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Superluminal and Slow Light Propagation in Quantum System

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Information Geometry, Quantum Mechanics and Applications

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Outline

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- Anomalous dispersion
- Superluminal
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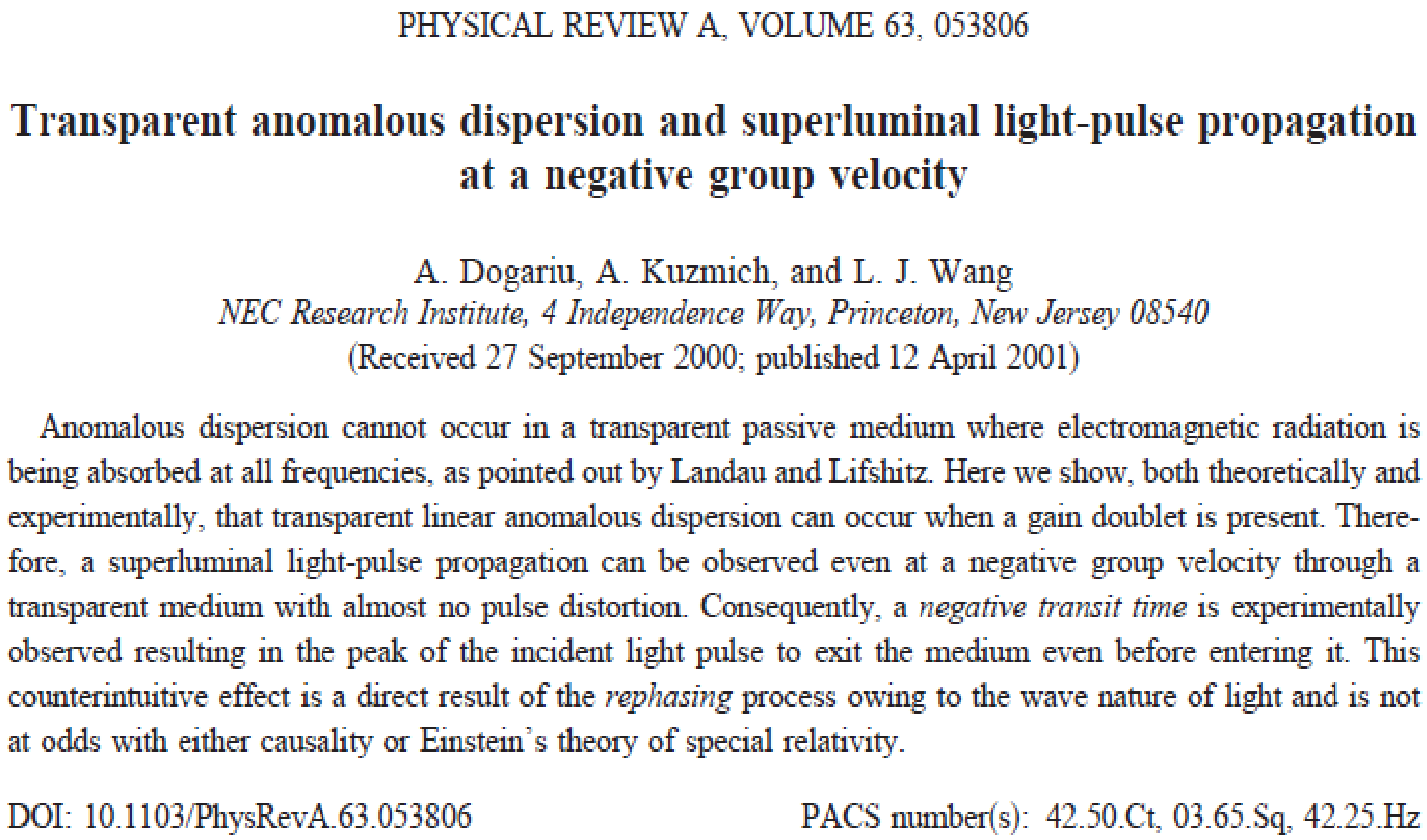
- References

WHY SUPERLUMINAL IS IMPORTANT?

