Ultra-slow light and coherent control of the optical response in a duplicated two-level system

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Ultra-slow Light

Ultra-slow light	Group velocity of the light pulse is significantly reduced
Examples	17 m/sec in ultra cold atoms Nature 397, 594 (1999) 57 m/sec at room temperature in solid Science 301, 200 (2003)
Applications	Important for all optical communication, real time optical delay, optical data storage, optical memory

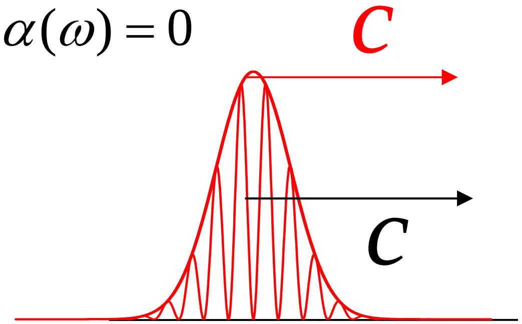
Plan

- Group velocity
- Techniques to slow light
  - Electromagnetic Induced Transparency (EIT)
  - Coherent Population Oscillations (CPO)
  - **Coherent Zeeman Oscillations (CZO)**
- Coherent Control of Susceptibility
- Conclusion

I-Group Velocity

$$n(\omega) = 1;$$

$$\alpha(\omega) = 0$$



$$E(t,z) = E_0(t - z/c)\,\mathrm{e}^{i(k_0 z - \omega_0 t)}$$

$$k_0 = \frac{\omega_0}{c}$$

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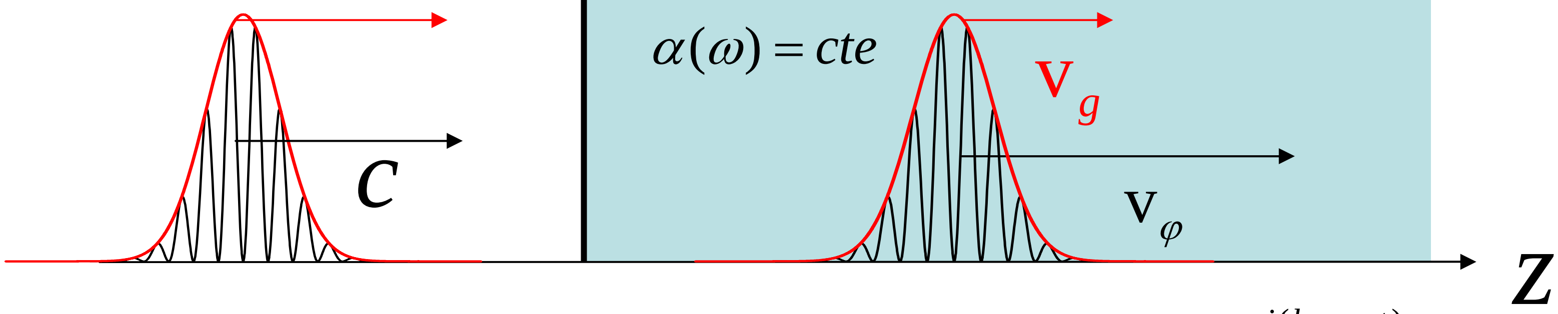
$$n(\omega)(\neq 1) \simeq n(\omega_0) + \left(\frac{dn}{d\omega}\right)_{\omega_0} (\omega - \omega_0)$$

$$\alpha(\omega) = cte$$



$$E(t,z) = E_0(t - z/c)\, \mathrm{e}^{i(k_0 z - \omega_0 t)}$$

$$E(t,z) = G\, E_0(t - z/\mathrm{v}_g)\, \mathrm{e}^{i(kz - \omega_0 t)}$$

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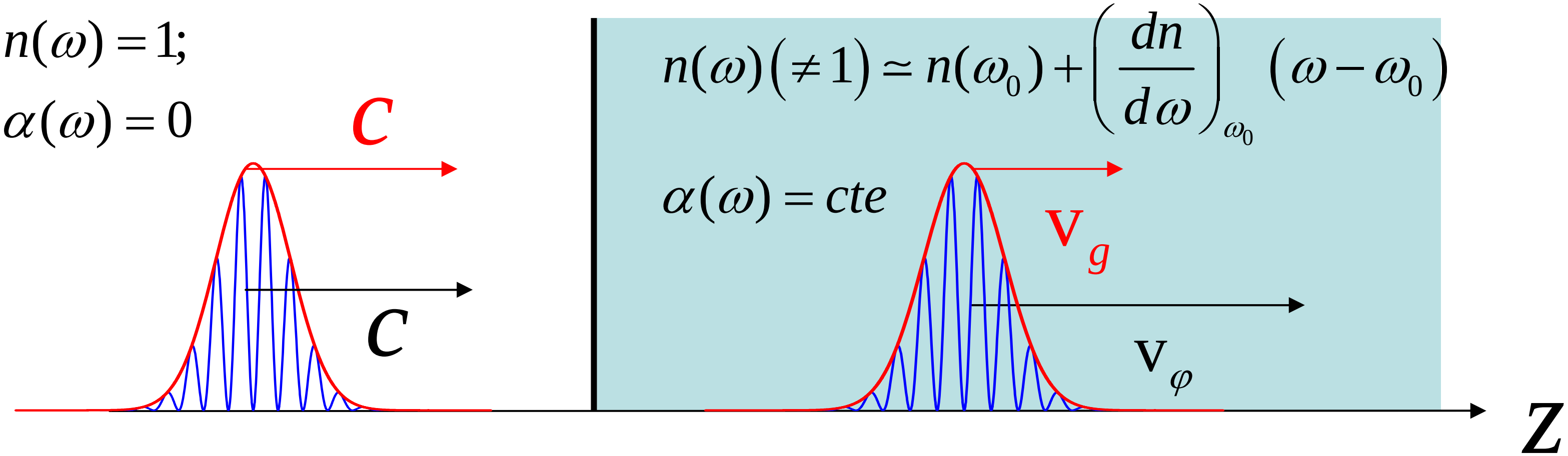

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$$\mathrm{v}_\varphi = c / n(\omega_0):$$ Phase velocity

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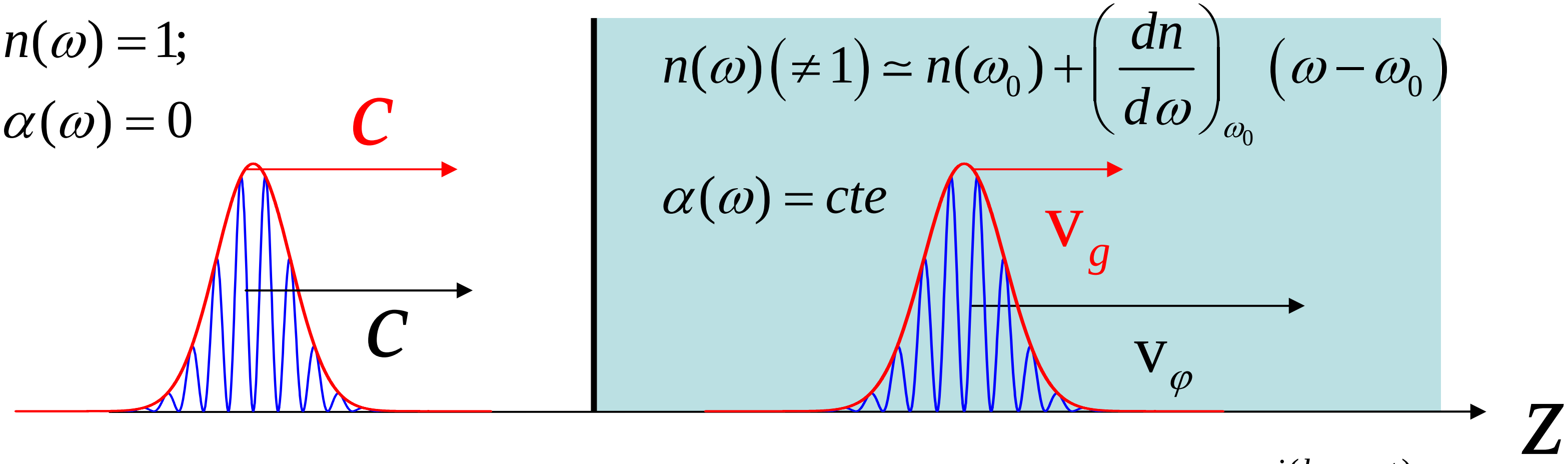

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$$\mathrm{v}_g = \frac{c}{n(\omega_0) + \omega_0 \left(\frac{dn}{d\omega}\right)_{\omega_0}}:$$ Group velocity

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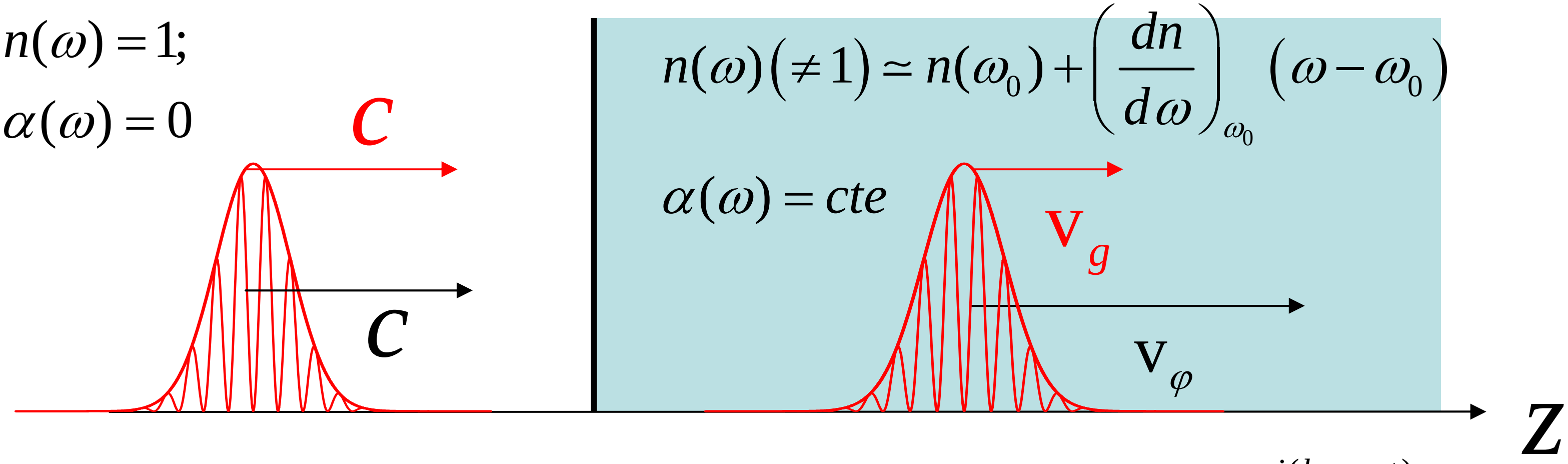

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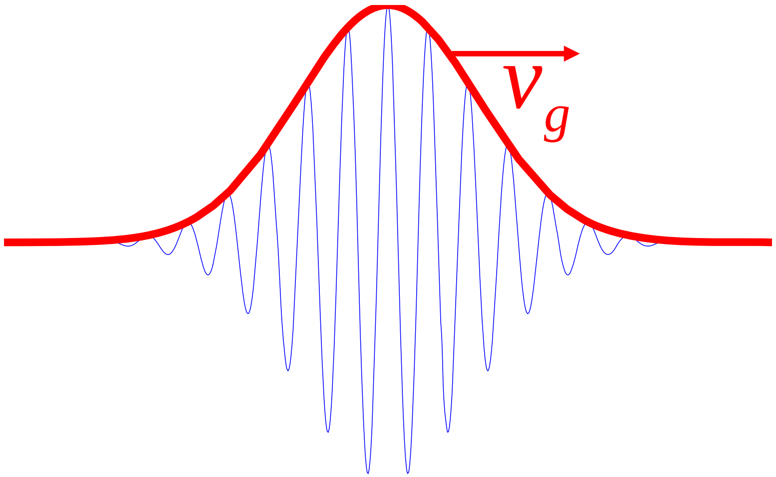
<u>Pure linear-dispersive medium</u>: PROPAGATION WITHOUT DISTORTION

<u>High orders contributions</u>: RESHAPING EFFECTS

I-Group Velocity



$$v_g = \left.\frac{d\omega}{dk}\right|_{\omega_0} = \frac{c}{n(\omega_0) + \omega_0 \left.\frac{dn}{d\omega}\right|_{\omega_0}}$$

- Dilute medium $n \simeq 1$ but v_g may be very different from c

For slow light $\omega_0 \frac{dn}{d\omega} >> 1$

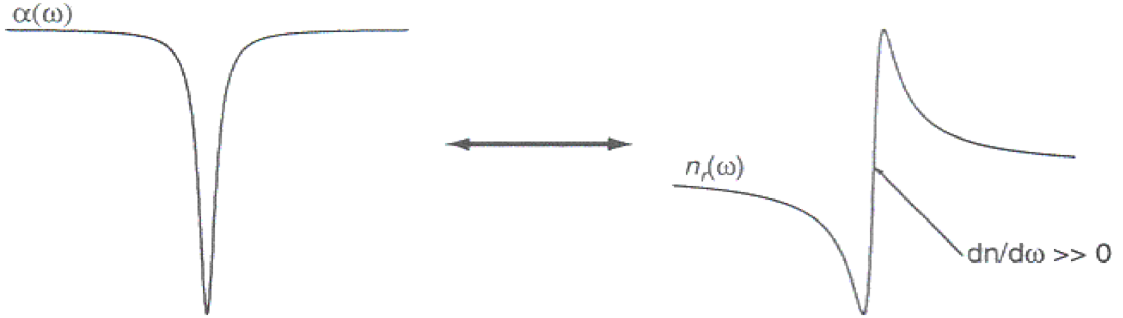
II- How to produce slow light?

