Group velocity of light in coupled system

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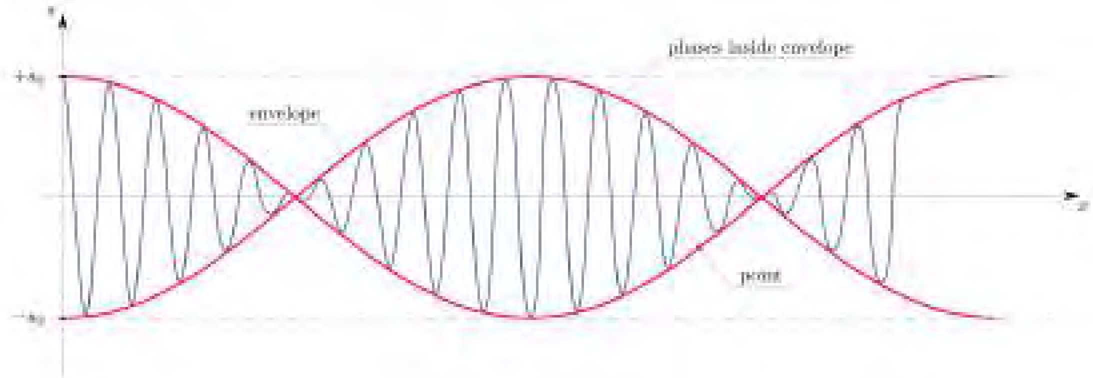
Group Velocity of a dispersive wave

$$v_g = \frac{d\omega}{dk}$$

ω – angular frequency
k – wavenumber



Phase shift according to propagation constant

$$\phi = -kl$$

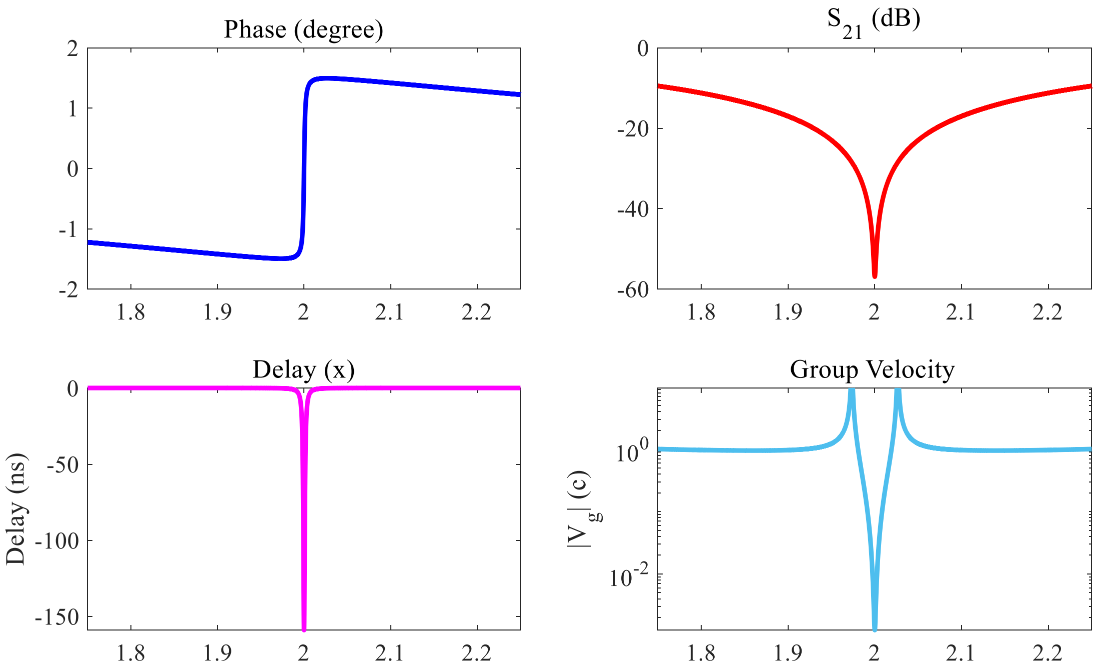
l – physical length

$$k = -\frac{\phi}{l} \longrightarrow dk = -\frac{d\phi}{l}$$

Group delay:

$$\tau_g = -\frac{d\phi}{d\omega}$$

$$v_g = -l\frac{d\omega}{d\phi} = \frac{l}{\tau_g}$$



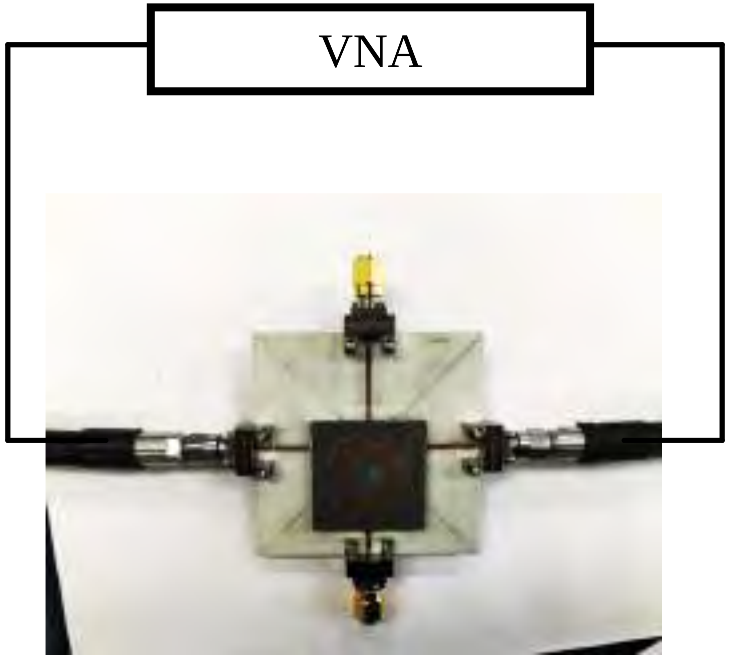
Calculation:

$\omega_0 = 2GHz$

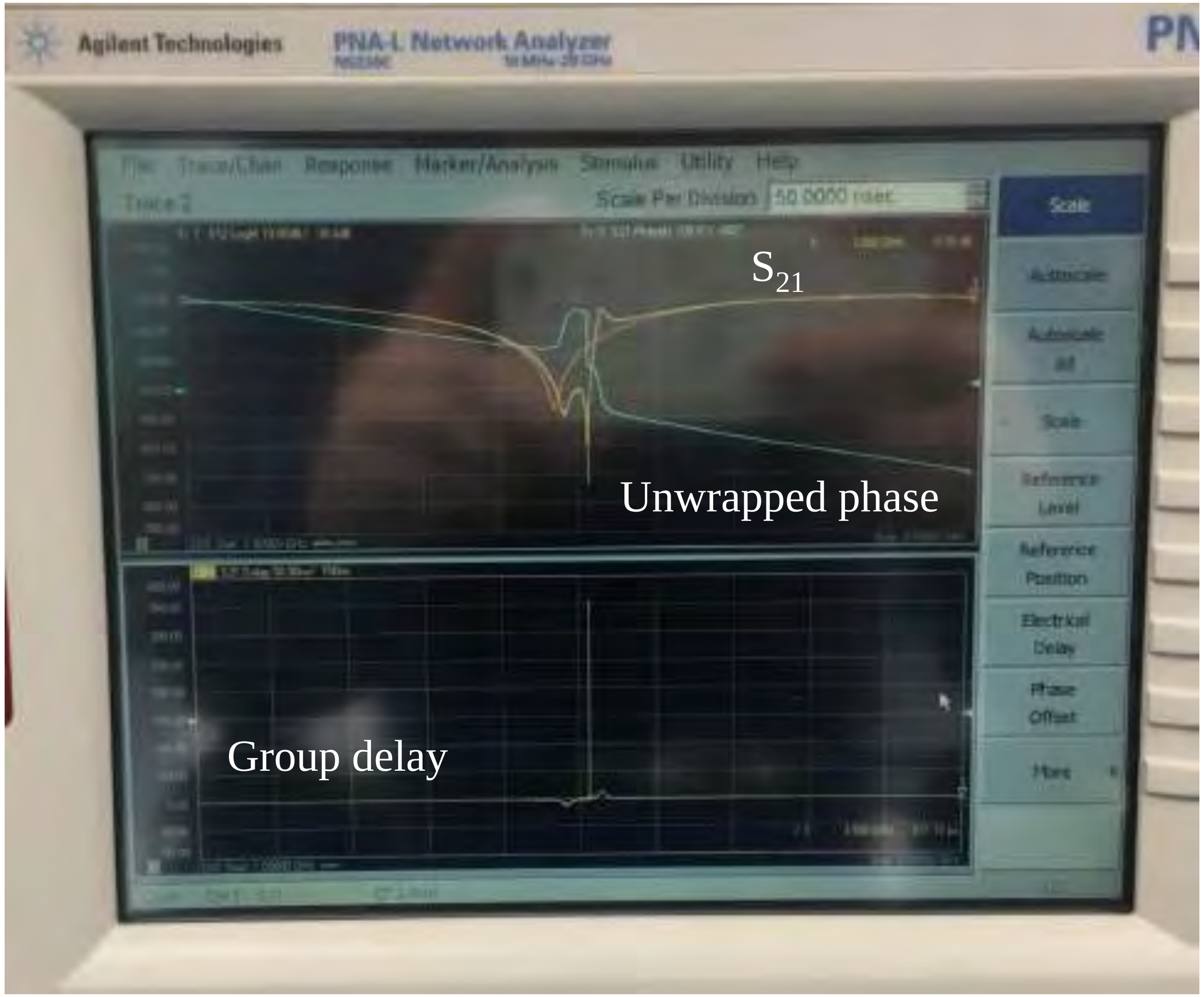
$\kappa = 700MHz$

$\gamma = 1MHz$

New measurement method



Directly measure the **group delay time** and **unwrapped phase**:



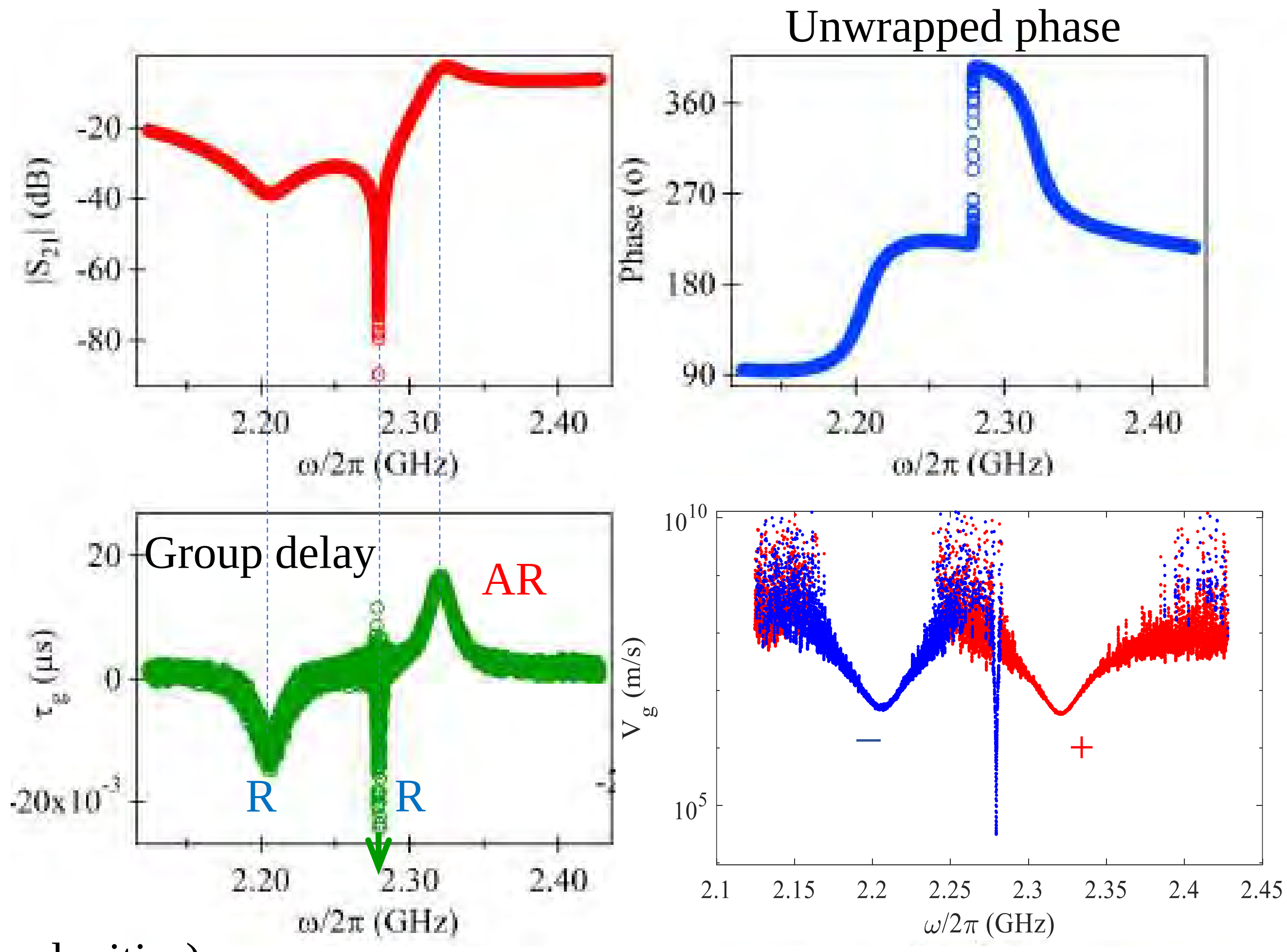
The fast and slow light

The slow light is defined as:

$$v_g \ll c$$

The speed of light is slowed can be slowed to:

$$v_g \approx 10^{-5}c = 2km/s$$



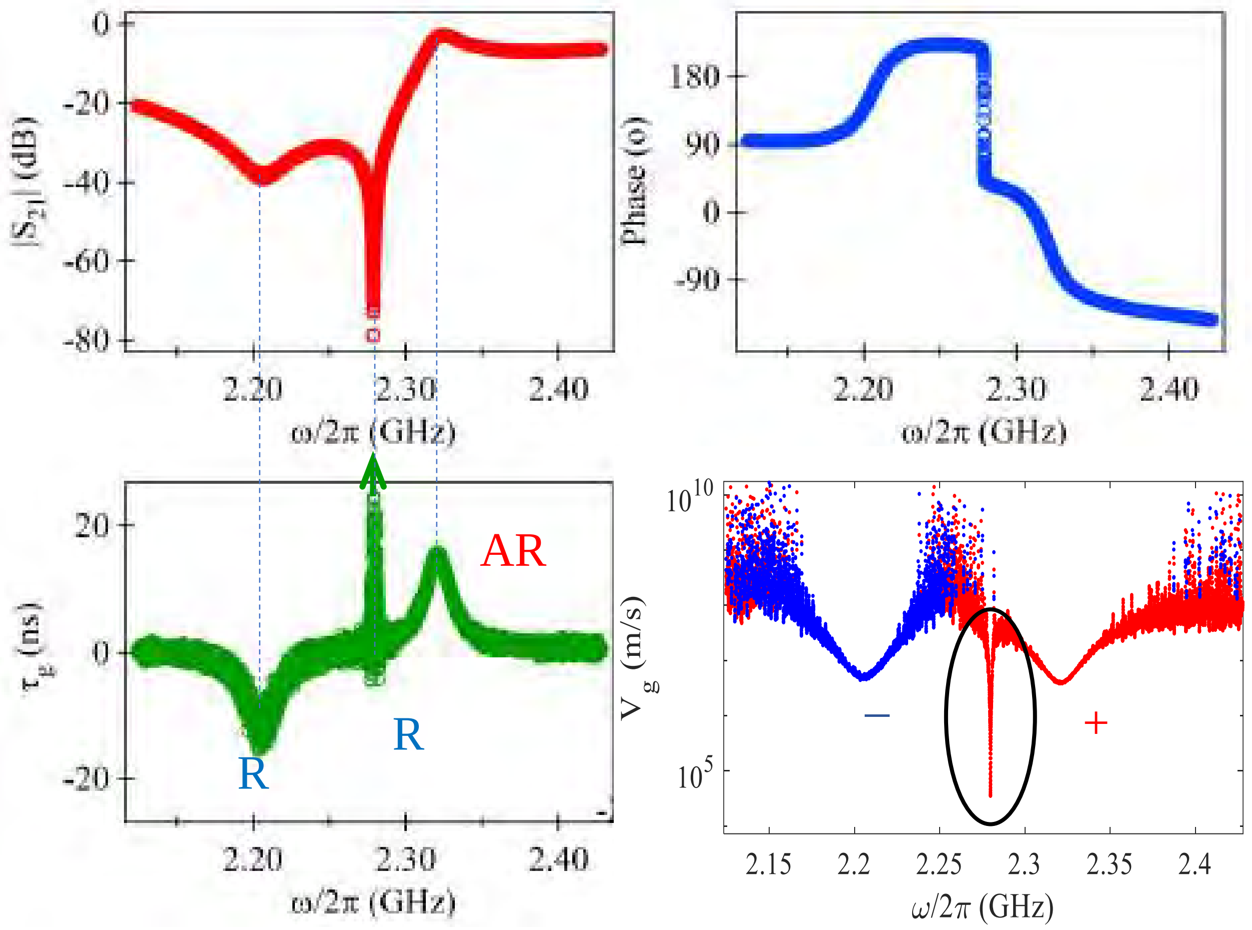
The fast light is defined as: (superluminal group velocities)