APPLICATIONS:

- ✓ fast fiber-optic communication
- ✓ Controllable optical delay lines
- ✓ Optical data storage
- ✓ Optical memories
- ✓ Devices for quantum information



PHYSICAL REVIEW A, VOLUME 63, 053806

Transparent anomalous dispersion and superluminal light-pulse propagation at a negative group velocity

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Anomalous dispersion cannot occur in a transparent passive medium where electromagnetic radiation is being absorbed at all frequencies, as pointed out by Landau and Lifshitz. Here we show, both theoretically and experimentally, that transparent linear anomalous dispersion can occur when a gain doublet is present. Therefore, a superluminal light-pulse propagation can be observed even at a negative group velocity through a transparent medium with almost no pulse distortion. Consequently, a *negative transit time* is experimentally observed resulting in the peak of the incident light pulse to exit the medium even before entering it. This counterintuitive effect is a direct result of the *rephasing* process owing to the wave nature of light and is not at odds with either causality or Einstein's theory of special relativity.

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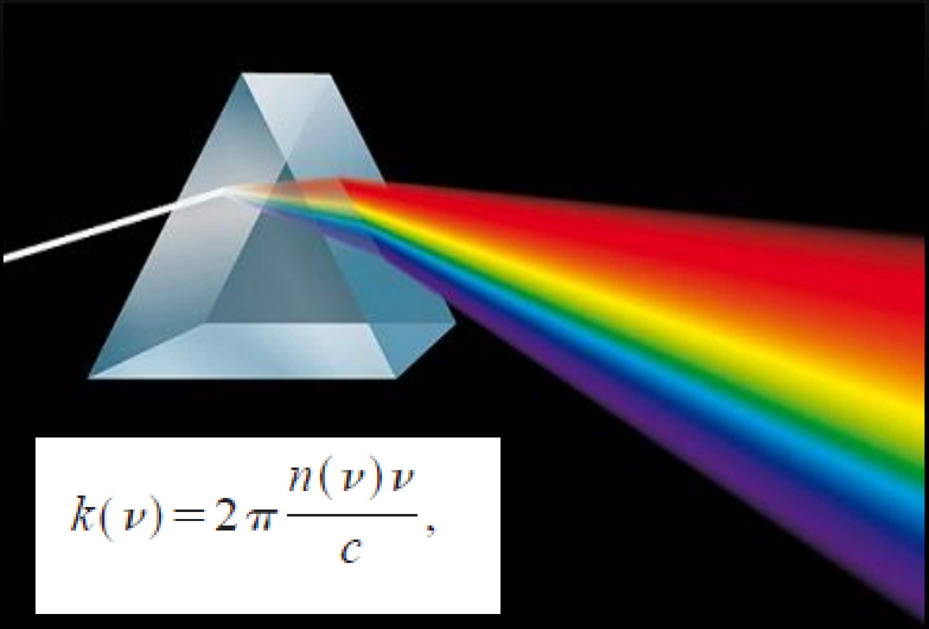
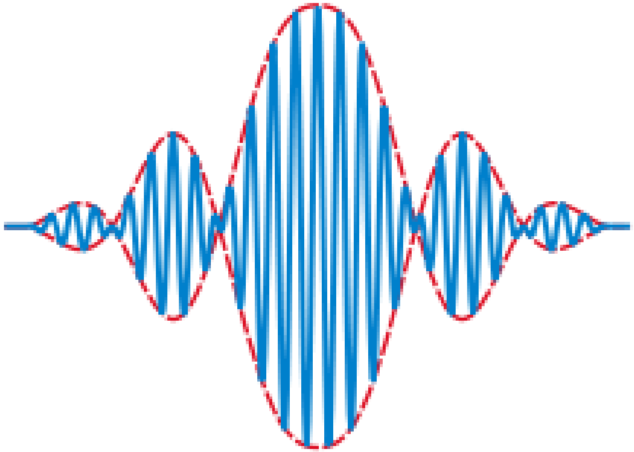
DISPERSION



$$k(\nu) = 2\pi \frac{n(\nu)\nu}{c},$$

When the phase velocity and the group velocity vary with frequency, the medium is called dispersive.