$$V_g = \frac{c}{n + \omega \frac{dn}{d\omega}} :$$

Kramers-Kronigs relations

$$n(\omega) - 1 = \frac{c}{\pi} \wp \int_0^\infty \frac{\alpha(\omega')}{\omega'^2 - \omega^2} d\omega'$$

$$\alpha(\omega) = -\frac{4\omega^2}{\pi c} \wp \int_0^\infty \frac{n(\omega') - 1}{\omega'^2 - \omega^2} d\omega'$$



A narrow spectral hole produce a strong normal dispersion

- Electromagnetic Induced Transparency
- Coherent Population Oscillations
- **Coherent Zeeman Oscillations (CZO)**

II-a Electromagnetic Induced Transparency

VOLUME 66, NUMBER 20 PHYSICAL REVIEW LETTERS 20 MAY 1991

Observation of Electromagnetically Induced Transparency

K.-J. Boller, A. Imamoğlu, and S. E. Harris
Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305
(Received 12 December 1990)

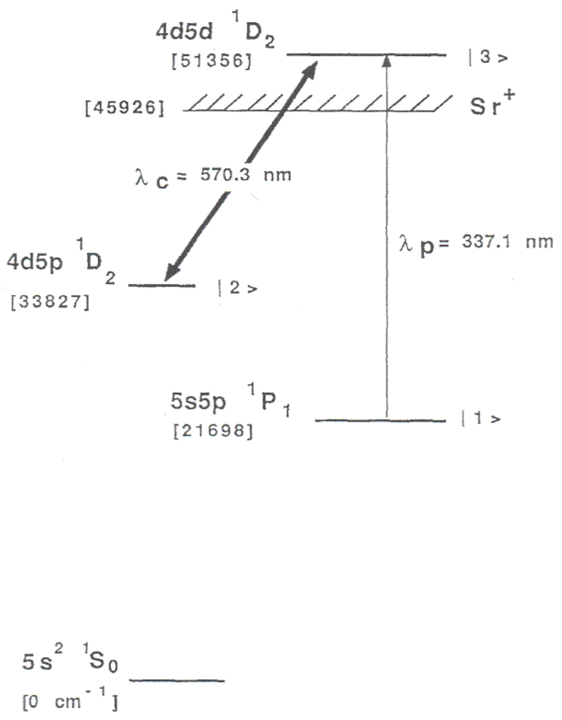


FIG. 1. Energy-level diagram of neutral Sr. Inset: Dressed-state picture.

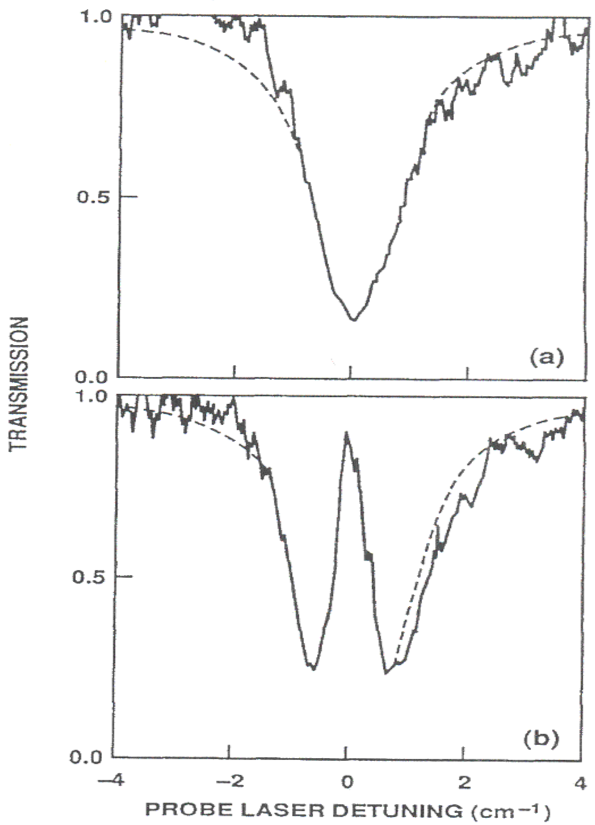


FIG. 2. Transmission vs probe laser detuning for (a) $\Omega_{23}=0$ and (b) $\Omega_{23}=1.3$ cm^{-1}, $\Delta\omega_c=-0.2$ cm^{-1}. Minimum transmission is exp(−1.7).

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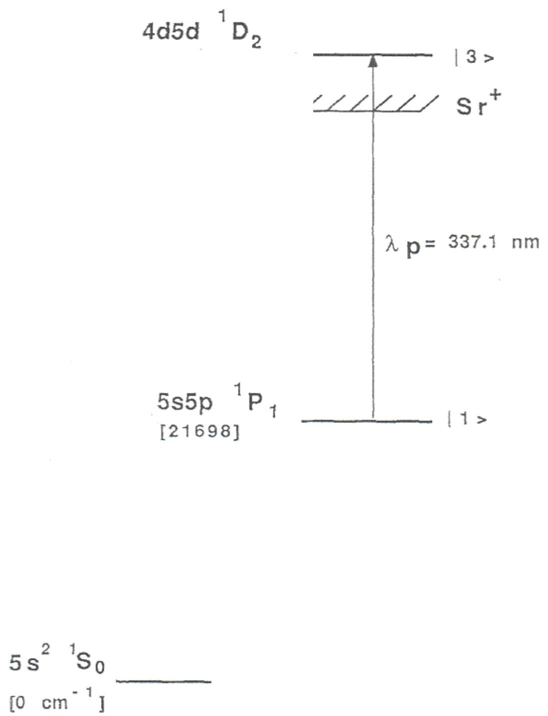

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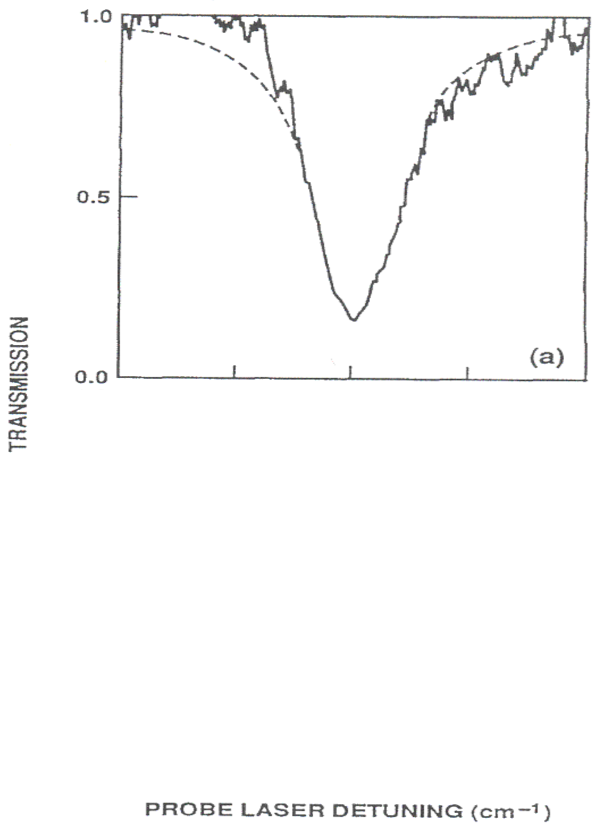

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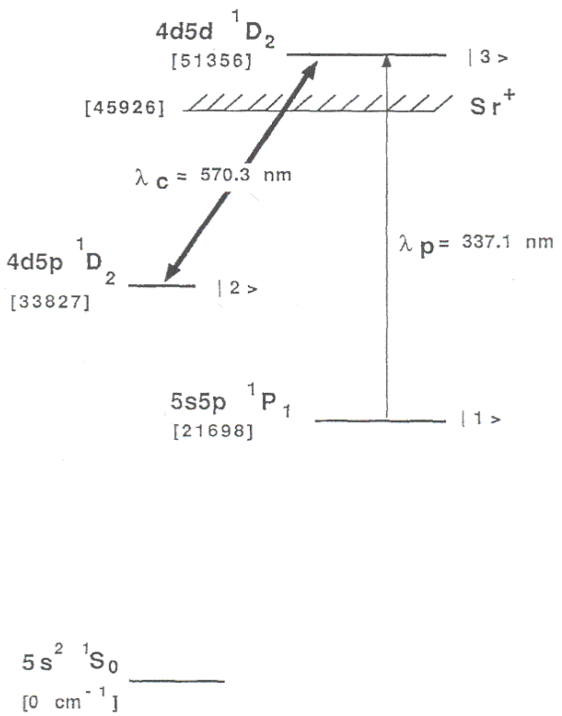

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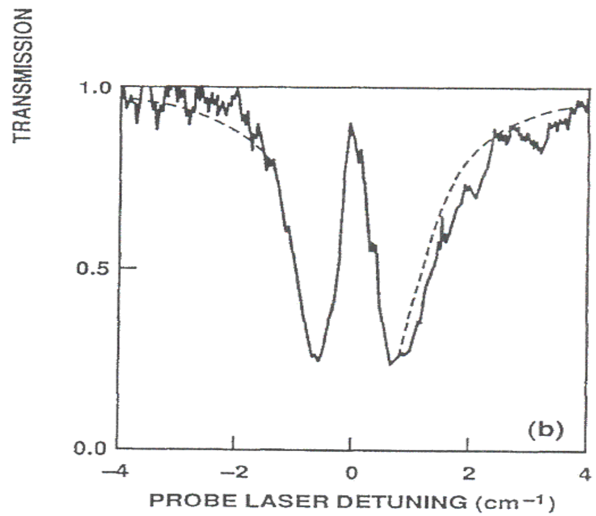

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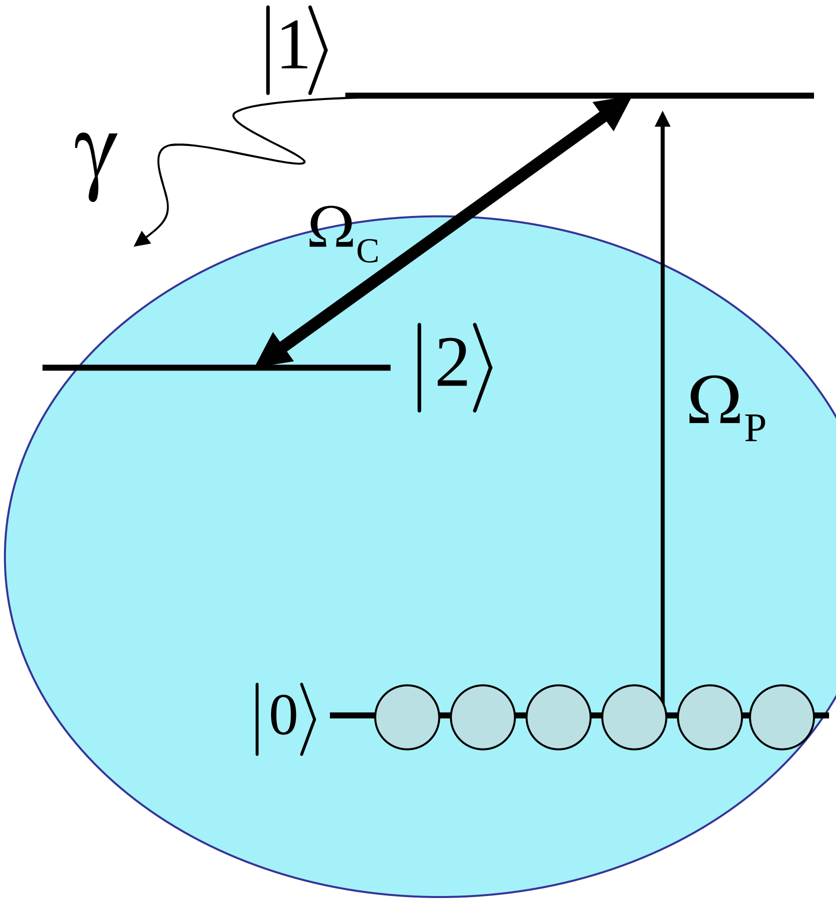
II-a Electromagnetic Induced Transparency

