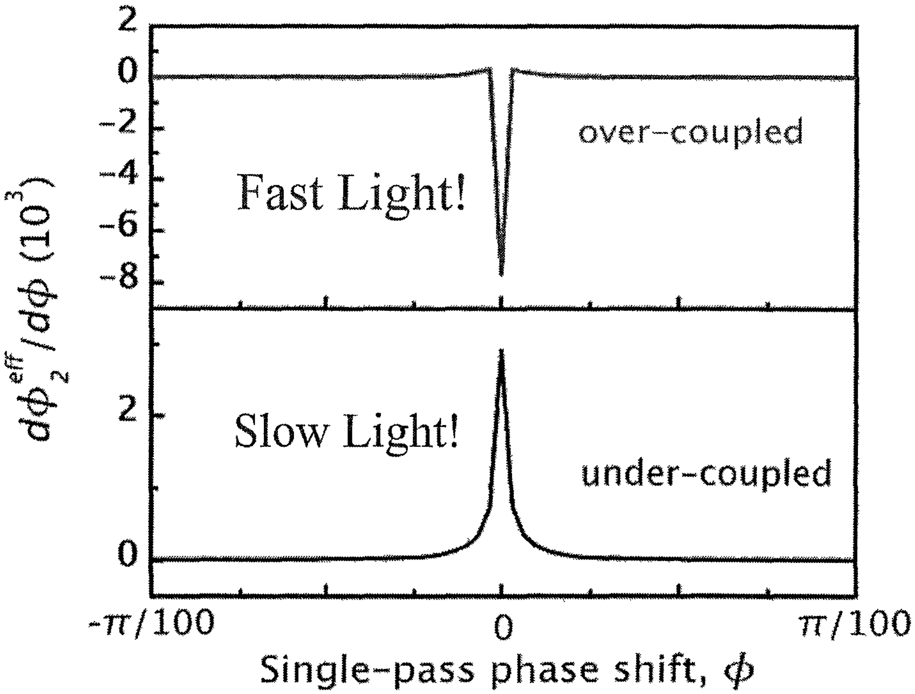
D.D. Smith, H. Chang, K. Fuller, A.T. Rosenberger, R.W. Boyd, *PRA* (2003).



Coupled-Resonator-Induced Absorption (CRIA)

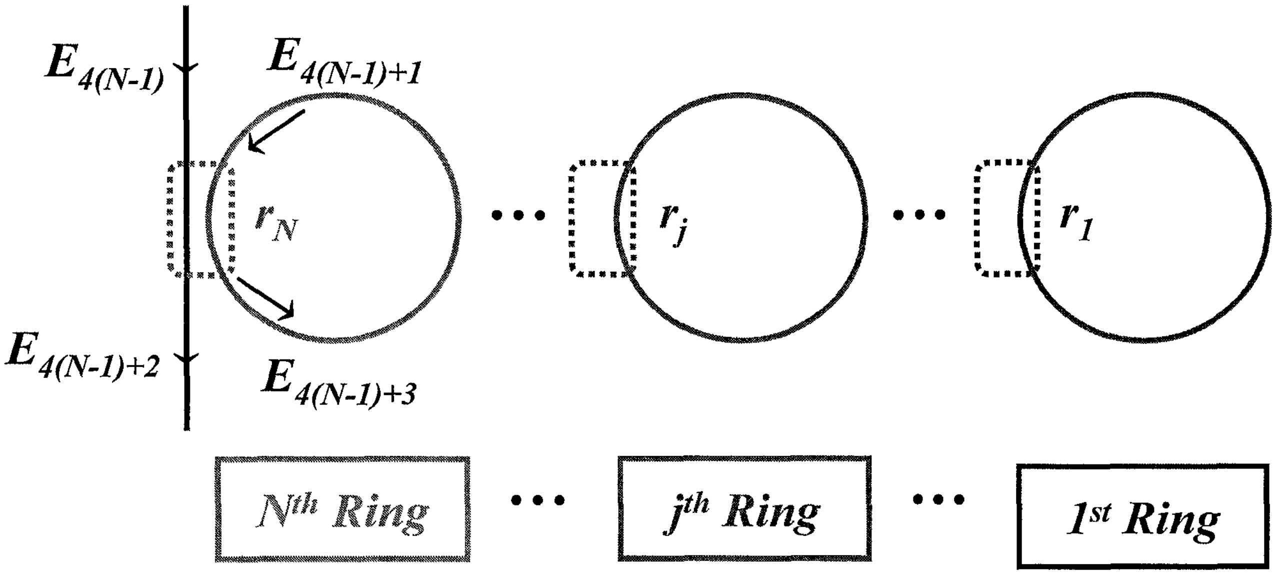
- Analogous to Electromagnetically-Induced Absorption (EIA)
- Typically results from ***Constructive*** Interference!
- Requires the second resonator to be over-coupled ($r_2 < a_2$)





D.D. Smith, H. Chang, K. Fuller, *JOSA B* **20**, 1967 (2003).

N Coupled Ring Resonators



Coupling

$$\begin{pmatrix} E_{4(j-1)+2} \\ E_{4(j-1)+3} \end{pmatrix} = \begin{pmatrix} r_j & it_j \\ it_j & r_j \end{pmatrix} \begin{pmatrix} E_{4(j-1)} \\ E_{4(j-1)+1} \end{pmatrix}$$

\+

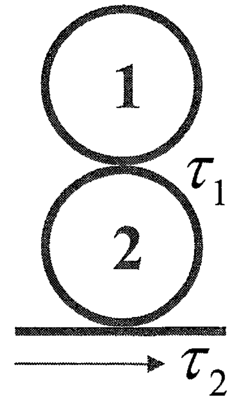
Feedback

$$E_{4(j-1)+1} = a_j e^{i\phi_j} E_{4(j-1)+3}$$

$$i = e^{i\pi/2}$$

→ π phase shift results after 2 passes across coupler!