GROUP VELOCITY



- - - -The *envelope* of the wave packet. The envelope moves at the group velocity

$$V = \frac{\partial \omega}{\partial \kappa}$$

Group velocity and dispersion

$$v_g = \frac{c}{n_g} = \mathrm{Re}\left[\frac{d\omega}{dk}\right] = \frac{c}{\mathrm{Re}[n + \nu dn/d\nu]} \approx \frac{c}{n + \nu dn/d\nu},$$

$$n_g = n + \nu \frac{dn}{d\nu}$$

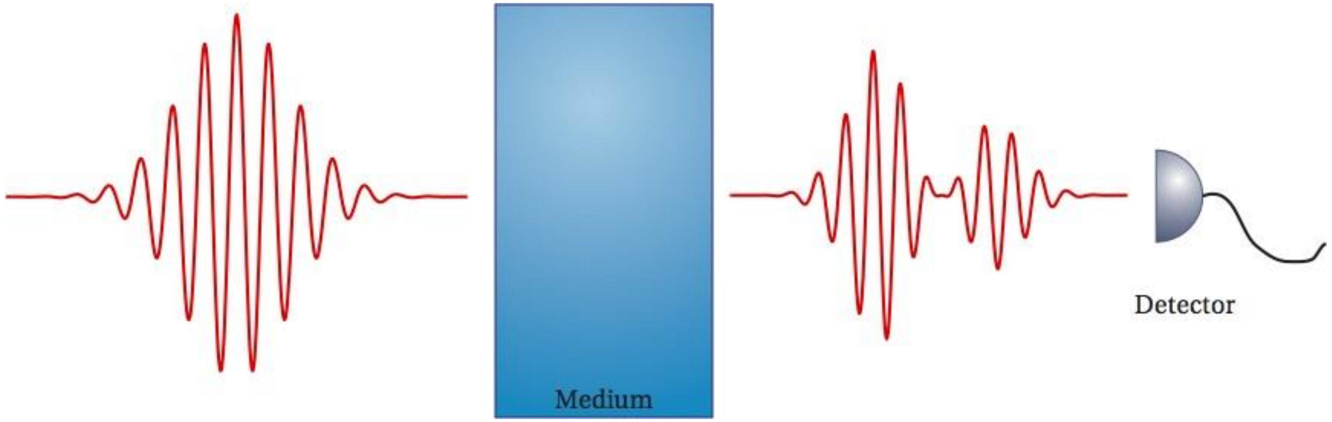
Normal dispersion

$$dn/d\upsilon \geq 0$$

Anomalous dispersion

$$\upsilon dn/d\upsilon \leq -1$$

Negative transit time



A negative transit time is experimentally observed resulting in the peak of the incident light pulse to exit the medium even before entering it [1].

MODEL

By using the classical Lorentz oscillator model, the equation of motion of the electron can be written as follows [1].

$$\ddot{x} + \Gamma \dot{x} + \omega_0^2 x = -\frac{eE}{m} = -\frac{eE_0}{m} e^{-i\omega t}.$$

$$\Gamma = 4\pi \gamma$$

$$x = \frac{eE}{m} \frac{1}{\omega^2 - \omega_0^2 + i\omega\Gamma} \approx \frac{eE}{2m\omega_0} \frac{1}{\omega - \omega_0 + i\Gamma/2},$$

DIELECTRIC SUSCEPTIBILITY

$$\chi(\nu) = -\frac{Ne^2}{4\pi\varepsilon_0 m\omega_0} \times \frac{1}{\nu-\nu_0+i\gamma} = -f \times \frac{M}{\nu-\nu_0+i\gamma},$$

$$M = \nu_P^2/\nu_0$$

f : oscillator strength [1]

When two absorption lines are placed nearby with equal oscillator strengths
The dielectric susceptibility can be written as: $f_1 = f_2 = 1,$

$$\chi(\nu) = -\frac{M}{\nu-\nu_1+i\gamma} - \frac{M}{\nu-\nu_2+i\gamma}.$$

DIELECTRIC SUSCEPTIBILITY

Between two closely placed gain lines, the effective dielectric constant can be written:

$$\epsilon(\nu)=1+\chi(\nu)=1+\frac{M}{\nu-\nu_1+i\gamma}+\frac{M}{\nu-\nu_2+i\gamma}.$$