$$v_g > c \;\text{ or }\; v_g < 0$$

What does it mean a negative delay or negative wave speed?

This can be achieved using anomalous dispersion near an absorption line. [2]

Positive and negative damping



Anti-Resonance:
S_{21} maximum & positive Group delay

Resonance with positive damping:
S_{21} minimum & negative Group delay

Resonance with negative damping :
S_{21} minimum & positive Group delay

The phase plays an important role to determining the damping rates.

→ Evidence of negative damping

[1]

PHYSICAL REVIEW LETTERS

Nonlinear Magneto-optics and Reduced Group Velocity of Light in Atomic Vapor with Slow Ground State Relaxation

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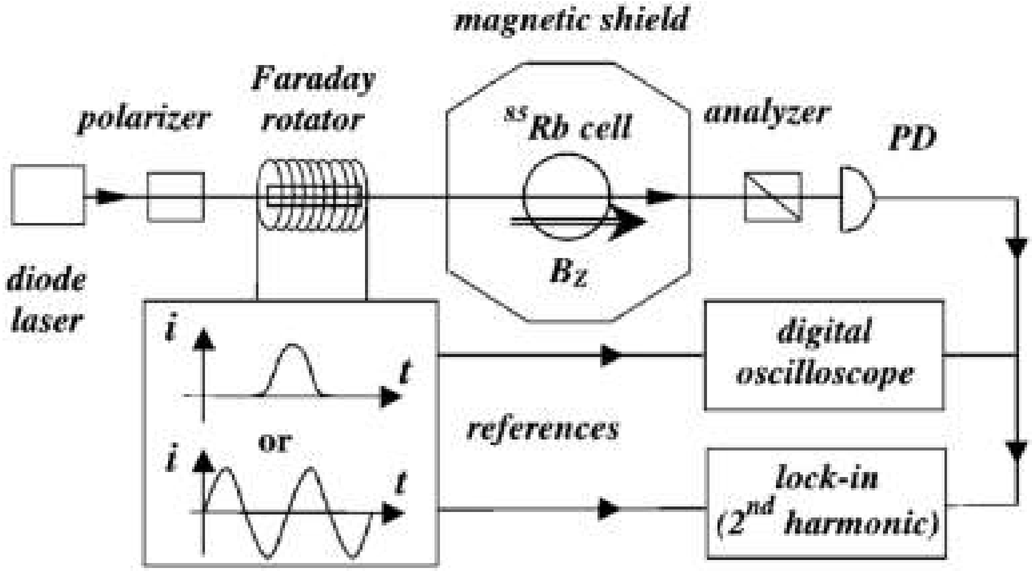
$$v_g = 8m/s$$