Coherent Population Trapping



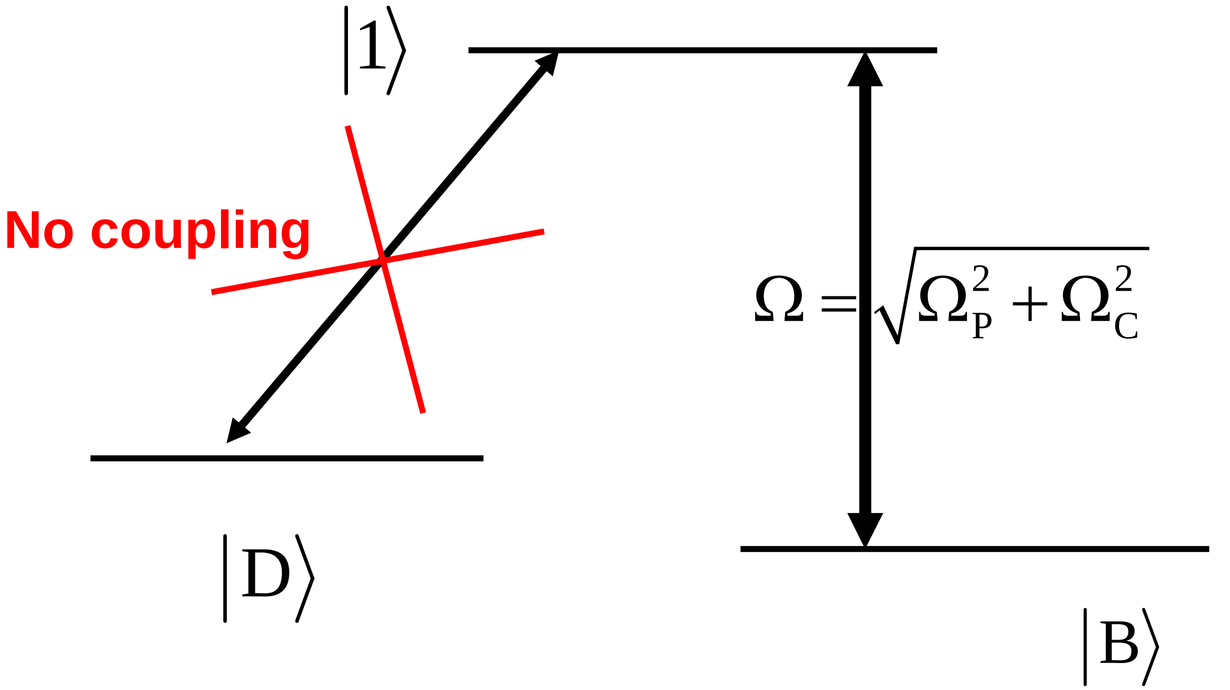
$$\omega_P = \omega_{10}$$

$|B\rangle = \sin\varphi|0\rangle + \cos\varphi|2\rangle$: Bright state

$|D\rangle = -\sin\varphi|2\rangle + \cos\varphi|0\rangle$: Dark state

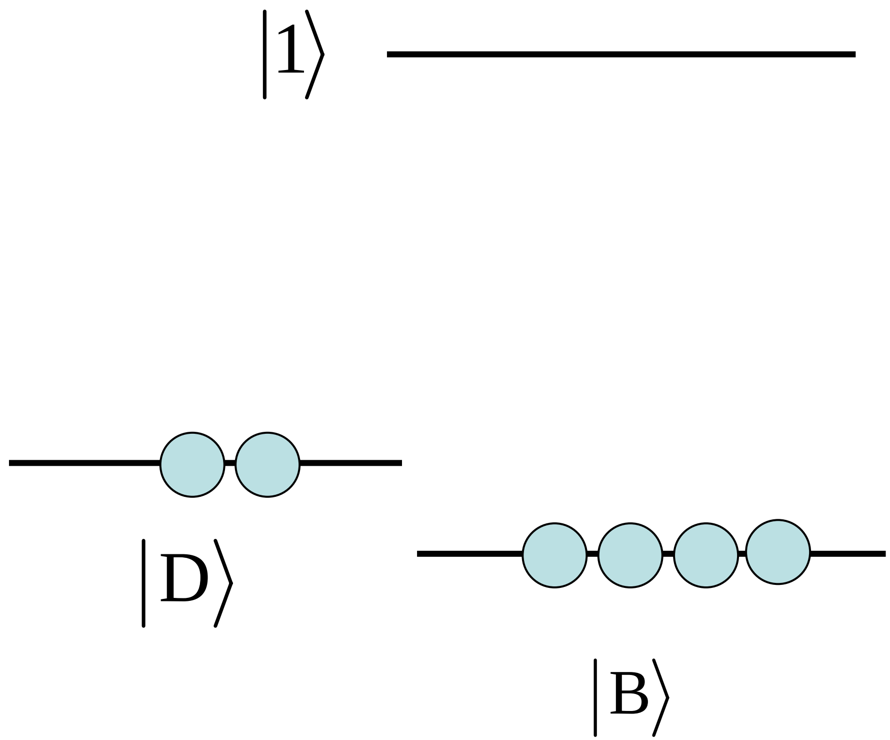
$$\tan\varphi = \frac{\Omega_p}{\Omega_c}$$

II-a Electromagnetic Induced Transparency



II-a Electromagnetic Induced Transparency

$$|0\rangle = \sin\varphi\,|B\rangle + \cos\varphi\,|D\rangle$$



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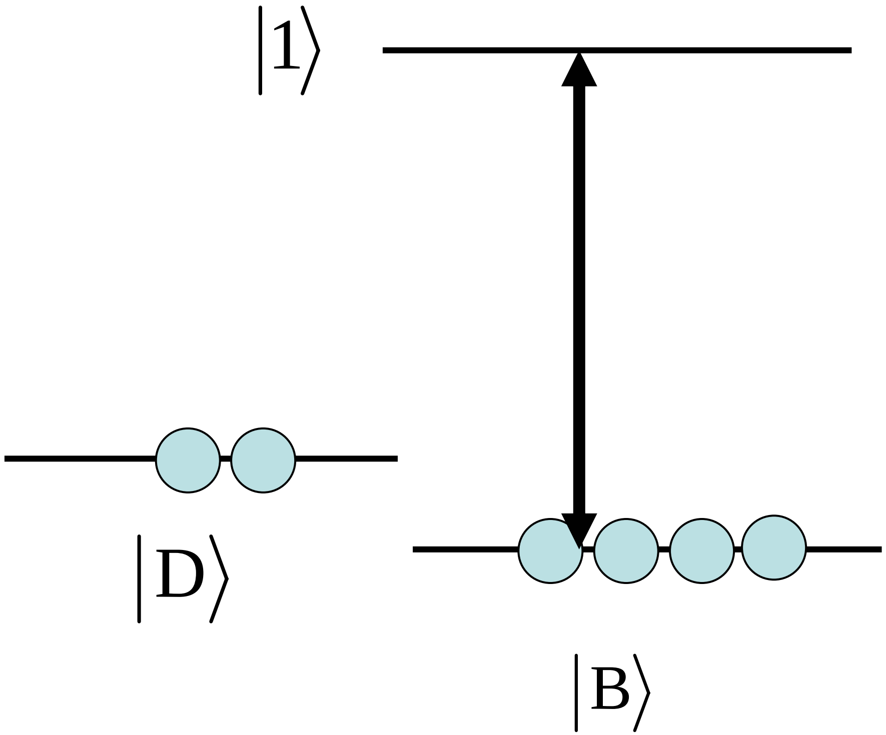

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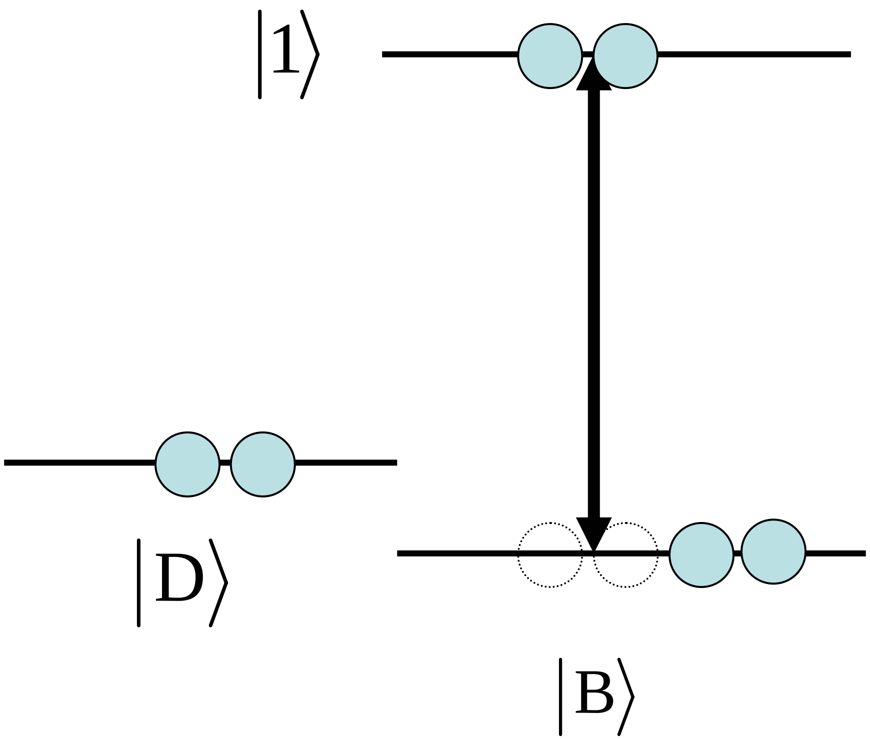

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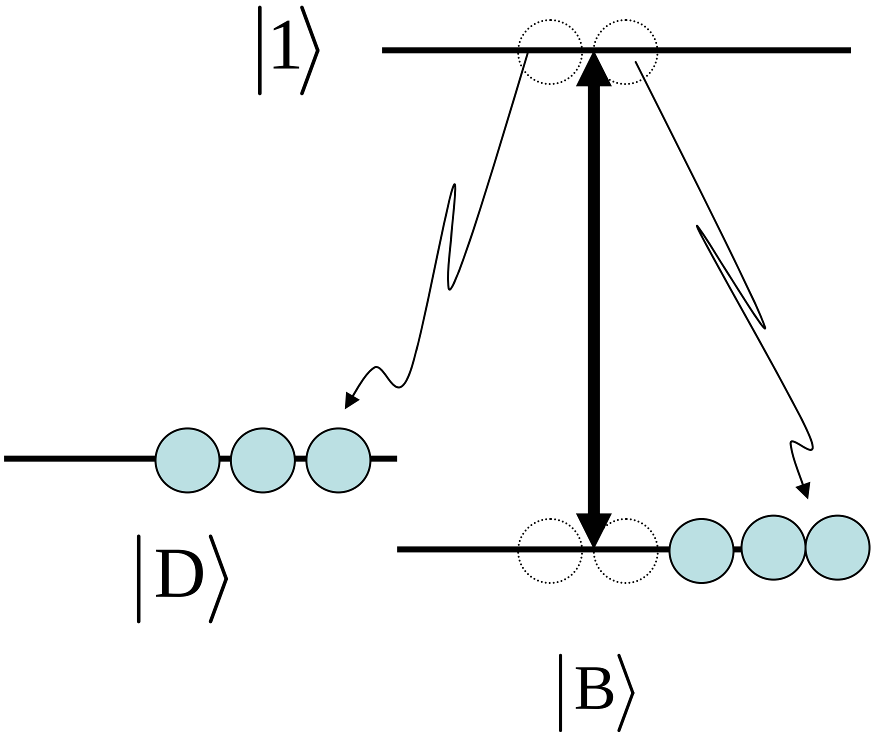

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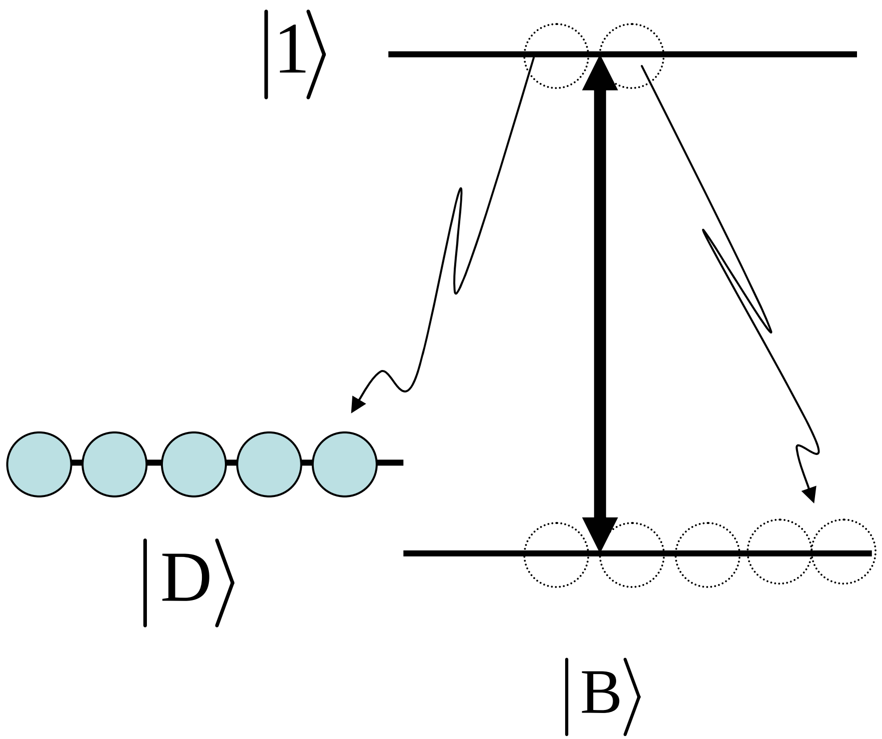


ALL THE ATOMS ARE IMMUNE TO INTERACTION:

perfect transparency

Light speed reduction to 17 metres per second in an ultracold atomic gas

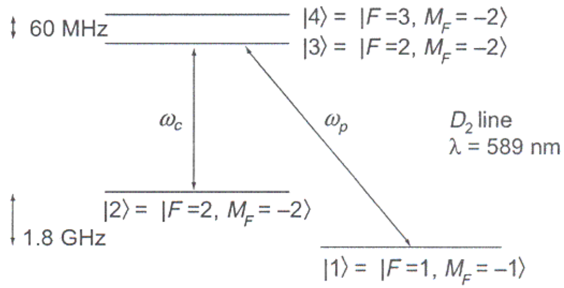
Lene Vestergaard Hau*†, S. E. Harris‡, Zachary Dutton*† & Cyrus H. Behroozi*§

** Rowland Institute for Science, 100 Edwin H. Land Boulevard, Cambridge, Massachusetts 02142, USA*

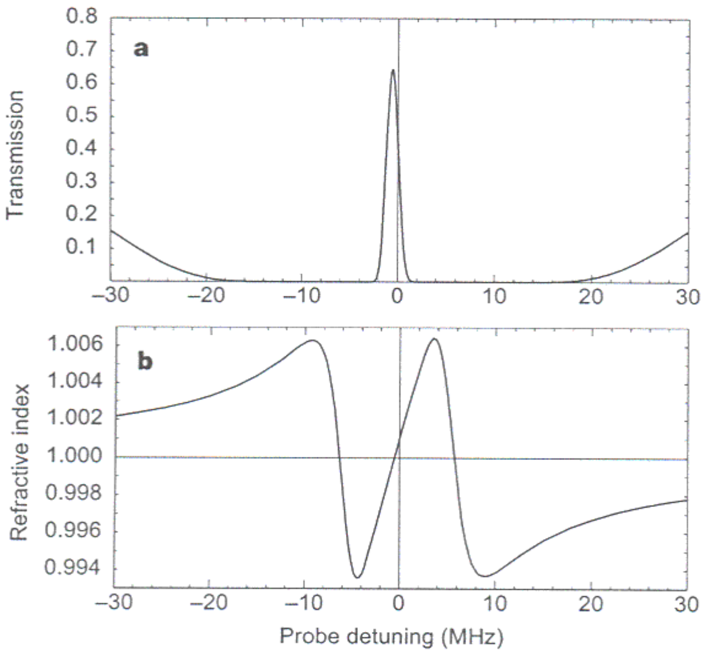
† Department of Physics, § Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA

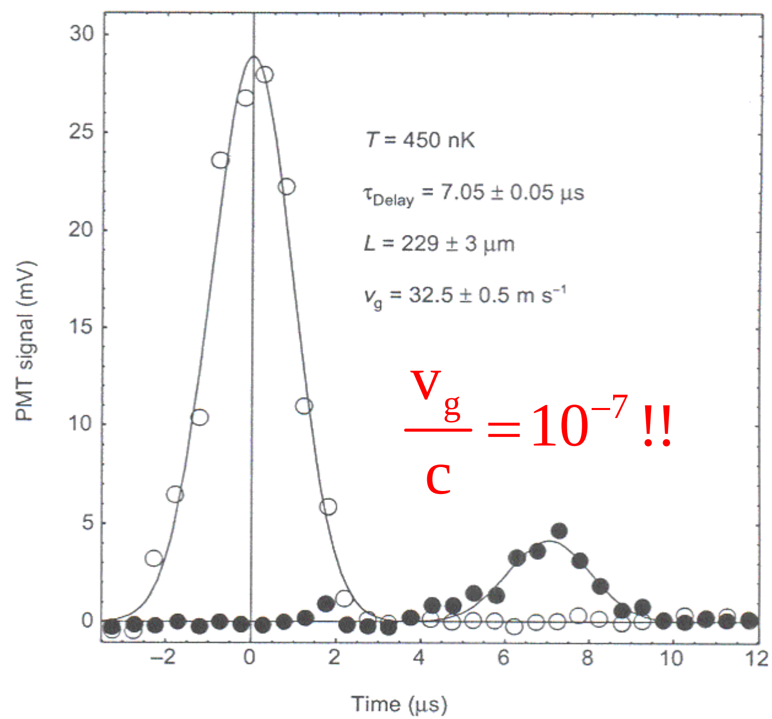
‡ Edward L. Ginzton Laboratory, Stanford University, Stanford, California 9 USA

NATURE, **397**, 594, (1999)



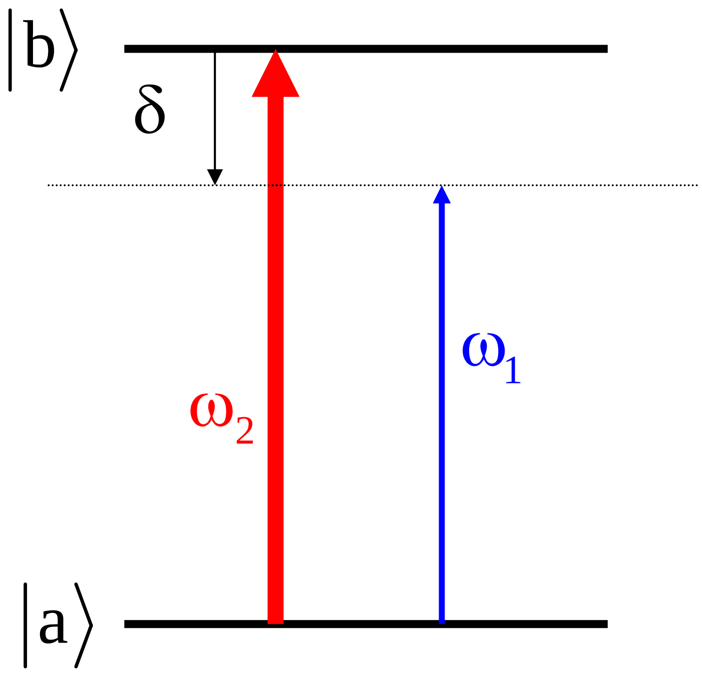
$$v_g = \frac{c}{n(\omega_p) + \omega_p \dfrac{dn}{d\omega_p}} \approx \frac{\hbar c \epsilon_0}{2\omega_p} \frac{|\Omega_c|^2}{|\mu_{13}|^2 N}$$





II-b Coherent Population Oscillations

Bichromatic field :

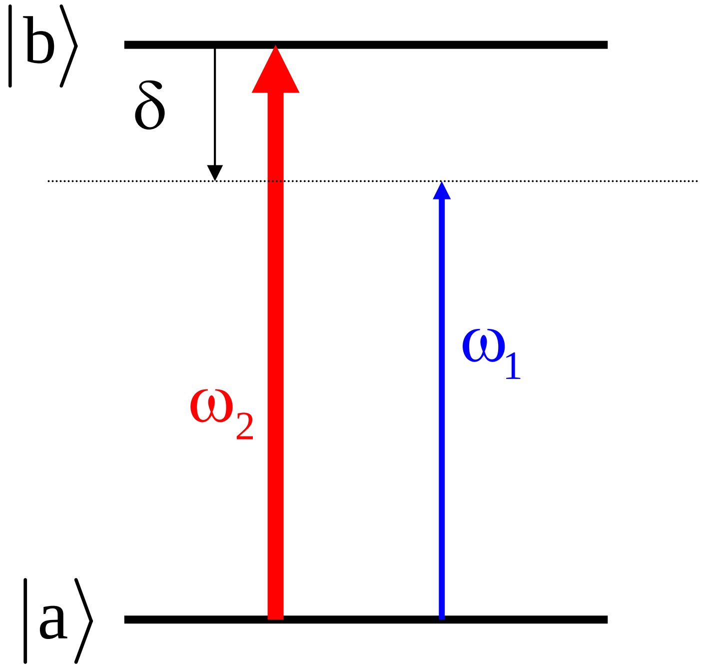


II-b Coherent Population Oscillations

Bichromatic field :

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\omega_2 - \omega_1)t$$

BEATING



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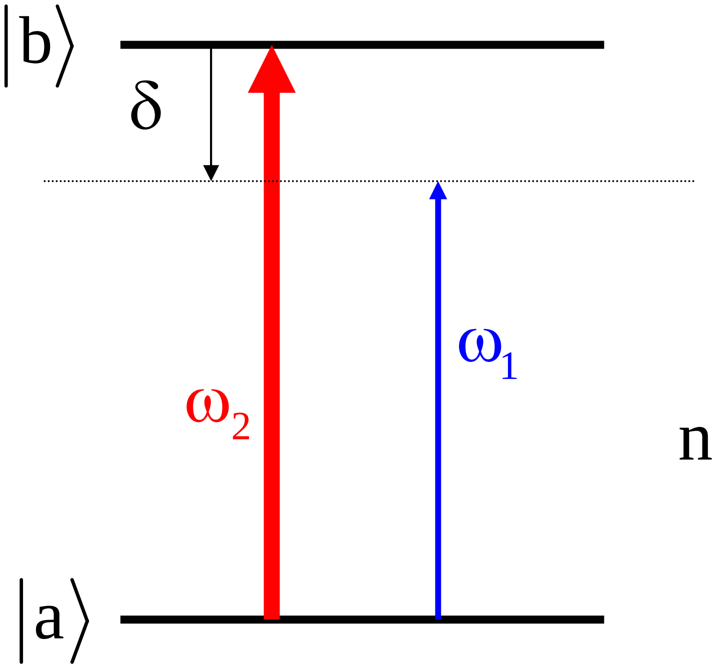
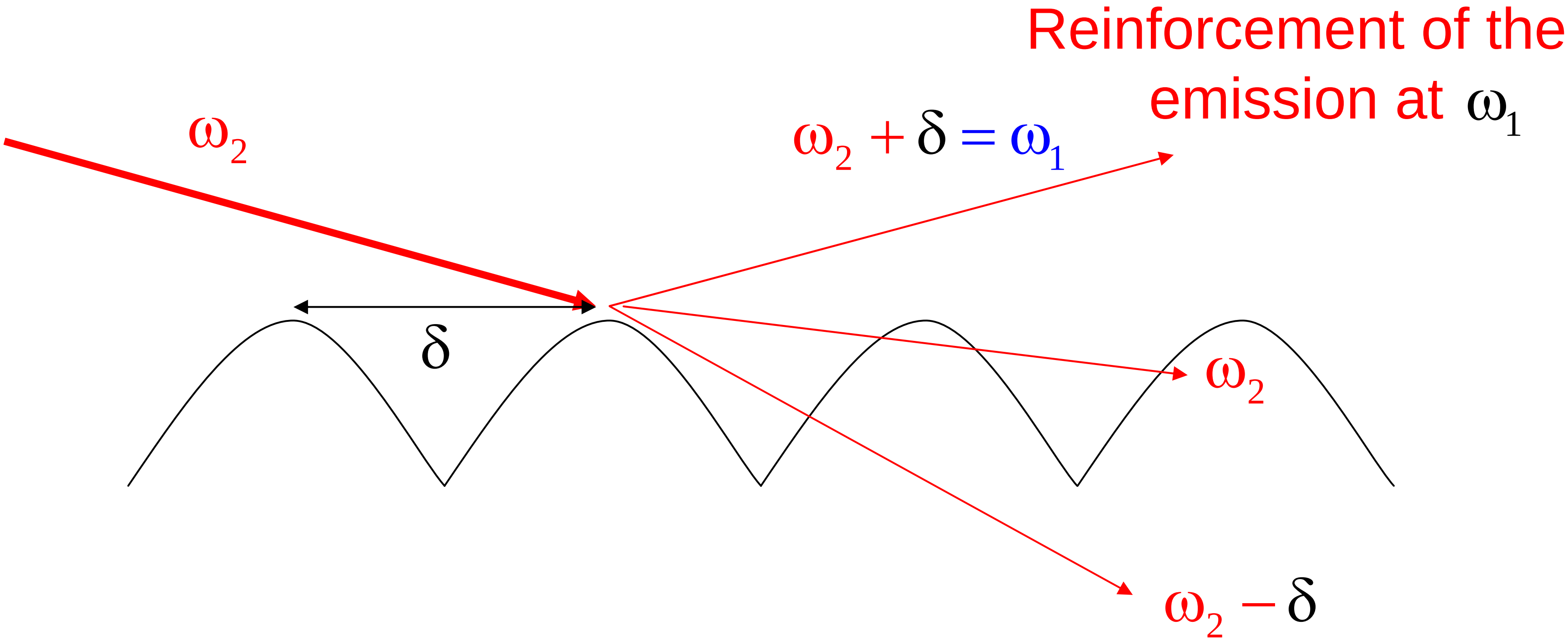


BEATING

$$n_{ba} = n_b - n_a = n_{ba}^{(0)} + n_{ba}^{(+)} e^{i\delta t} + n_{ba}^{(-)} e^{-i\delta t}$$

TEMPORAL GRATING

II-b Coherent Population Oscillations



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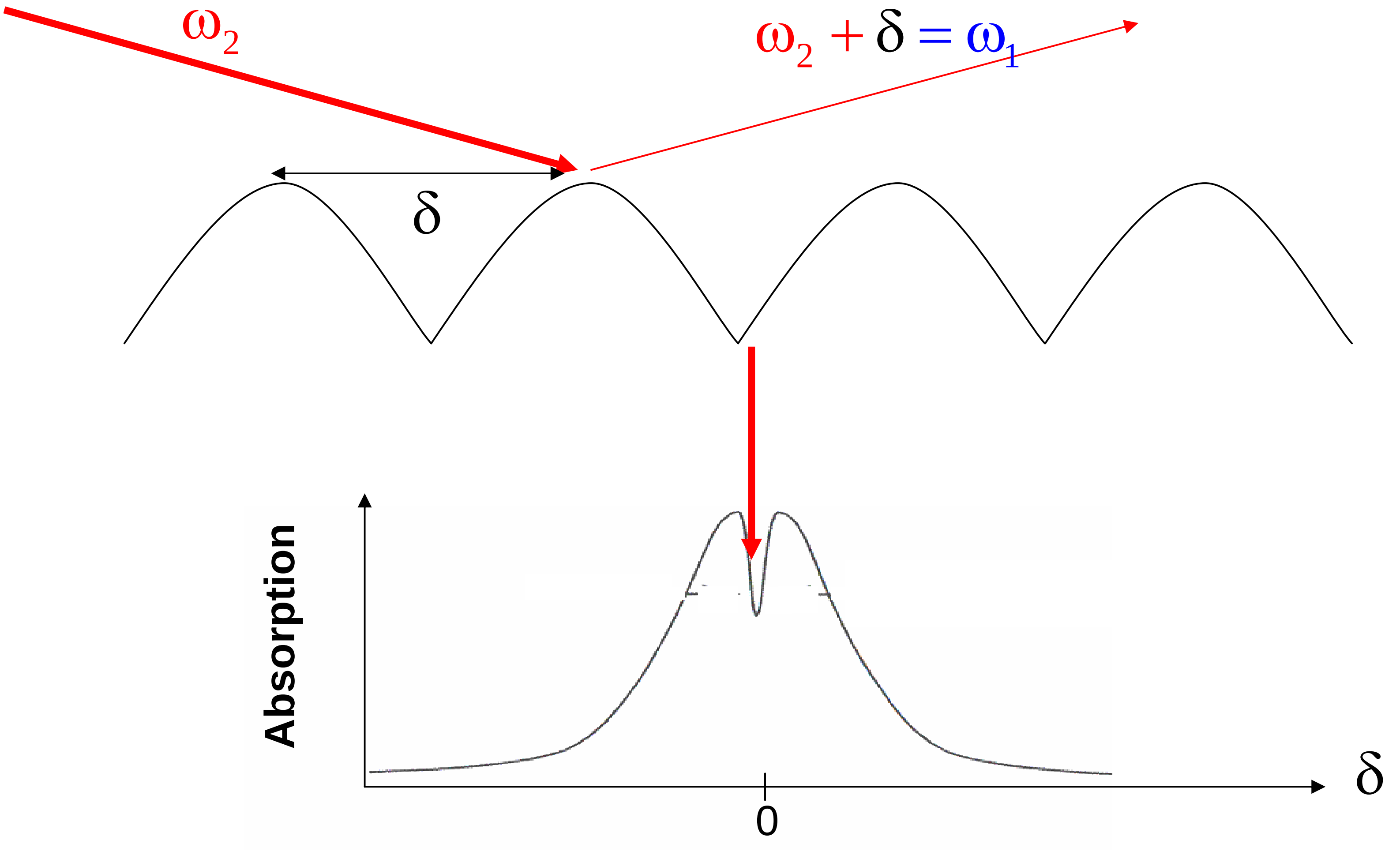