Frequency Response



$$\tau_1(\phi_1) = \frac{r_1 - a_1 e^{i\phi_1}}{1 - r_1 a_1 e^{i\phi_1}} = |\tau_1| \exp\left[i\phi_1^{(\text{eff})} \right]$$

Airy Expressions

$$\tau_2(\phi_1, \phi_2) = \frac{r_2 - a_2 \tau_1 e^{i\phi_2}}{1 - r_2 a_2 \tau_1 e^{i\phi_2}} = |\tau_2| \exp\left[i\phi_2^{(\text{eff})} \right]$$

$$= \exp\left[i\tilde{\phi}_2^{(\text{eff})} \right] \qquad \tilde{\phi}_2^{(\text{eff})} = \phi_2^{(\text{eff})} - i \ln|\tau_2|$$

Complex Phase

Dispersive Response

$$\phi_2^{(\text{eff})}(\phi_1, \phi_2) = \arg(\tau_2)$$

> ➢ ***Slow or Fast Light***

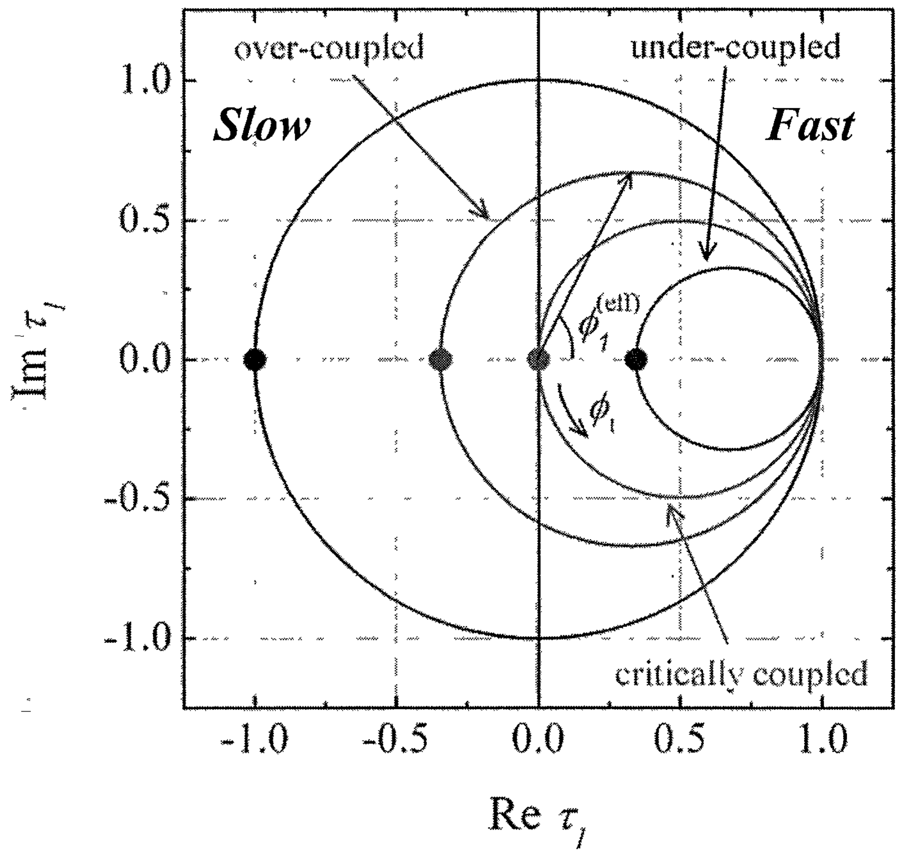
Absorptive Response

$$T_2 = |\tau_2|^2 \qquad A_2 = 1 - T_2$$

> ➢ ***CRIT or CRIA***

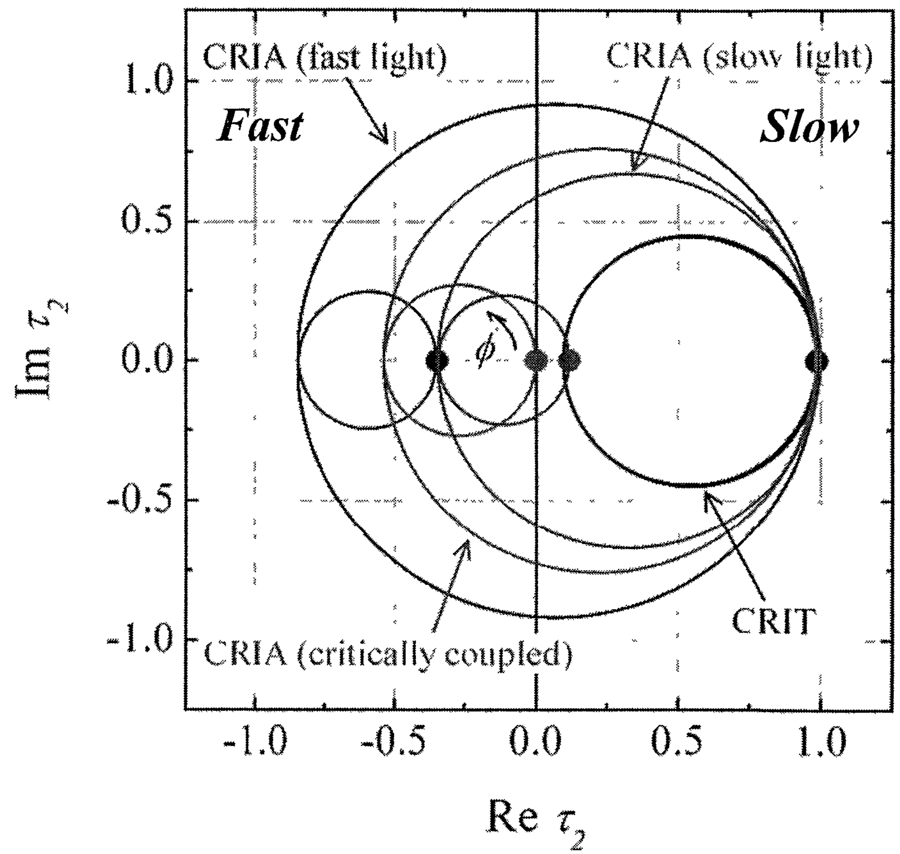
Transmission Argand Diagrams

Single Resonator



> ➢ ***Slow light on the left!***

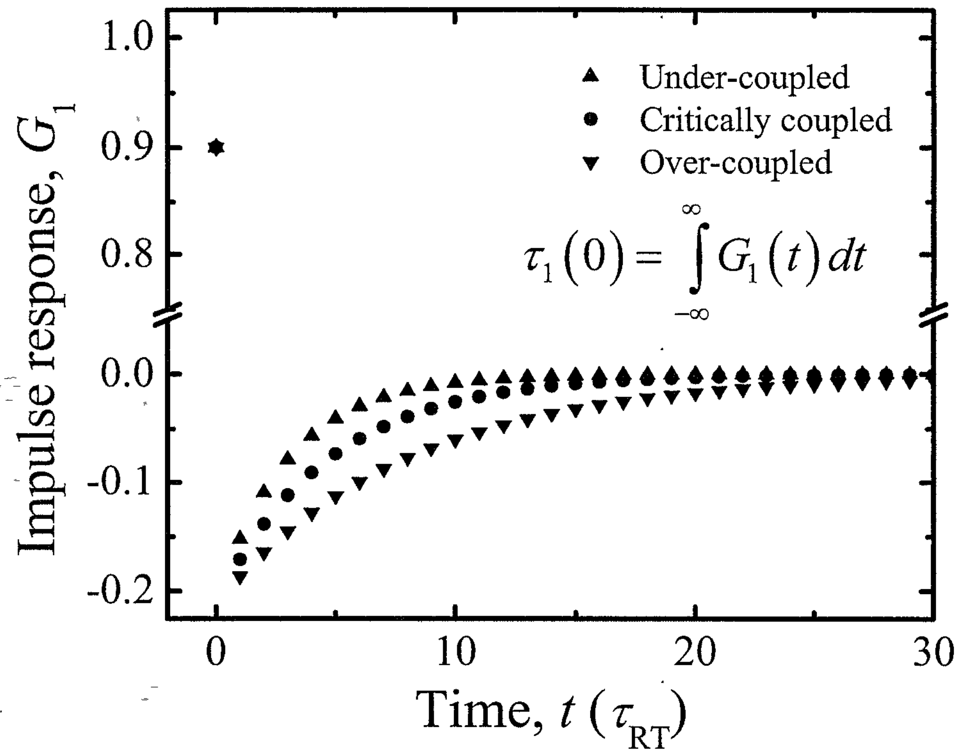
Two Resonators



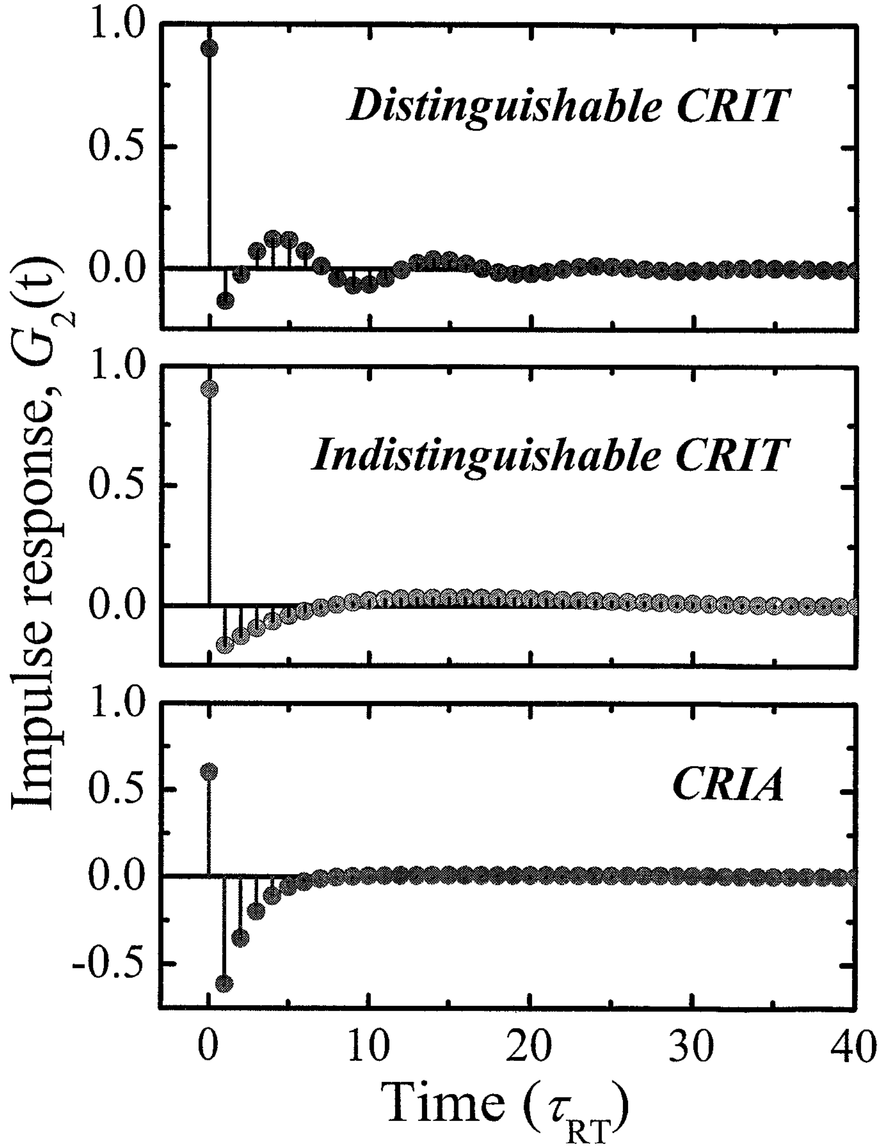
> ➢ ***Slow light on the right!***

Impulse Response

Single Resonator:

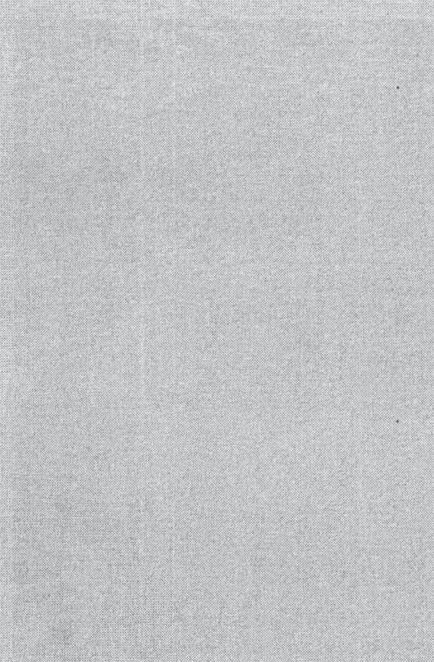


Coupled Resonators:

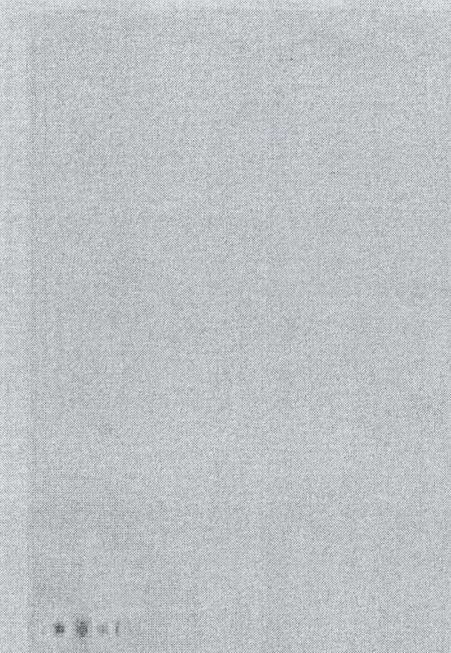


- ***Single - Exponential Decay***
- ***Coupled - Non-exponential Decay***

FDTD of CRIA and CRIT

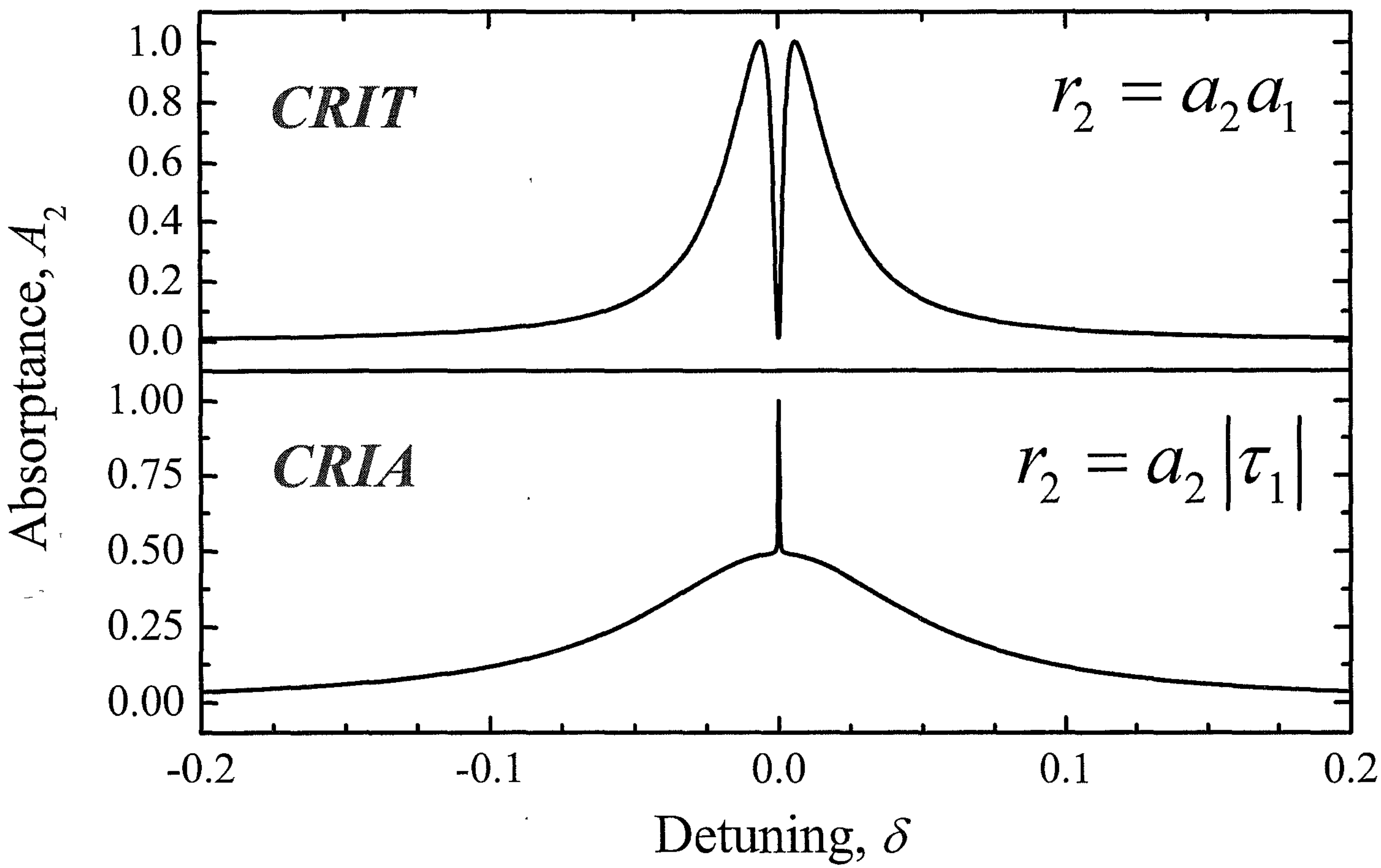


CRIA

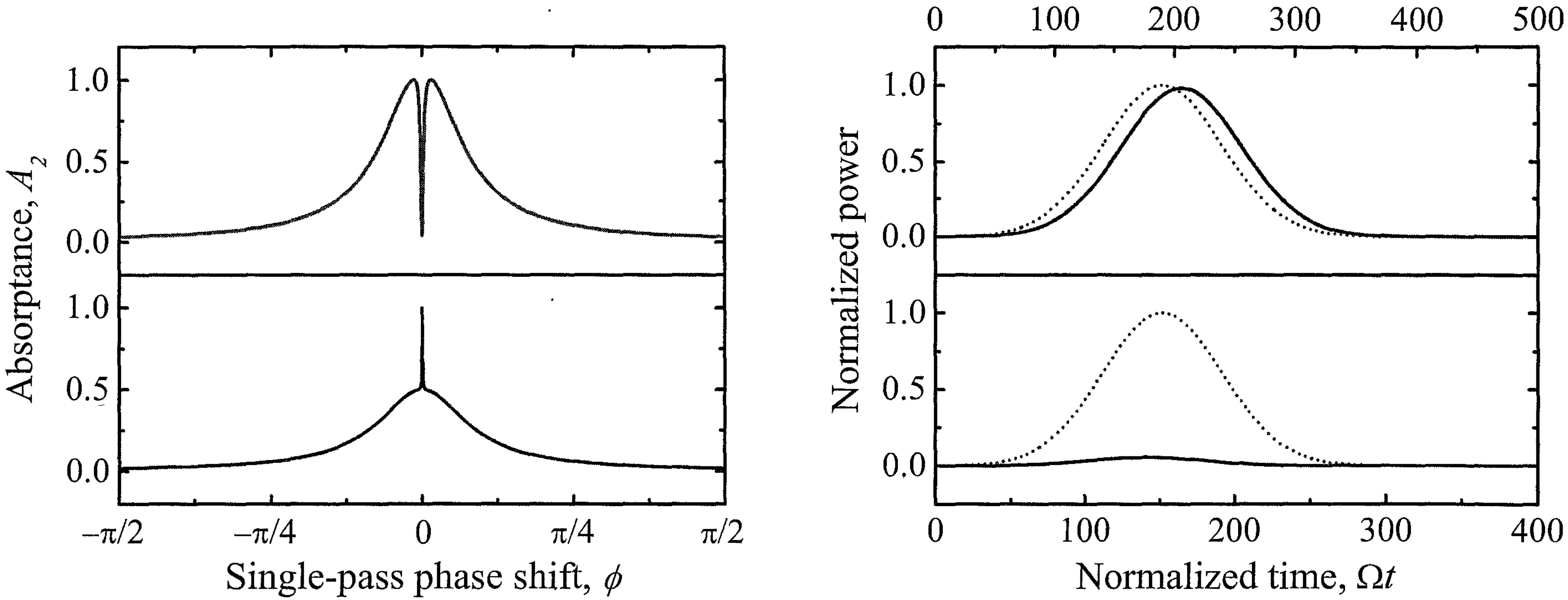


CRIT

Critical Coupling of CRIT and CRIA

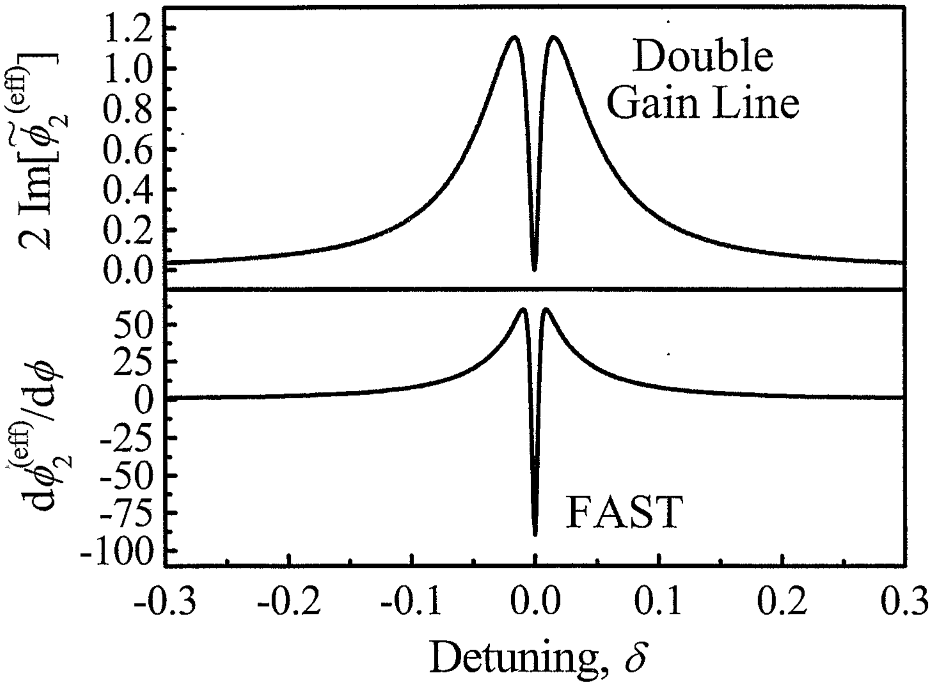


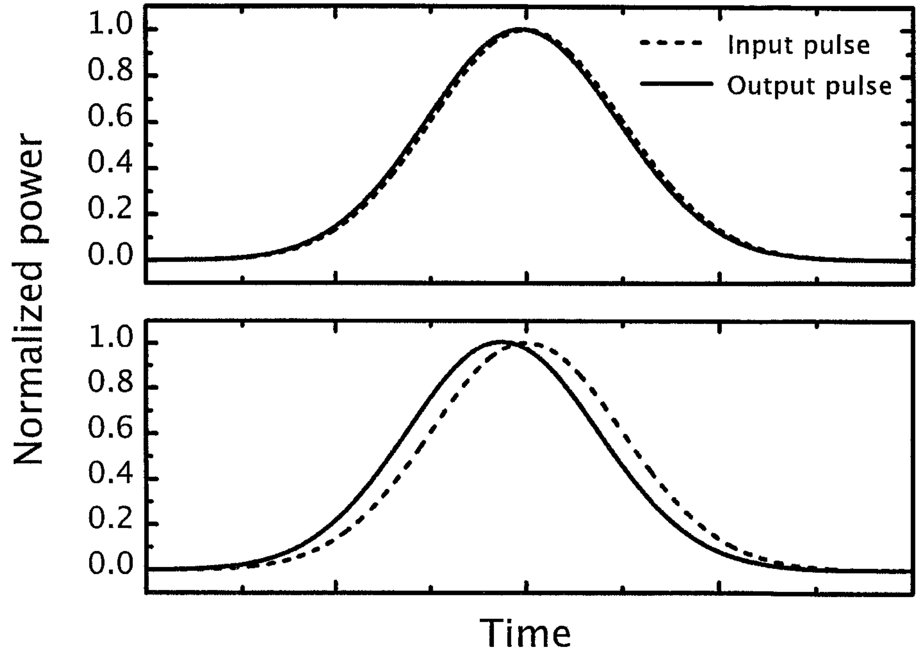
Slow and Fast Pulse Propagation