For a dilute gaseous medium, refractive index is:

$$n(\upsilon)=n'(\upsilon)+in''(\upsilon)=1+\chi(\upsilon)/2$$

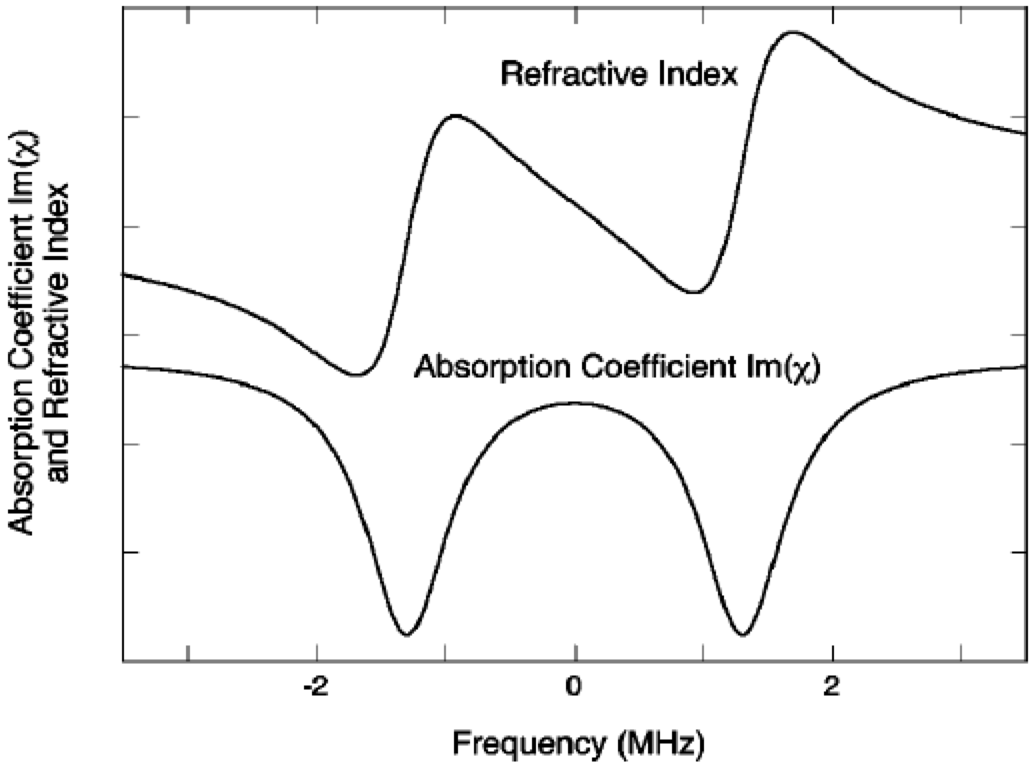
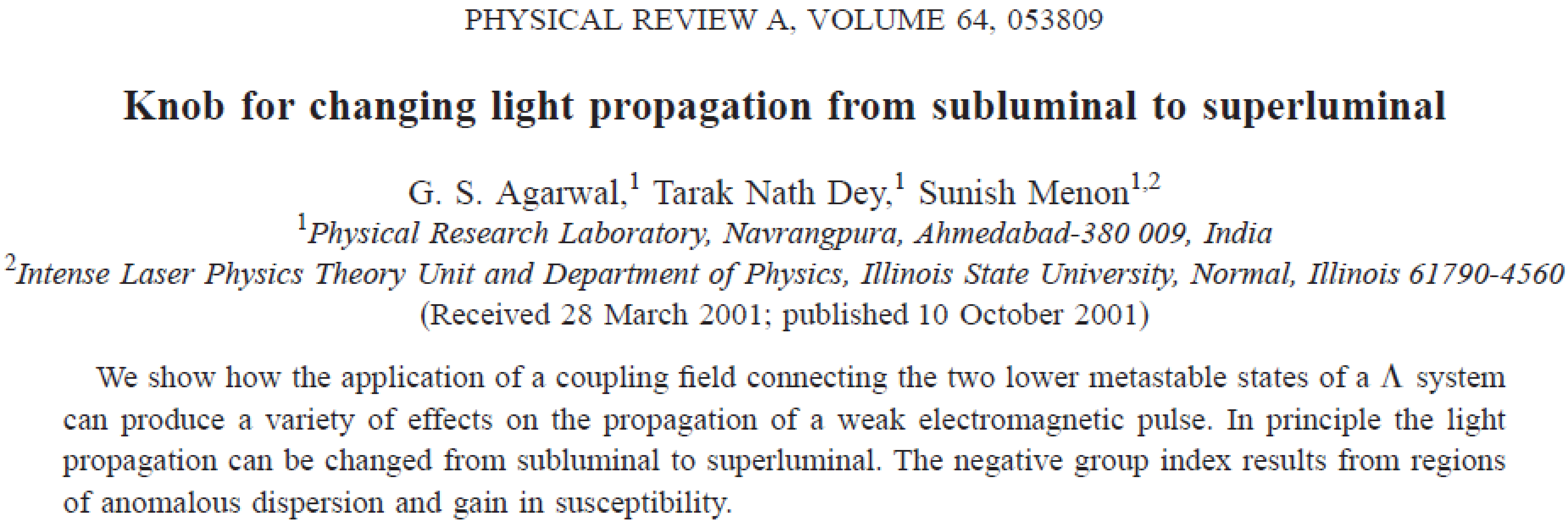