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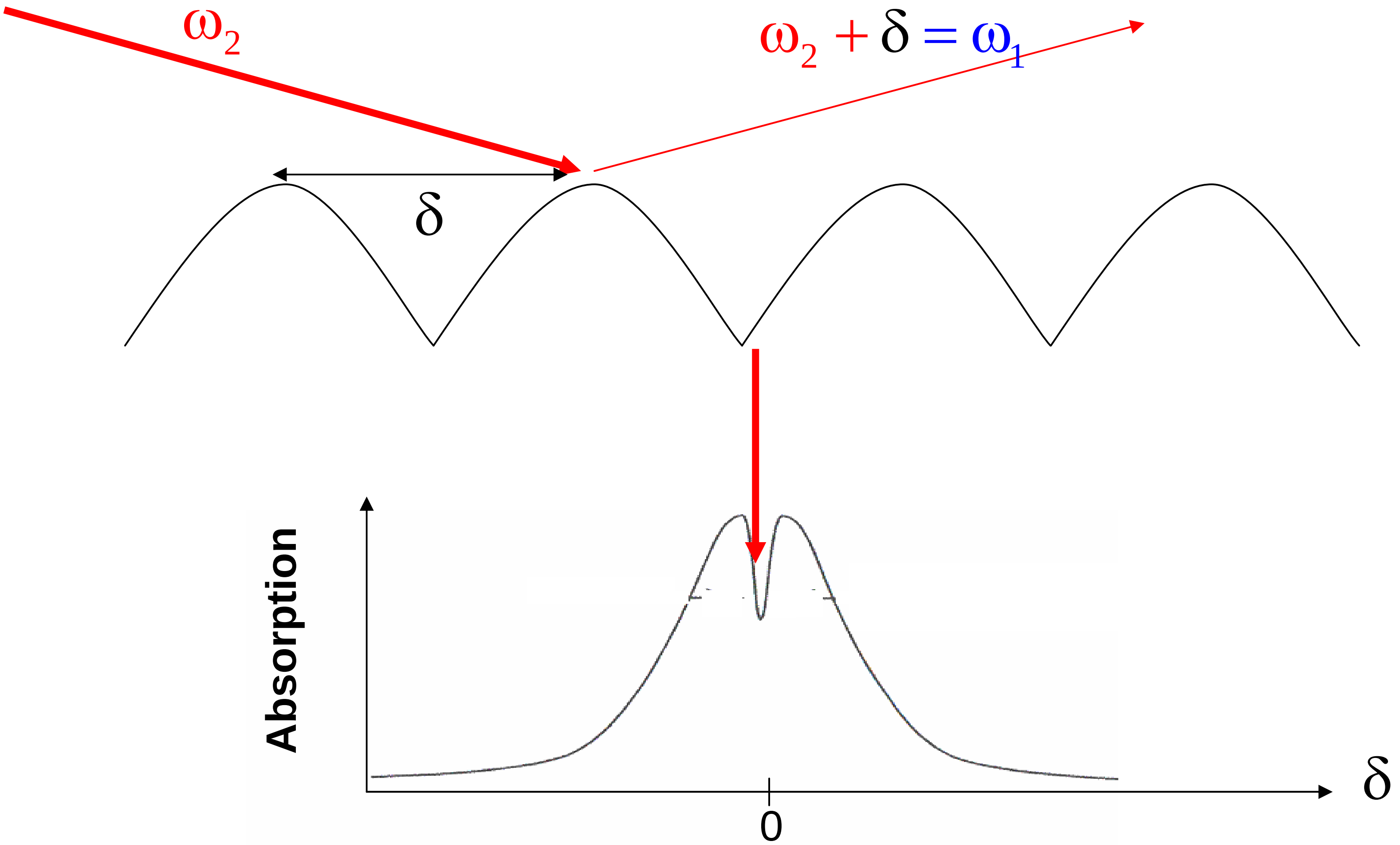


$$\Delta t_{\text{POPULATION}} = T_1 \leq \Delta t_{\text{OSCILLATION}} = \delta^{-1}$$

Observation of Ultraslow Light Propagation in a Ruby Crystal at Room Temperature

Matthew S. Bigelow, Nick N. Lepeshkin, and Robert W. Boyd
The Institute of Optics, University of Rochester, Rochester, New York 14627
(Received 31 October 2002; published 21 March 2003)

We have observed slow light propagation with a group velocity as low as 57.5 ± 0.5 m/s at room temperature in a ruby crystal. A quantum coherence effect, coherent population oscillations, produces a very narrow spectral "hole" in the homogeneously broadened absorption profile of ruby. The resulting rapid spectral variation of the refractive index leads to a large value of the group index. We observe slow light propagation both for Gaussian-shaped light pulses and for amplitude modulated optical beams in a system that is much simpler than those previously used for generating slow light.

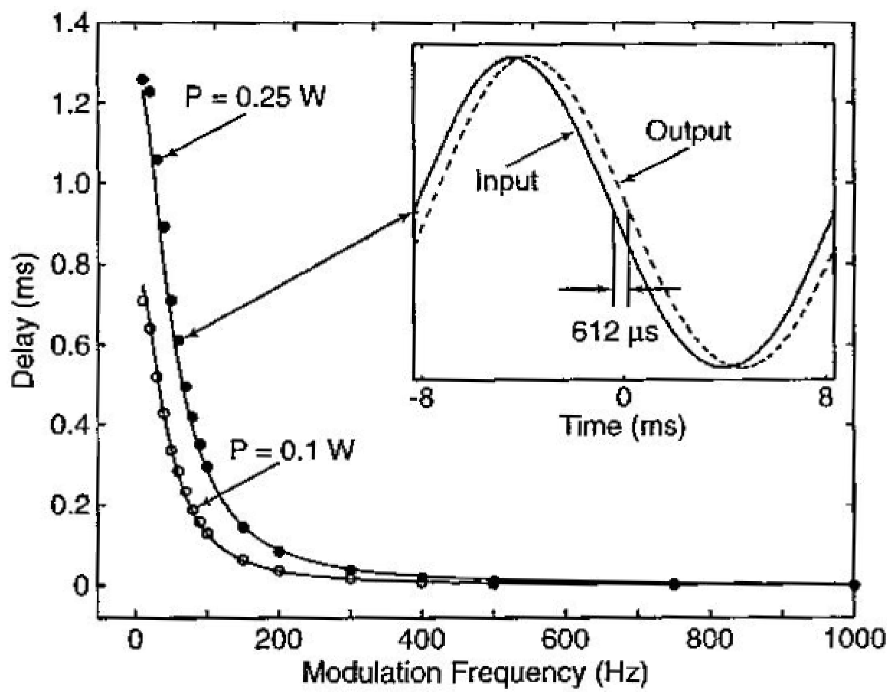
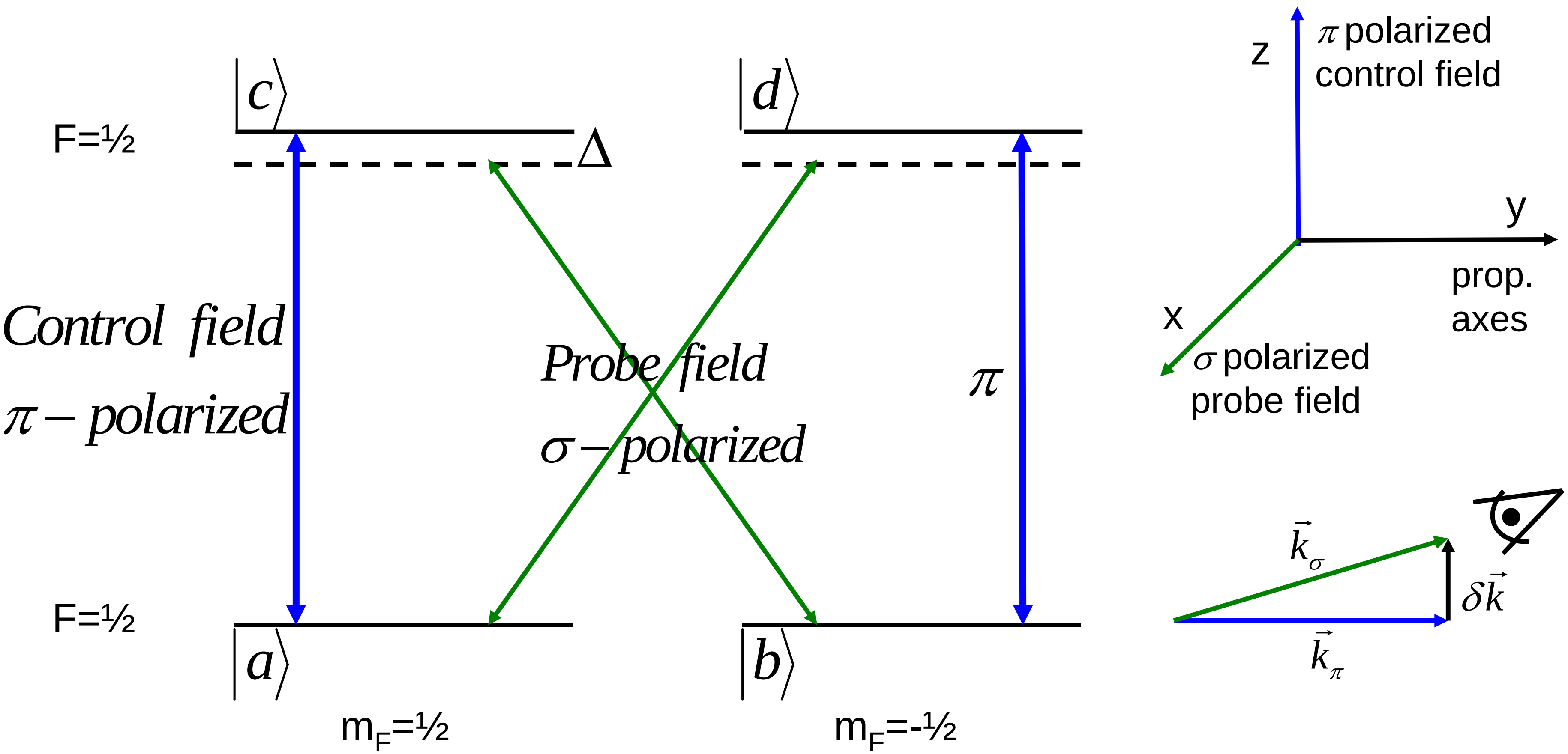


Figure 10. Observed time delay as a function of the modulation frequency for input pump powers of 0.1 and 0.25 W. The inset shows the normalized 60 Hz input (solid curve) and output (dashed curve) signal at 0.25 W. The 60 Hz signal was delayed 612 μs corresponding to an average group velocity of 118 m s^{-1}.

II-c **Coherent Zeeman Oscillations**

A double two level system

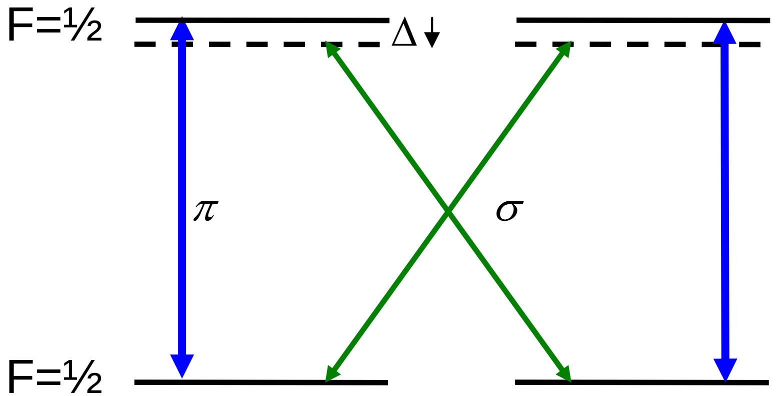


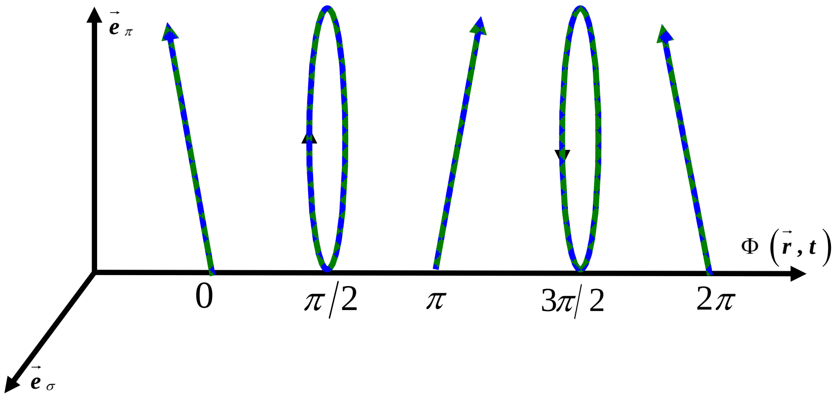
II-c **Coherent Zeeman Oscillations**

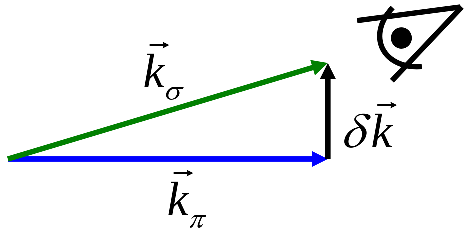
A double two level system

$$\Phi(\vec{r},t) = \Delta t - \delta\vec{k}.\vec{r} + \varphi$$

$$\vec{e}_T = \vec{e}_\pi + \vec{e}_\sigma \frac{E_\sigma}{E_\pi} e^{-i\Phi(\vec{r},t)}$$