- Slow light with no absorption
- But fast light requires loss to obey causality / Relativity

Gain-Assisted Superluminality



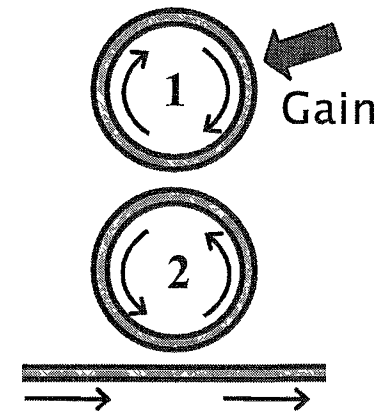


H. Chang, D.D. Smith, JOSA B (2005).

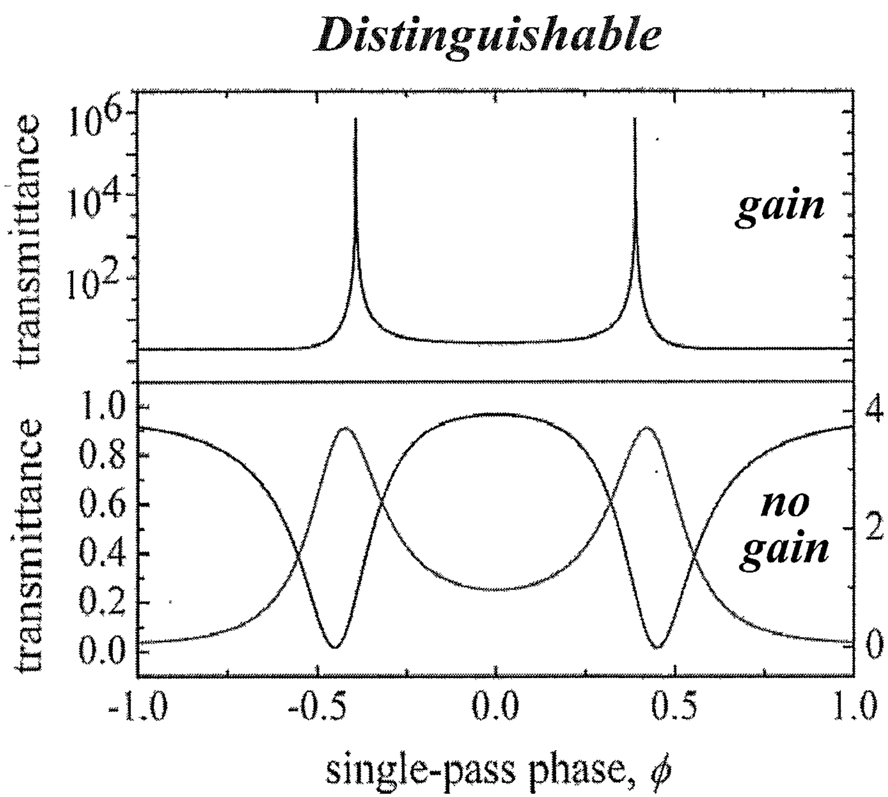
- Fast light in a transparent medium!
- Gain-assist reverses dispersion / CRIA boosted to transparency
- Still does not violate causality