Fig. 1. Anomalous dispersion. Figure shows frequency-dependent gain coefficient and refractive index. [1]



PHYSICAL REVIEW A, VOLUME 64, 053809

Knob for changing light propagation from subluminal to superluminal

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We show how the application of a coupling field connecting the two lower metastable states of a Λ system can produce a variety of effects on the propagation of a weak electromagnetic pulse. In principle the light propagation can be changed from subluminal to superluminal. The negative group index results from regions of anomalous dispersion and gain in susceptibility.

MODEL

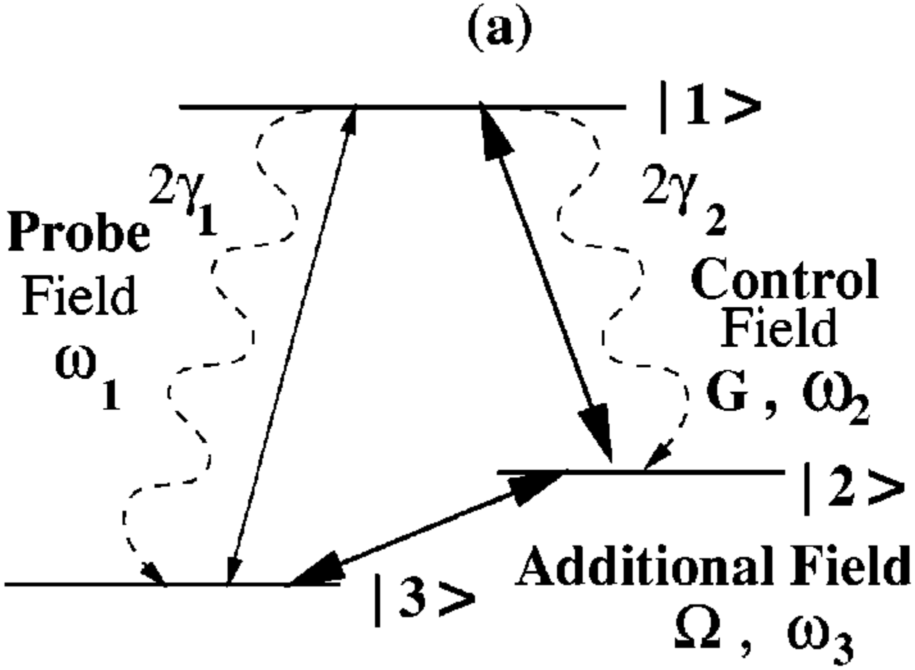


Fig 2. Schematic diagram of three- level lambda system [3].

EQUATIONS

$$\dot{\sigma}_{11}=iG\sigma_{21}+ige^{-i\Delta_4 t}\sigma_{31}-iG^*\sigma_{12}-ig^*e^{i\Delta_4 t}\sigma_{13}$$
$$-2(\gamma_1+\gamma_2)\sigma_{11},$$

$$\dot{\sigma}_{22}=iG^*\sigma_{12}+i\Omega\sigma_{32}-iG\sigma_{21}-i\Omega^*\sigma_{23}+2\gamma_2\sigma_{11},$$

$$\dot{\sigma}_{12}=-[\gamma_1+\gamma_2+\Gamma_{12}-i\Delta_2]\sigma_{12}+iG\sigma_{22}+ige^{-i\Delta_4 t}\sigma_{32}$$
$$-iG\sigma_{11}-i\Omega^*\sigma_{13},$$