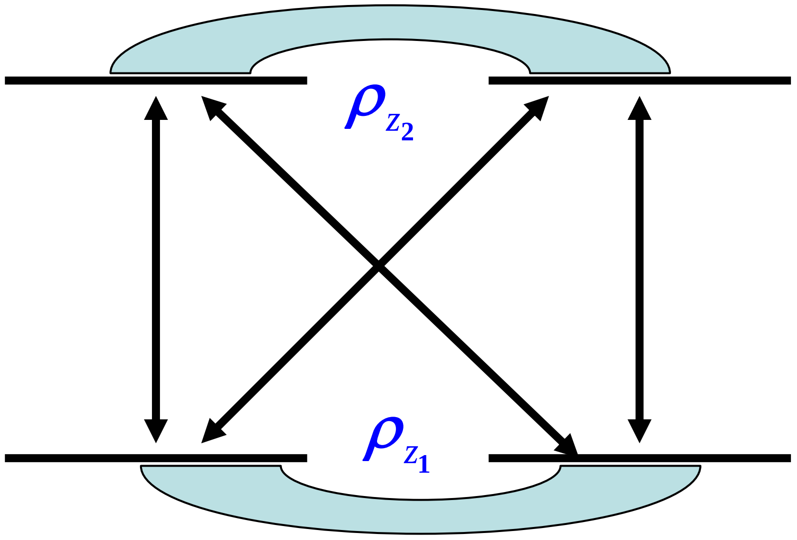




Polarization is a modulated structure that produces a grating in space/time

grating imprints on Zeeman coherences

$$\rho_Z = \rho_{z_1} + \rho_{z_2} = \sum_n \rho^{(n)} e^{in\left(\Delta t - \delta \vec{k}.\vec{r}\right)}$$



grating imprints on Zeeman coherences

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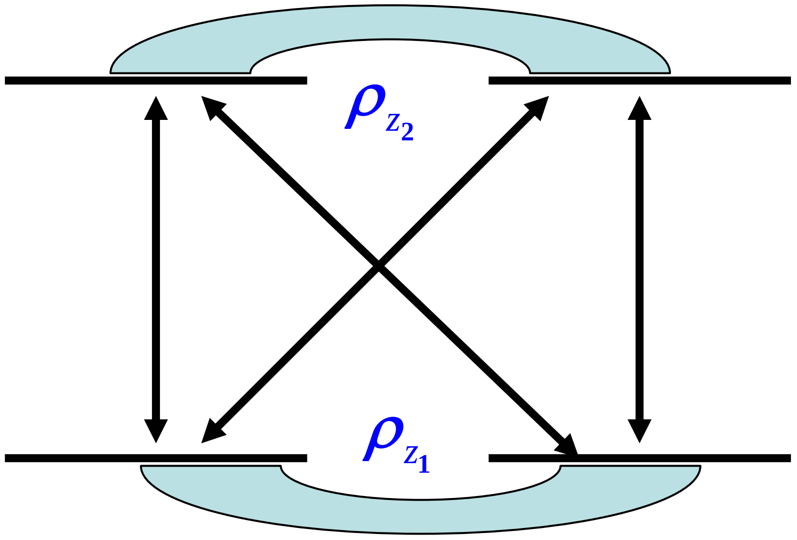

$$\dot{\rho}_\sigma = -\theta_\pi \, \mathrm{Im}\, \rho_Z - i\theta_\sigma e^{-i\Phi\left(\vec{r},t\right)}\left(n_e - n_g\right) - \frac{\rho_\sigma \Gamma}{2}$$

$$\theta_\pi = \frac{dE_\pi}{\hbar\Gamma};\ \theta_\sigma = \frac{dE_\sigma}{\hbar\Gamma}$$

grating imprints on Zeeman coherences

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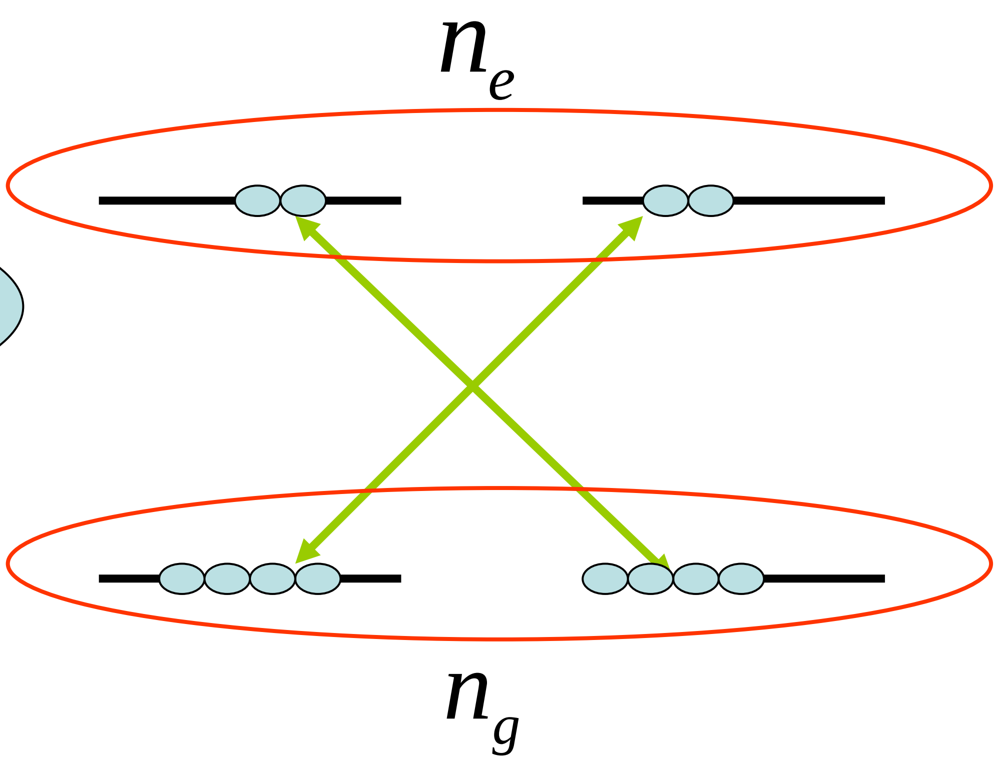

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$$\theta_\pi = \frac{dE_\pi}{\hbar\Gamma}; \theta_\sigma = \frac{dE_\sigma}{\hbar\Gamma}$$

Absorption by population

grating imprints on Zeeman coherences

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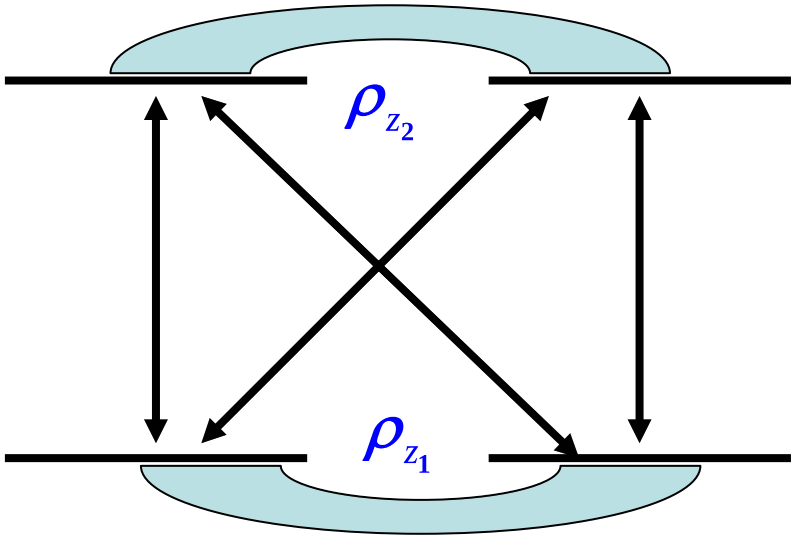
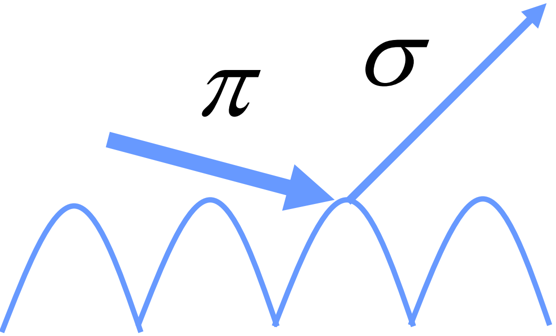


$$n = 1$$



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Diffraction of strong field by Zeeman coherence

grating imprints on Zeeman coherences

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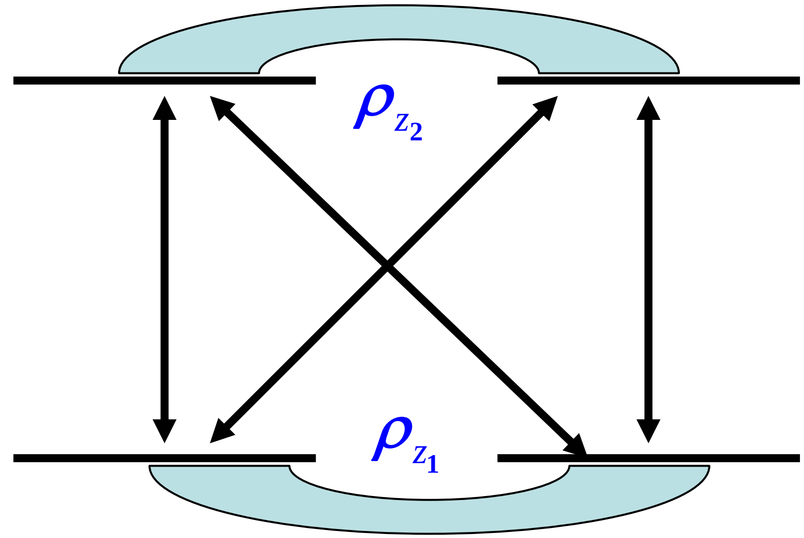

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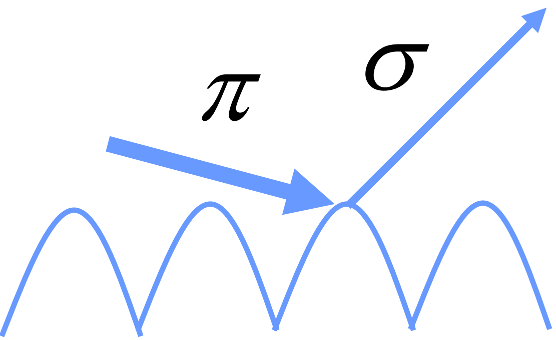


$$\dot{\rho}_\sigma = -\theta_\pi \, \mathrm{Im}\, \rho_Z - i\theta_\sigma e^{-i\Phi\left(\vec{r},t\right)} \left(n_e - n_g\right) - \frac{\rho_\sigma \Gamma}{2}$$

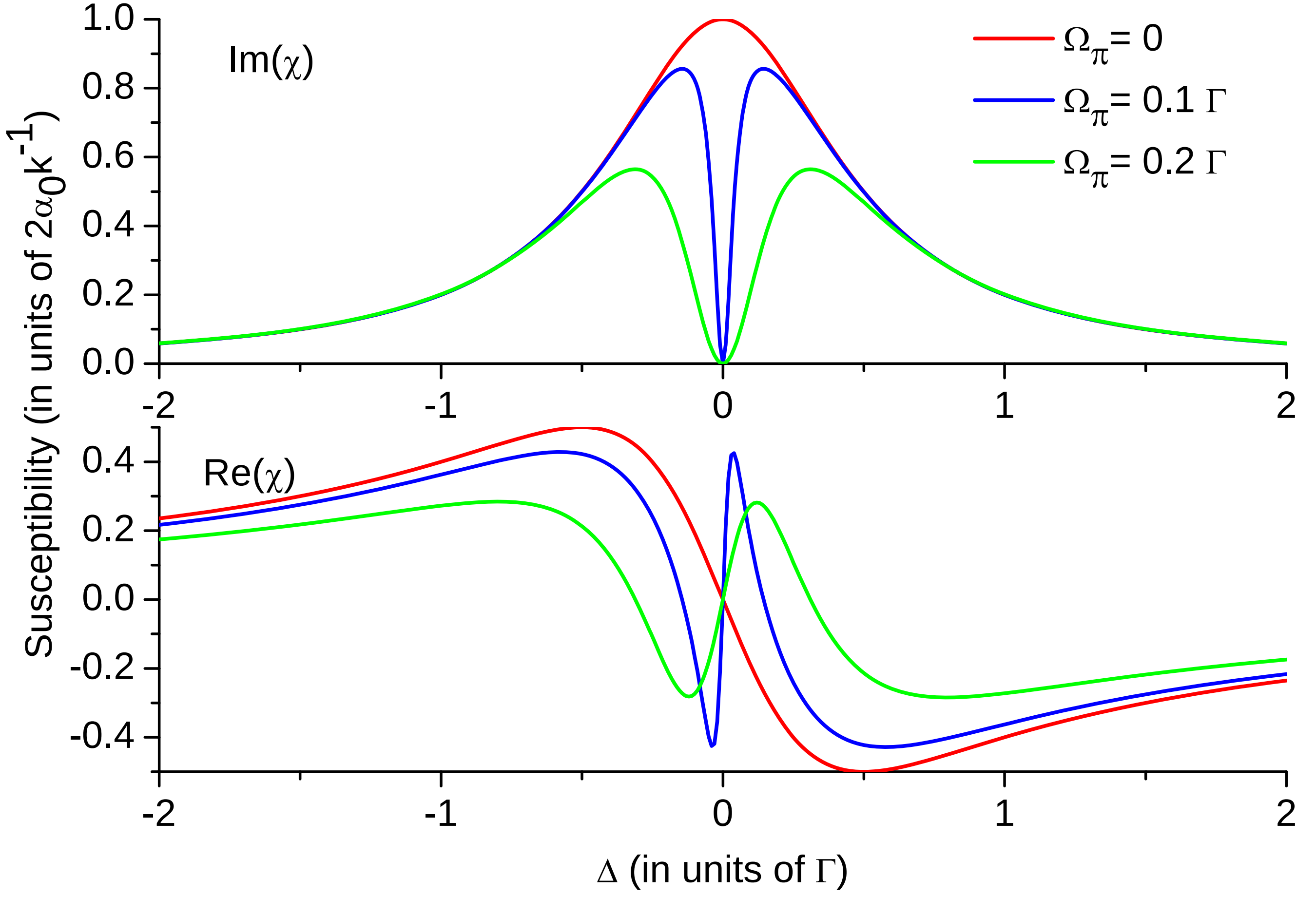
Diffraction of strong field by Zeeman coherence