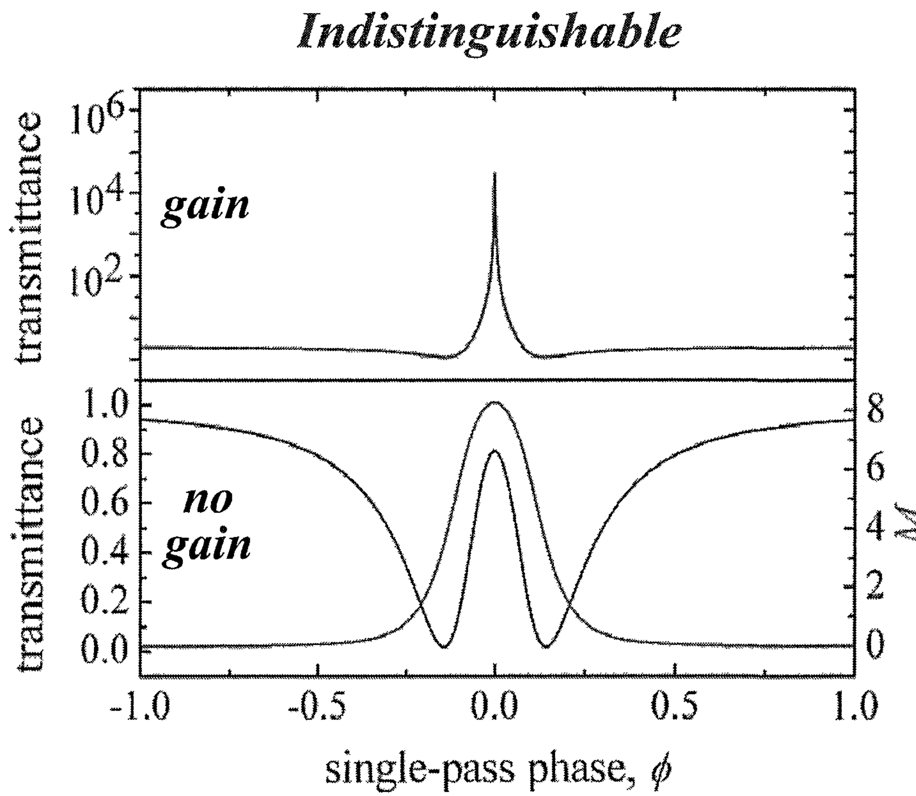
Wang, Kuzmich, Dogarlu, Nature, 406, 277 (2000).

Lasing in Coupled Resonators



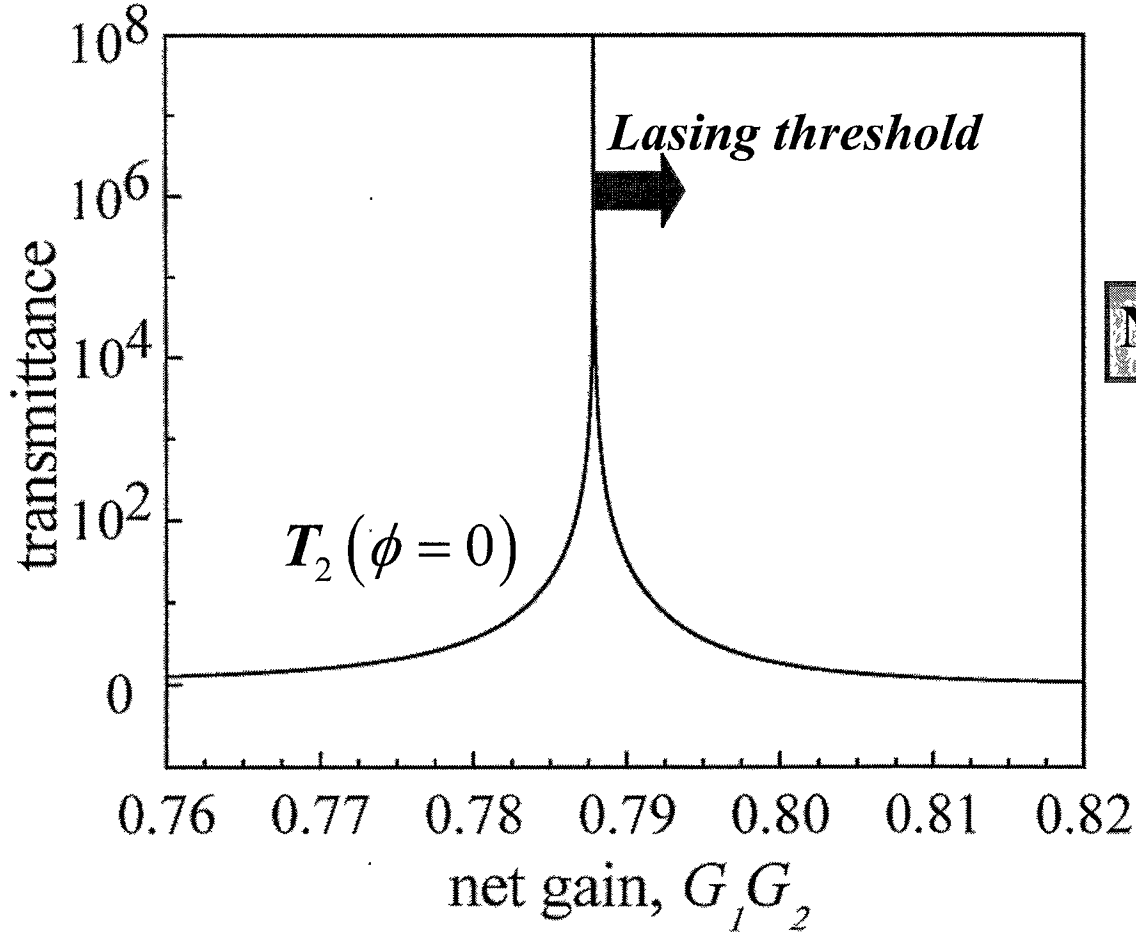
- Coherence affects lasing threshold!
- LWI and Super-radiance analogs