$$\dot{\sigma}_{13}=-[\gamma_1+\gamma_2+\Gamma_{13}-i(\Delta_2+\Delta_3)]\sigma_{13}+iG\sigma_{23}$$
$$+ige^{-i\Delta_4 t}\sigma_{33}-ige^{-i\Delta_4 t}\sigma_{11}-i\Omega\sigma_{12},$$

$$\dot{\sigma}_{23}=-(\Gamma_{23}-i\Delta_3)\sigma_{23}+iG^*\sigma_{13}+i\Omega\sigma_{33}-ige^{-i\Delta_4 t}\sigma_{23}$$
$$-i\Omega\sigma_{22},$$

$$\rho_{12}=\sigma_{12}e^{-i\omega_2 t},\quad \rho_{13}=\sigma_{13}e^{-i(\omega_2+\omega_3)t},\quad \rho_{23}=\sigma_{23}e^{-i\omega_3 t}$$

$$\Delta_1=\omega_1-\omega_{13},\ \ \Delta_2=\omega_2-\omega_{12},\ \ \Delta_3=\omega_3-\omega_{23},$$

$$\Delta_4=\Delta_1-\Delta_2-\Delta_3,\ \ g=\frac{\vec{d}_{13}\cdot\vec{E}_p}{\hbar}.$$