Cancel exactly

at $\Delta = 0$

Absorption by population

II-c **Coherent Zeeman Oscillations**



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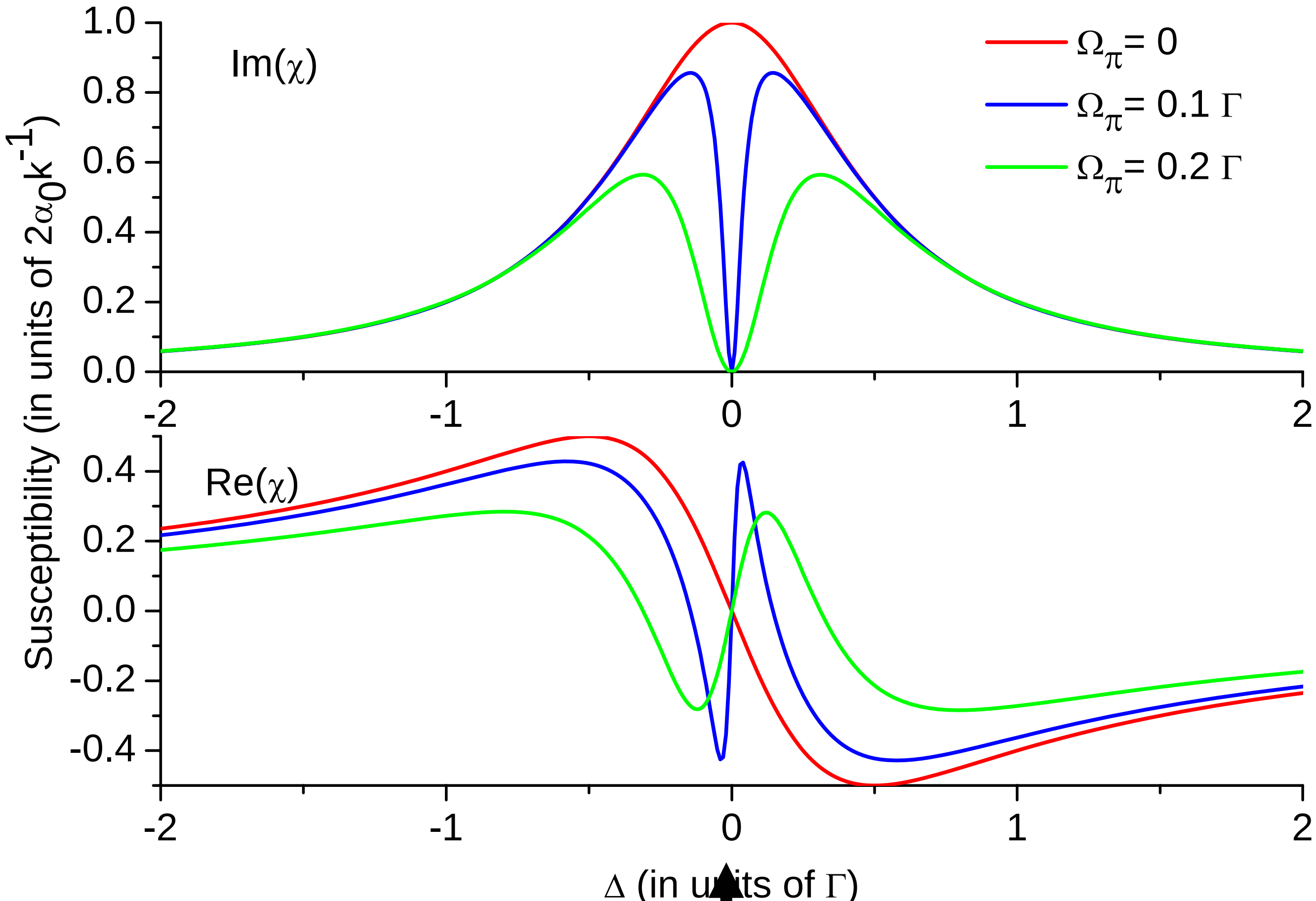
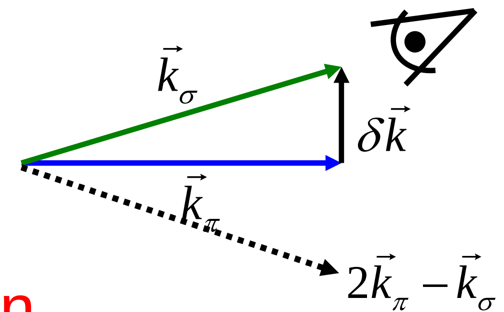
II-c **Coherent Zeeman Oscillations**

- Pure Non-linear effect
- No dark state
- Hybrid properties between CPO and EIT
- Pave the way to extension in more complex system



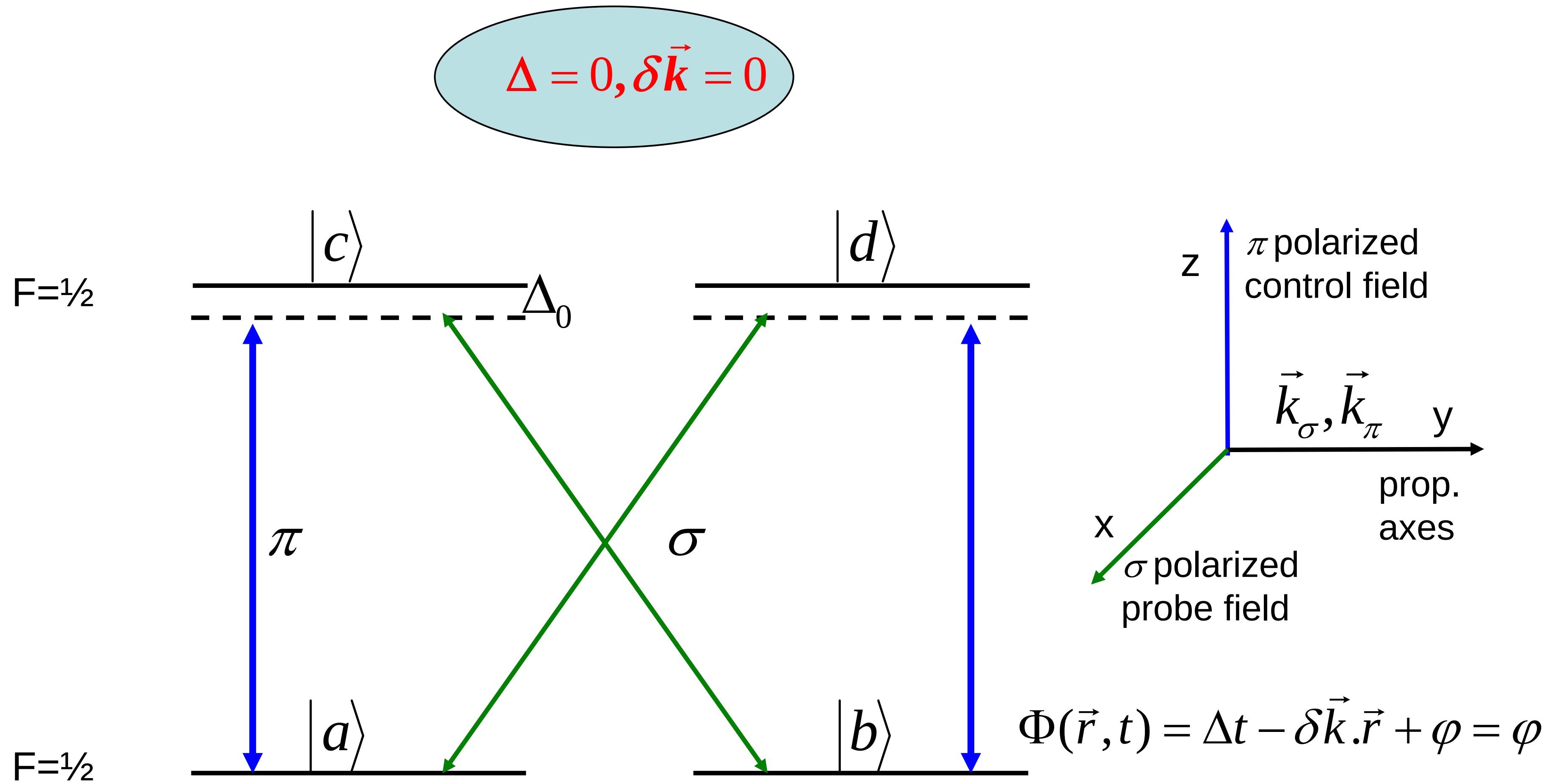


$\Delta = 0$:

Optical response canceled in the $\vec{k}_\sigma$ direction

Optical response determined by other emitted waves

III- Coherent Control of Susceptibility

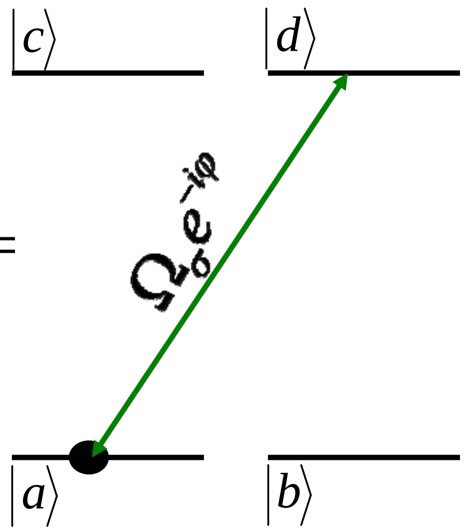


$$\rho_\sigma = \rho_{da} + \rho_{cb} = \rho_\sigma(\varphi):$$ Coherent Control

III- Coherent Control of Susceptibility

$$\rho_\sigma = \rho_{da} + \rho_{cb}$$

$\rho_{da} =$

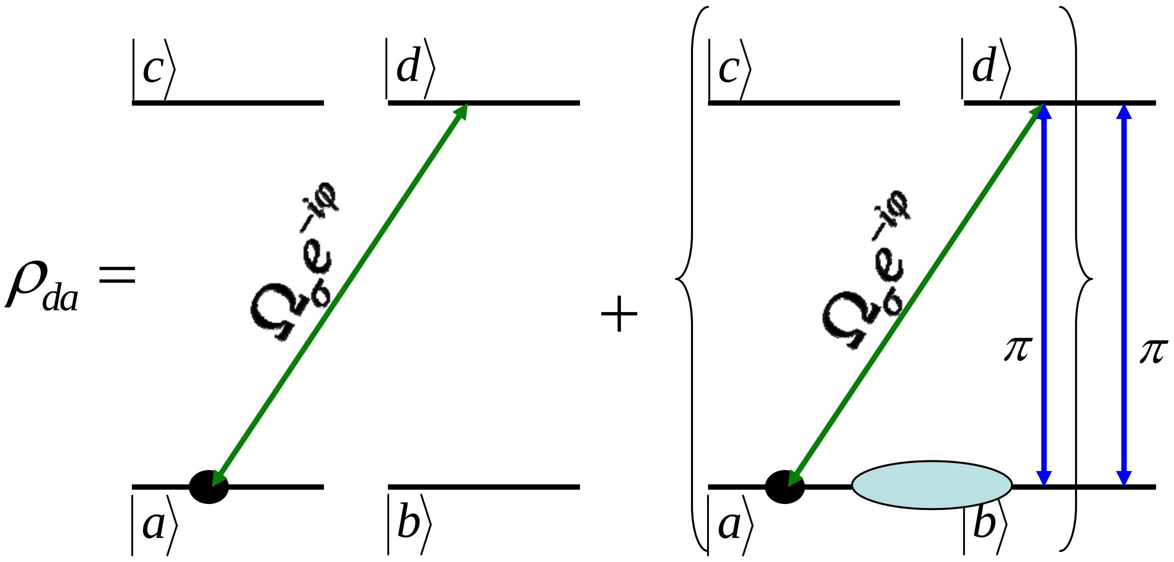


Absorption path

$\vec{k}_\sigma$

III- Coherent Control of Susceptibility

$$\rho_\sigma = \rho_{da} + \rho_{cb}$$



Absorption path

$\vec{k}_\sigma$

Cross- Kerr type path

$$\vec{k}_\pi + \left(\vec{k}_\sigma - \vec{k}_\pi\right) = \vec{k}_\sigma$$

III- Coherent Control of Susceptibility

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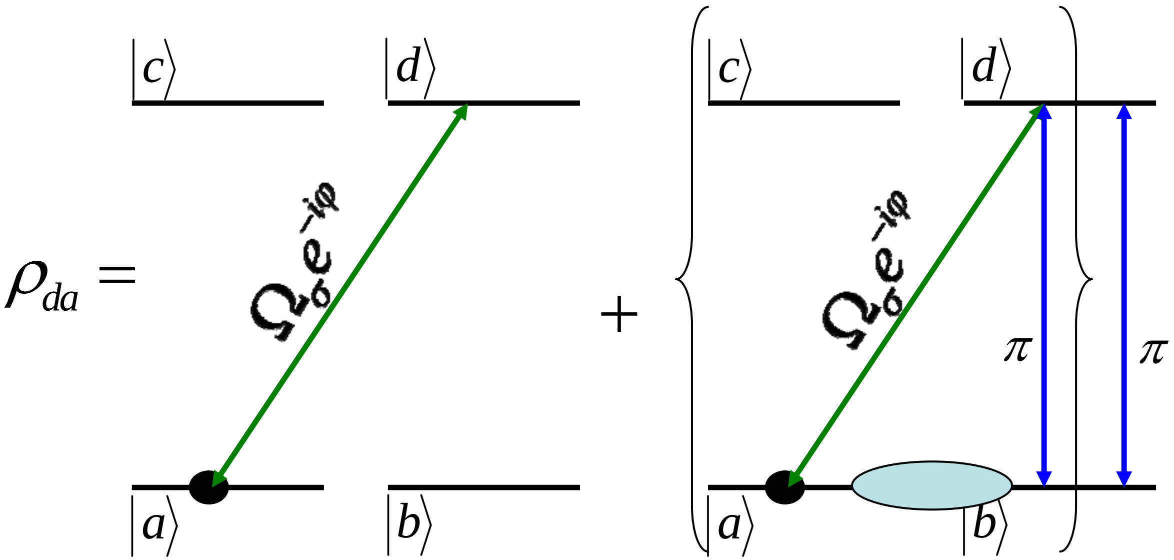