Lasing Without Gain in Coupled Resonators

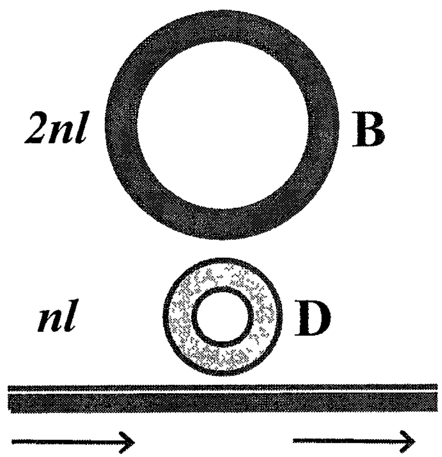
- Analogous to LWI ($N_e < N_g$): Gain in resonator 1 < Loss in resonator 2
- Lasing occurs by photon trapping – indistinguishability required.



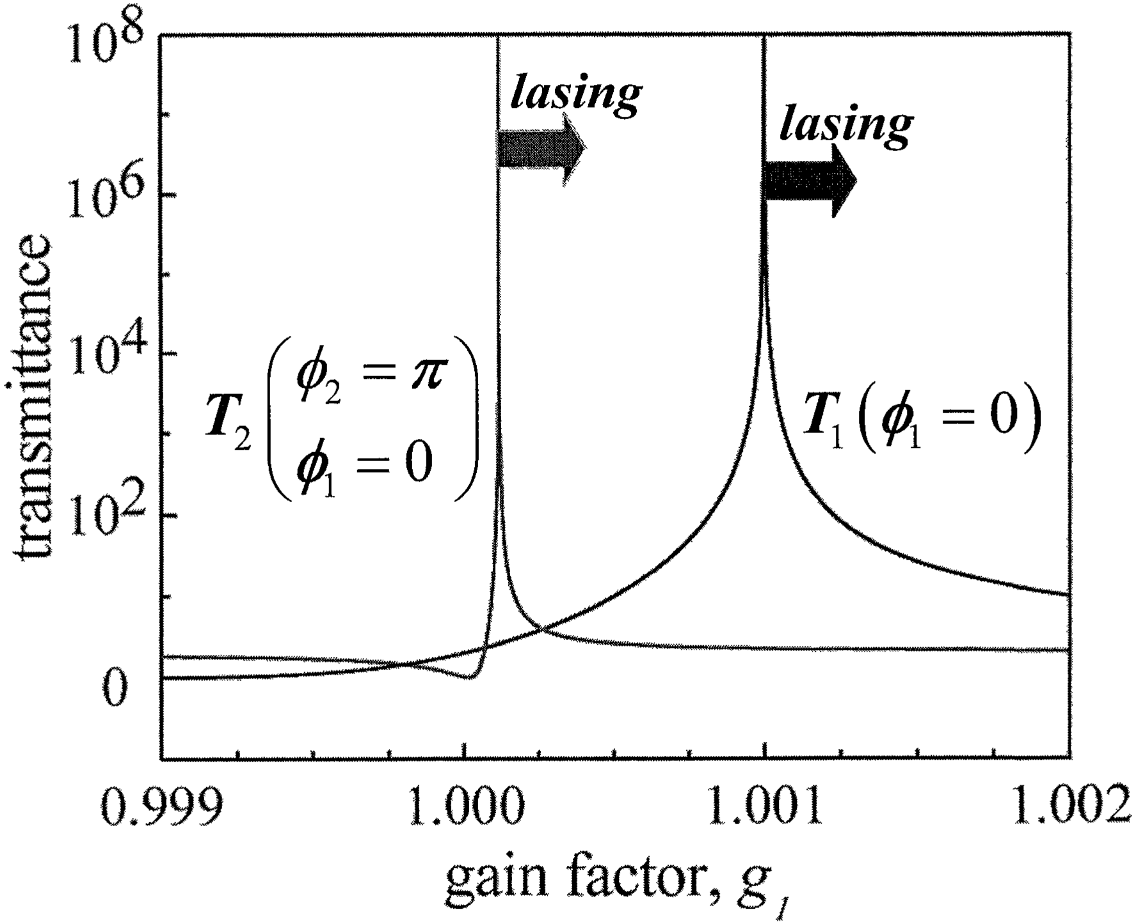
Note: $G_1G_2 < 1$

Reduced Thresholds in Coupled Resonators

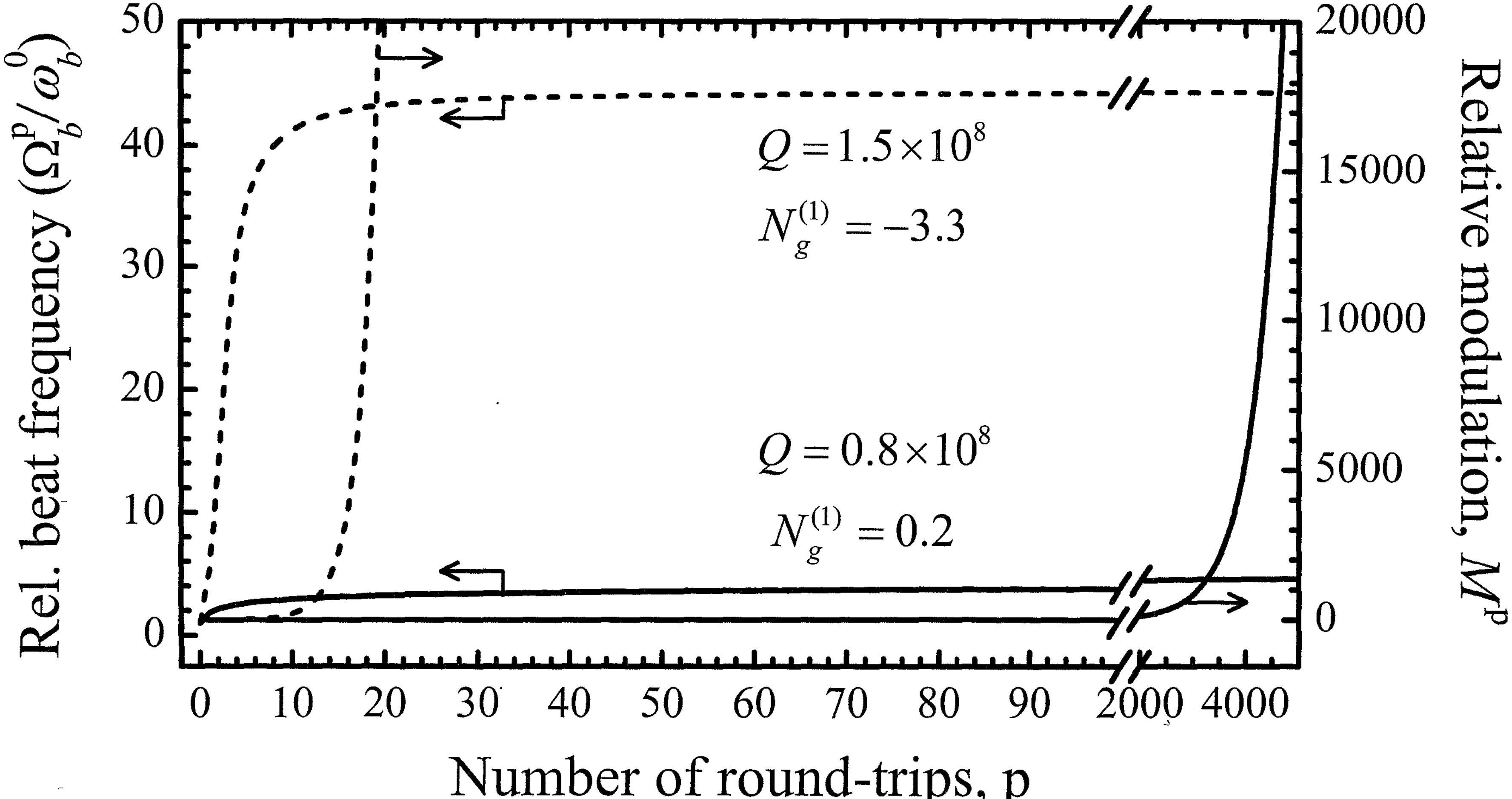
- Threshold for coupled resonators < threshold for single resonator
- Resonators must be properly phased for constructive interference