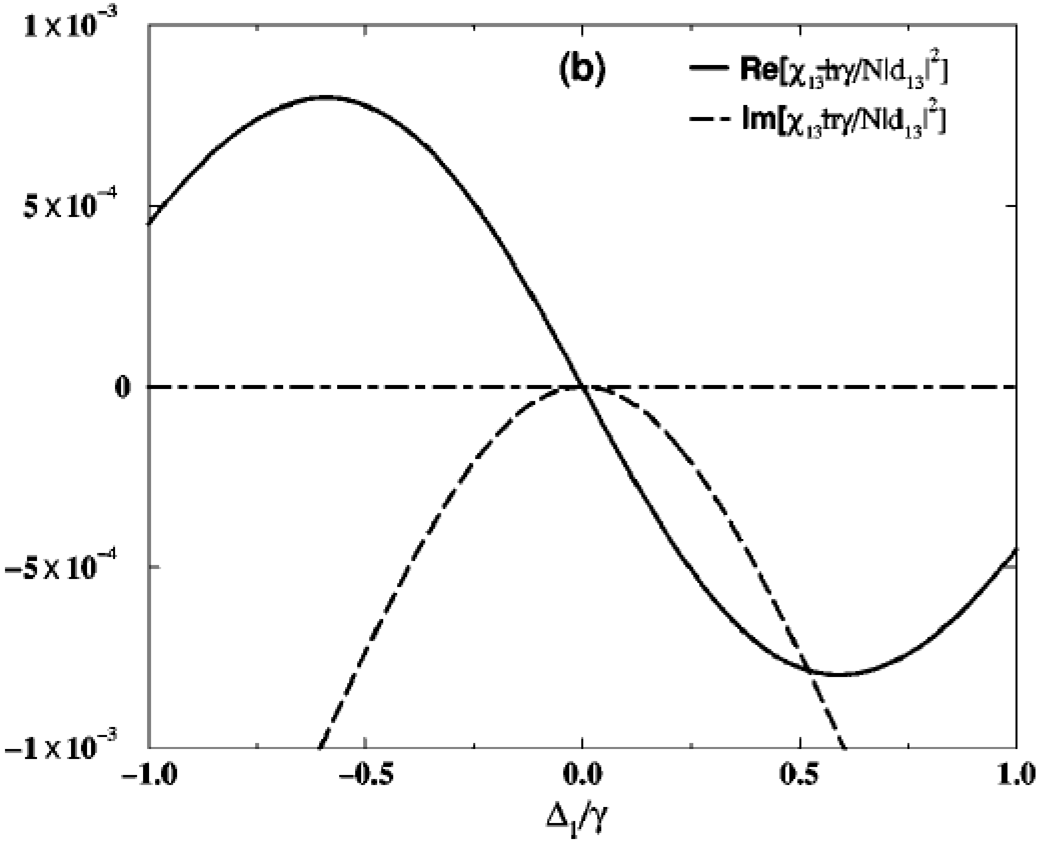
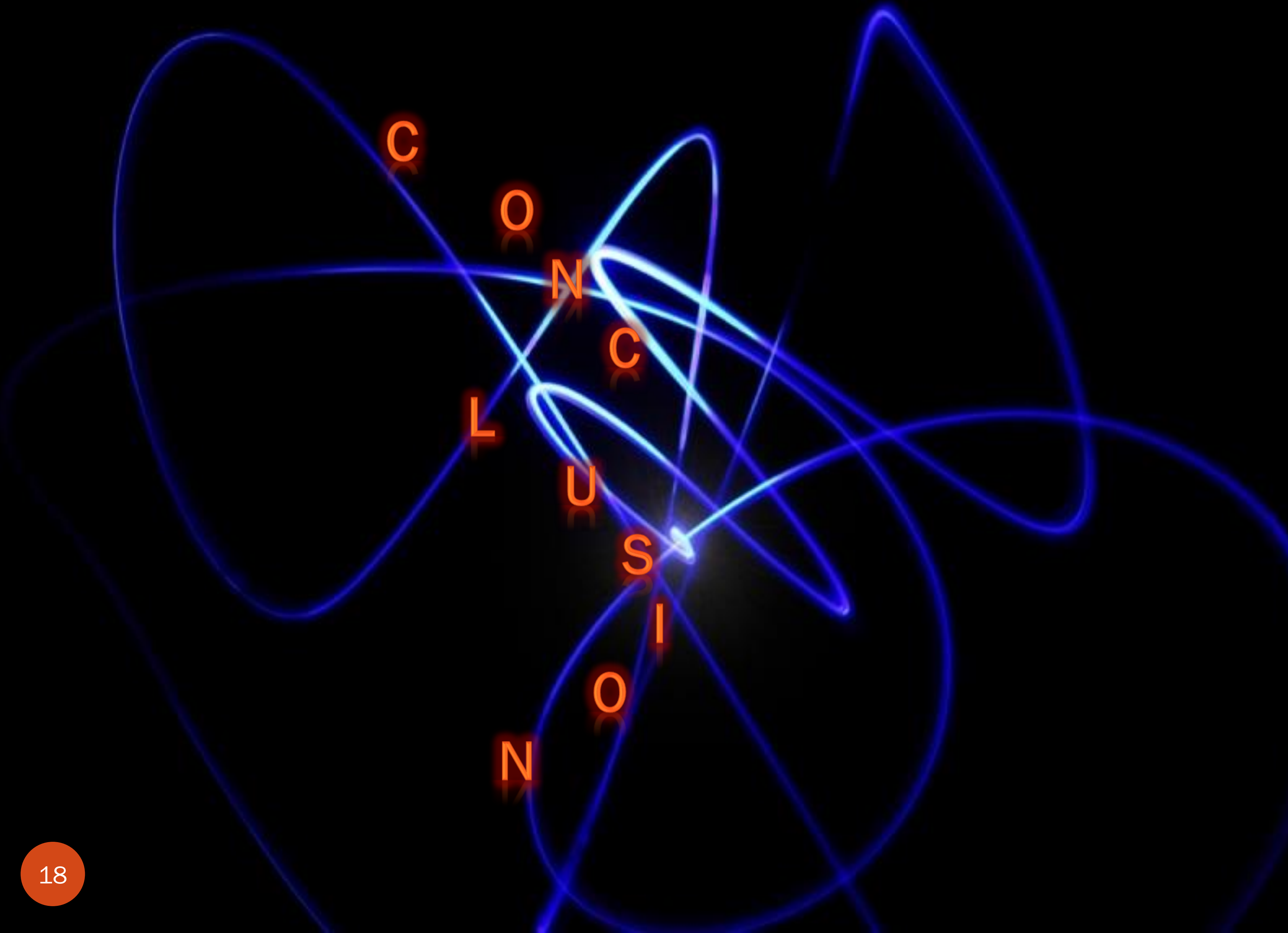


Fig 3. Real and imaginary parts of the susceptibility at a probe frequency in the presence of control and LL coupling field [3].



CONCLUSION

CONCLUSION

In this talk, the superluminal and slow light propagation in quantum system has been reviewed theoretically and experimentally. It is found that, the medium response to light such as absorption and dispersion could be controlled by the intensity of applied fields. In fact the probe pulse propagation can be switched from subluminal to superluminal by changing the intensity of the coupling field. It is shown that the group velocity can be faster the speed of light in vacuum and even can become negative; however this result is not in contradiction with either causality or Einstein's theory of special relativity.

References

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Thanks