Absorption path

$\vec{k}_\sigma$

Cross- Kerr type path

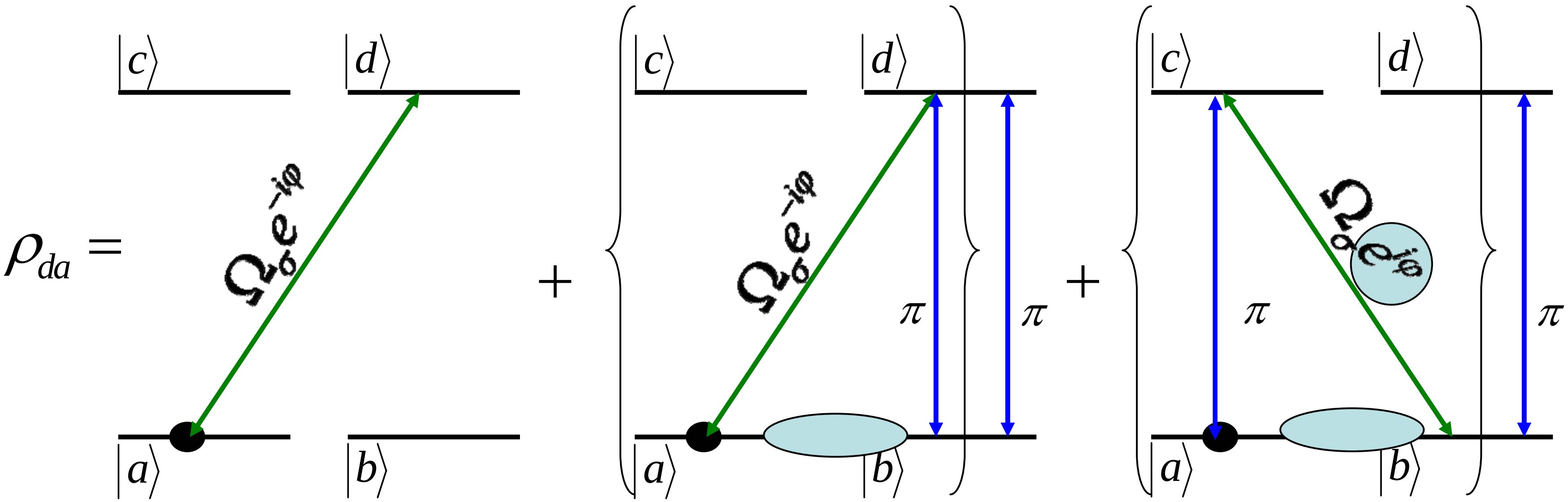
$\vec{k}_\pi + \left(\vec{k}_\sigma - \vec{k}_\pi\right) = \vec{k}_\sigma$

Cancel each other

$\Delta = 0$

III- Coherent Control of Susceptibility

$$\rho_\sigma = \rho_{da} + \rho_{cb}$$



Absorption path

$$\vec{k}_\sigma$$

Cross- Kerr type path

$$\vec{k}_\pi + \left(\vec{k}_\sigma - \vec{k}_\pi\right) = \vec{k}_\sigma$$

Phase Conjugate type path

$$\vec{k}_\pi - \left(\vec{k}_\sigma - \vec{k}_\pi\right) = 2\vec{k}_\pi - \vec{k}_\sigma$$

$$= \vec{k}_\sigma$$

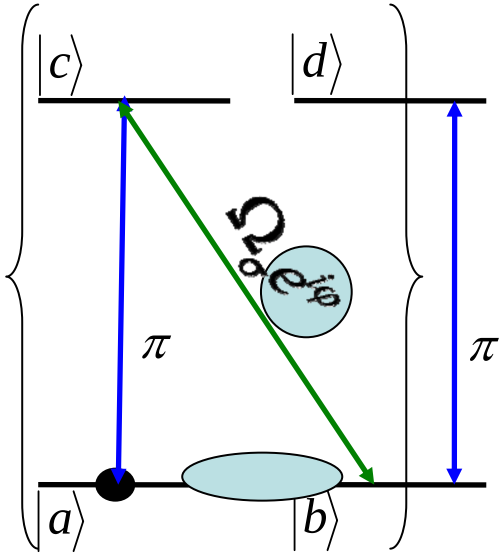
Cancel each other

$$\Delta = 0$$

Define the optical response

III- Coherent Control of Susceptibility

$if\ \Omega_{\pi} << \Gamma\ and\ \alpha_0 L << 1(thin\ sample):$

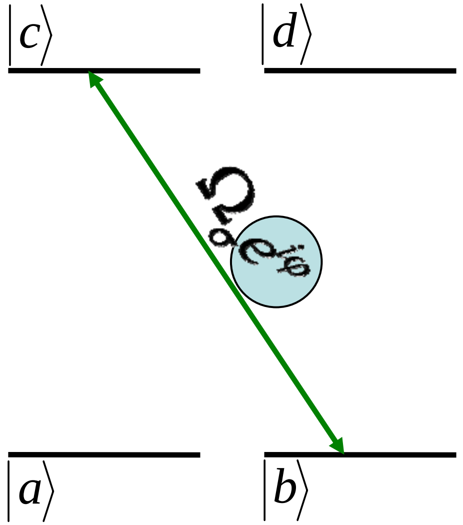


III- Coherent Control of Susceptibility

$if\ \Omega_\pi << \Gamma\ and\ \alpha_0 L << 1 (thin\ sample):$

Problem equivalent to linear propagation of field

$\Omega_\sigma e^{i\varphi}$ *in an assembly of two – level atoms :*



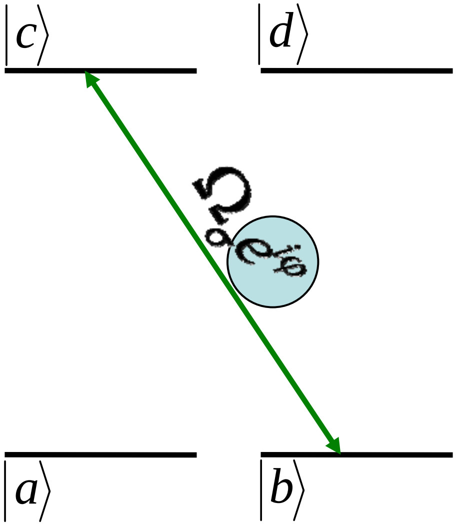
III- Coherent Control of Susceptibility

$if\ \Omega_\pi << \Gamma\ and\ \alpha_0 L << 1\ (thin\ sample):$

Problem equivalent to linear propagation of field

$\Omega_\sigma e^{i\varphi}$ *in an assembly of two-level atoms :*

$$P_\sigma\left(\propto \rho_\sigma\right) \simeq \chi_{lin}\left(\Omega_\sigma e^{i\varphi}\right) = \left(\chi_{lin} e^{2i\varphi}\right)\Omega_\sigma e^{-i\varphi}$$



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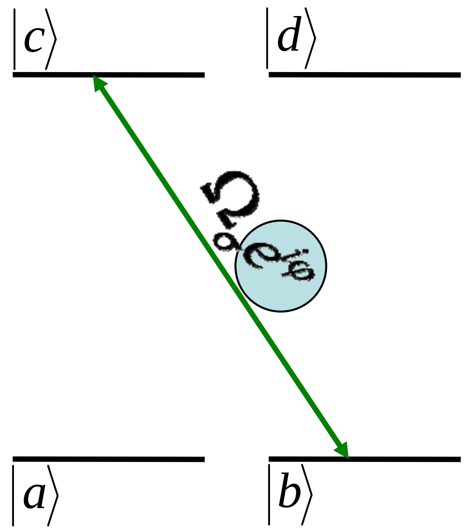

$$\longrightarrow \quad \chi_{eff} \approx \chi_{lin} e^{2i\varphi}\ !$$

Independent from pump field characteristics!

III- Coherent Control of Susceptibility

$if\ \Omega_\pi << \Gamma\ and\ \alpha_0 L << 1\ (thin\ sample):$

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$\Omega_\sigma e^{i\varphi}$ *in an assembly of two-level atoms:*

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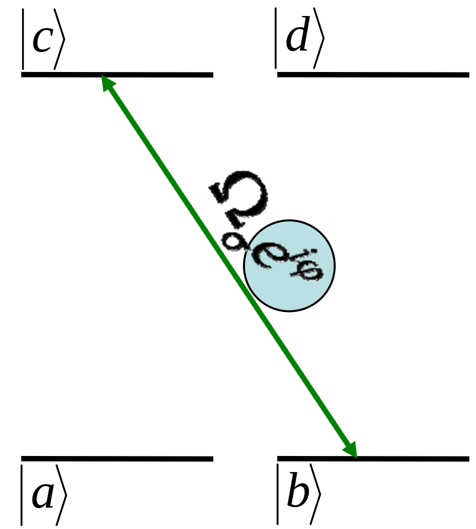

$$\longrightarrow \quad \chi_{eff} \approx \chi_{lin} e^{2i\varphi}\ !$$

Independent from pump field characteristics!

-The system behaves as a <u>linear</u> medium with a modified (linear) suceptibility <u>controlled by the phase shift</u>
-Giant non-linearity

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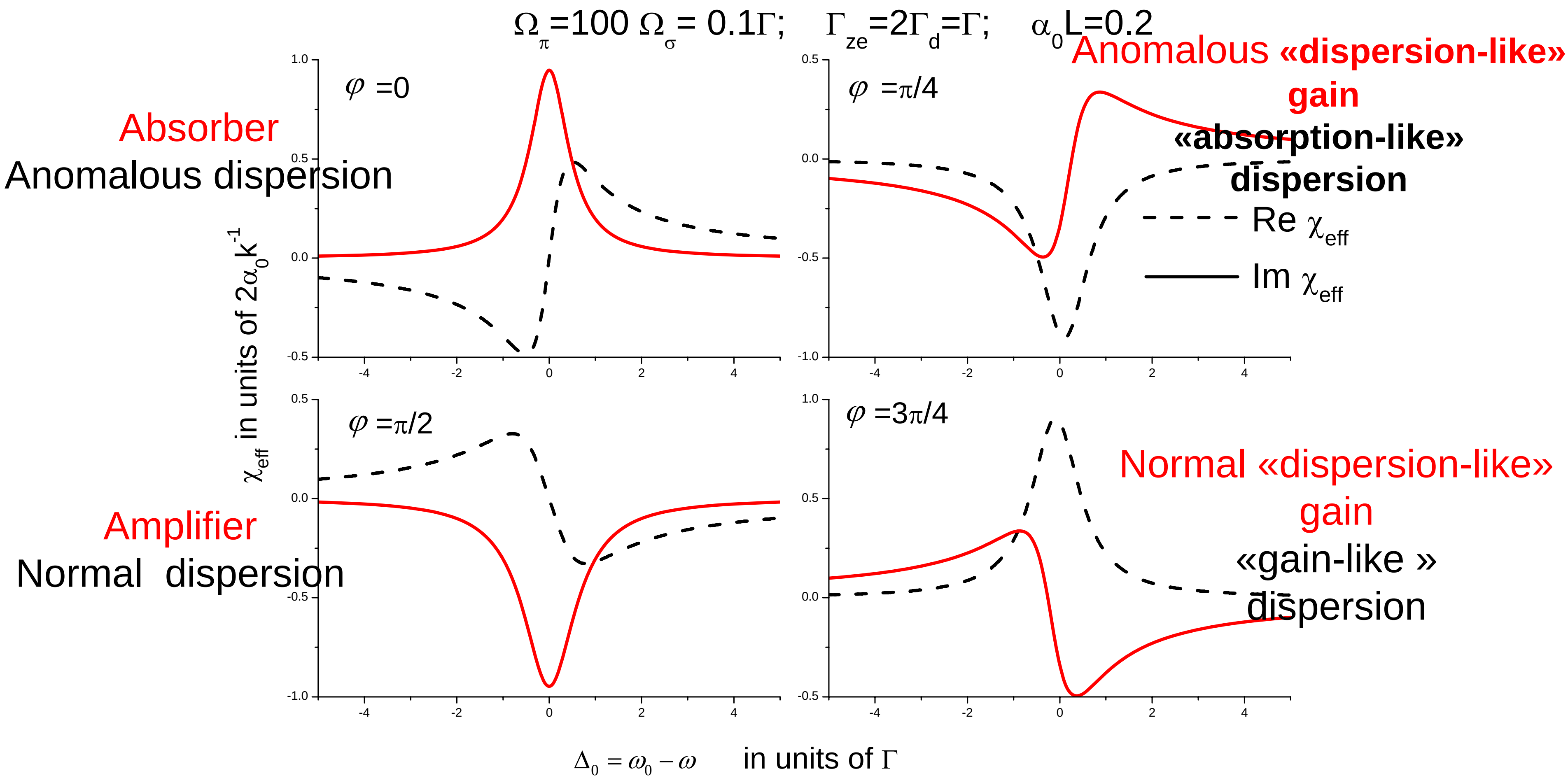
III- Coherent Control of Susceptibility

$$\chi_{eff} \approx \chi_{lin} e^{2i\varphi} : gain - dispersion\ coupling$$



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Conclusion

- CZO: a new method to slow light without any trapping dark state
  - Possibility to slow light in more complex atomic structures
  - General treatment that combines EIT, CPO and CZO
- Control of the optical response of the medium
  - Absorber into gain medium with normal or anomalous dispersion <u>by adjusting the phase shift</u>
  - Control of mechanical action of light