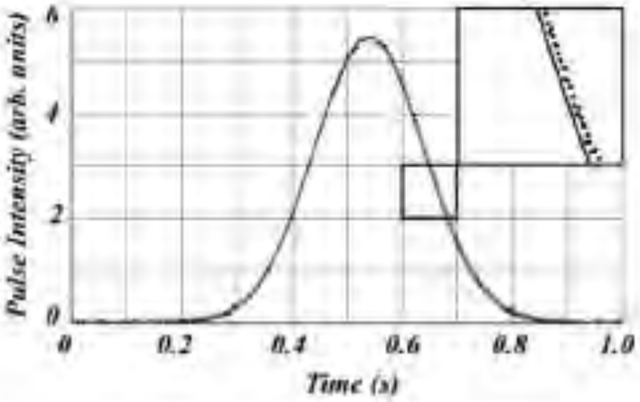


FIG. 4. An example of pulse delay measurement on the $D1$ line. The laser is tuned to the same frequency as in Fig. 3. Dotted line: time-dependent signal recorded by the photodetector with $B_z = 0$; solid line: same with $B_z = 10\ \mu$G (corrected for the time-independent Faraday rotation produced by the magnetic field). The timing of the latter curve is within experimental uncertainty identical with that recorded for off-resonant laser light. The measured delay in this particular case is $\tau_d = 2.5(1)$ ms. Similar observations were also made on the $D2$ line. The inset shows an enlarged view of the highlighted area of the plot.

letters to nature

[1]

Gain-assisted superluminal light propagation

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The group velocity of a laser pulse in this region exceeds c and can even become negative.

$$v_g = -c/310$$

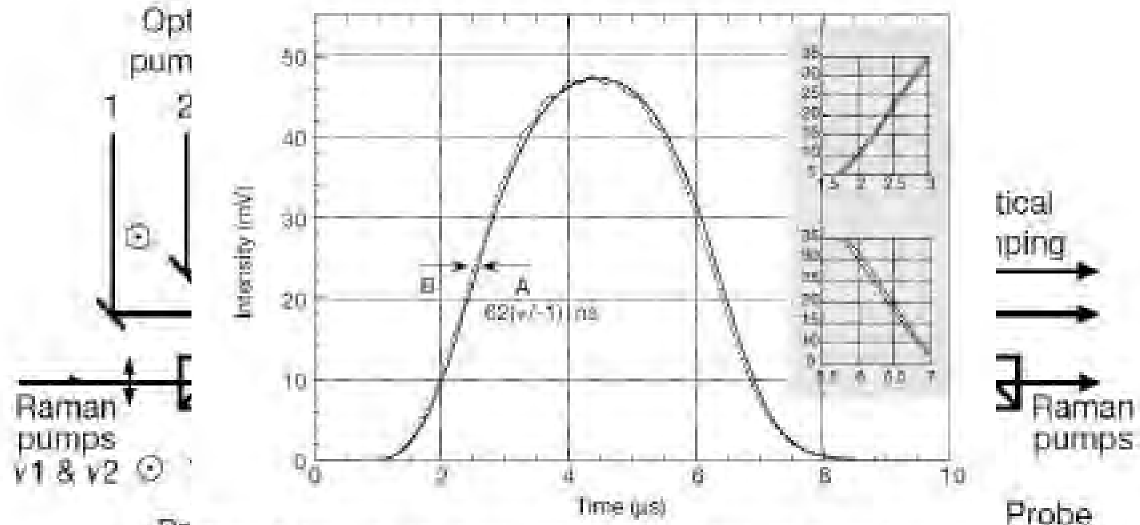

Figure 4 Measured pulse advancement for a light pulse traversing through the caesium vapour in the gain-assisted superluminality state. A indicates a light pulse far off-resonance from the caesium D_2 transitions propagating at speed c through 6 cm of vacuum. B shows the same light pulse propagating through the same caesium-cell near resonance with a negative group velocity $-c/310$. Insets show the front and trailing portions of the pulses. Pulses A and B are both the average of 1,000 pulses. The off-resonance pulse (A) is normalized to the magnitude of B.

It can be understood by the classical theory of wave propagation in an anomalous dispersion region where interference between different frequency components produces this rather counterintuitive effect.