Upper resonator twice OPL of lower



Beat Frequency and Relative Modulation

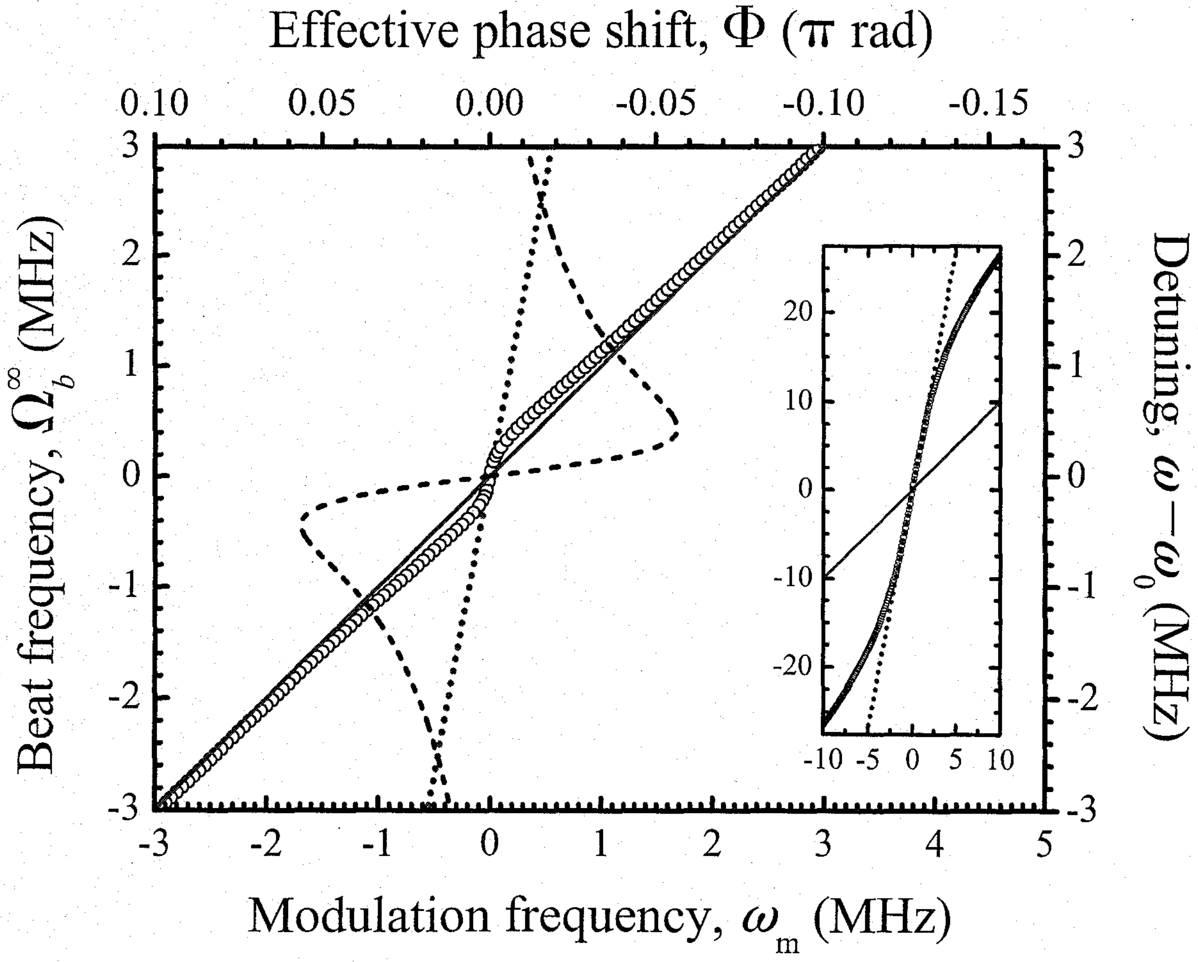


Laser Gyro Enhancement

$$Q = 0.8 \times 10^8$$

$$N_g^{(1)} = 0.2$$

- *Scale-Factor increased by 1/N*
- *Elimination of Gyro Dead-band*
- *Single Resonators: under-coupled (Anomalous) or over-coupled (Normal), but no gain.*
- *Coupled Resonators: CRIA or GAS but not CRIT.*



Summary and Conclusions

- Coupled resonators are analogous to multilevel atoms and are described approximately by the damped Rabi problem.
- Photons can be shuffled from one resonator to another using coherent and adiabatic photon transfer techniques. Coupled resonators can store light.
- Coherence phenomena such as EIT, EIA, GAS, and LWI are fundamental to systems of coherently coupled oscillators. They are not unique to atoms nor are they uniquely quantum phenomena.
- The dispersion in optical micro-resonators has application to the improvement of laser gyroscopes.

Acknowledgements

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