The true speed at which information is carried by a light pulse should be defined as the "frontal" velocity of a step-function-shaped signal which has been shown not to exceed c.

letters to nature

[2]

The speed of information in a 'fast-light' optical medium

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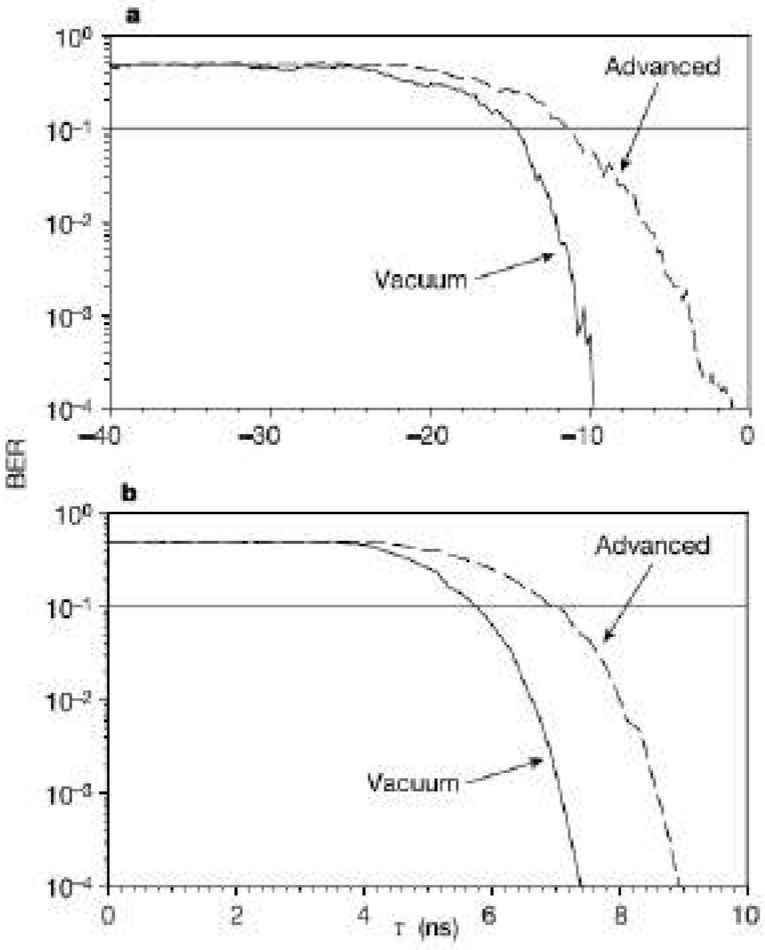
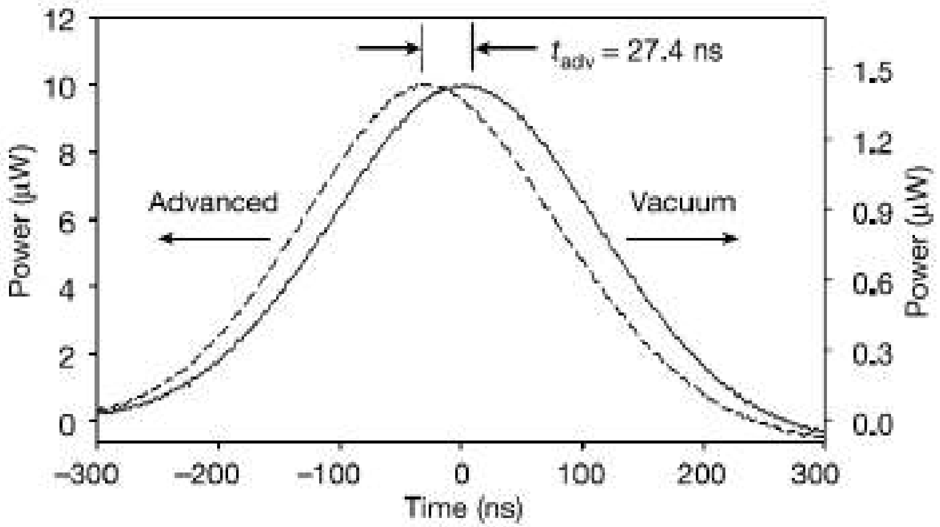
Bit Error Rate





$$v_g = -c/20$$

$$v_i = 0.4c$$

Summary

Fast light ($v_g > c$ or $v_g < 0$)

1. This counterintuitive phenomenon is a consequence of the wave nature of light.
2. The speed of the information v_i is less than c and does not violate Relativity.

Slow light ($v_g \ll c$)

1. Has been intensively studied since 1998.
2. Potential applications on electronic computer such as new generation optical switch.

In coupled system around ZDCs / BICs

1. The rapid transition between slow light and fast light.
2. The negative damping do exist if we take the phase into consideration.