Superluminal propagation of pulsed squeezed vacuum

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Squeezed state
Why superluminal squeezing?

- Quantum memories


Light group velocity

Group velocity \( v_g = \frac{c}{\omega} \frac{\partial n}{\partial \omega} \)

Susceptibility

\[
\chi' = \chi''
\]

\[
\chi'' \quad \chi'
\]

detuning

\[
-10 -5 0 5 10
\]
Susceptibility and Faraday effect

$^{87}$Rb $D_1$ line

Susceptibility vs detuning with magnetic field
Susceptibility and Faraday effect

$^{87}\text{Rb D}_1$ line

Susceptibility vs detuning with magnetic field

\[
\begin{align*}
\chi''(+\Delta) & \quad \chi''(-\Delta) \\
\chi'(+\Delta) & \quad \chi'(-\Delta)
\end{align*}
\]
Susceptibility and Faraday effect

$^{87}$Rb D$_1$ line

Susceptibility vs detuning with magnetic field

\[ \chi''(\pm \Delta), \chi'(\pm \Delta) \]

Polarization rotation vs B field

\[ \Delta \chi' \]

Superluminal squeezing
Susceptibility and Faraday effect

$^{87}$Rb D$_1$ line

- $F'=2$
- $F'=1$
- $F=2$
- $F=1$

$\sigma_+$
$\sigma_-$

$m=-1$
$m=0$
$m=1$

Susceptibility vs detuning with magnetic field

$\chi''(+\Delta)$
$\chi''(-\Delta)$
$\chi'+(+\Delta)$
$\chi'+(-\Delta)$
Susceptibility and Faraday effect

$^{87}\text{Rb } D_1$ line

\begin{align*}
F' &= 2 \\
F' &= 1 \\
F &= 2 \\
F &= 1
\end{align*}

\begin{align*}
m &= 0 \\
m' &= 0 \\
m &= 1 \\
m &= -1
\end{align*}

\begin{align*}
\sigma_+ \\
\sigma_-
\end{align*}

Susceptibility vs detuning with magnetic field

\begin{align*}
\chi''(\text{+}\Delta) \\
\chi''(\text{-}\Delta) \\
\chi'(\text{+}\Delta) \\
\chi'(\text{-}\Delta)
\end{align*}

\begin{axis}[
width=\textwidth,
height=0.5\textwidth,
axis lines=left,
xticklabels={$-10$,$-5$,$0$,$5$,$10$},
xtick={-10,-5,0,5,10},
xticklabel style={/pgf/number format/1000 sep={}},
ymajorgrids=true,
axis x line*=bottom
]
\addplot[red, thick, mark=none] coordinates {(-10,-1) (-5,0) (0,0) (5,1) (10,1)}; \addlegendentry{$\chi''(\text{+}\Delta)$}
\addplot[red, thin, mark=none] coordinates {(-10,0.5) (-5,0) (0,0) (5,-0.5) (10,-0.5)}; \addlegendentry{$\chi''(\text{-}\Delta)$}
\addplot[blue, thick, mark=none] coordinates {(-10,0) (-5,0) (0,1) (5,0) (10,0)}; \addlegendentry{$\chi'(\text{+}\Delta)$}
\addplot[blue, thin, mark=none] coordinates {(-10,0) (-5,0) (0,-1) (5,0) (10,0)}; \addlegendentry{$\chi'(\text{-}\Delta)$}
\end{axis}
**Susceptibility and Faraday effect**

\[^{87}\text{Rb D}_1\] line

\[ F'=2 \]
\[ F'=1 \]
\[ F=2 \]
\[ m=-1 \quad m=0 \]
\[ F=1 \]

**Susceptibility vs detuning with magnetic field**

\[ \chi''(+\Delta) \quad \chi''(-\Delta) \]
\[ \chi'(+\Delta) \quad \chi'(-\Delta) \]

**Polarization rotation vs B**

\[ \Delta \chi' \]

**Susceptibility**

\[ \chi'' \quad \chi' \]
Susceptibility and non linear Faraday effect

Naive model of rotation

Experiment

Graph showing the relationship between B field and Δχ′.

Diagram of an experiment setup with labels for Laser, SMPM Fiber, Lean, GP, λ/2, 87Rb, Magnetic Shielding, Scope, PBS, BPD.
Susceptibility and non linear Faraday effect

Naive model of rotation

Experiment

\[ \Delta \chi' \]

\[ B \text{ field} \]

\[ \lambda/2 \]

\[ \text{Laser} \]

\[ \text{SMPM Fiber} \]

\[ \text{Lens} \]

\[ \text{GP} \]

\[ \text{87Rb Cell} \]

\[ \text{Scope} \]

\[ \text{BPD} \]

\[ \text{PBS} \]

\[ \text{Scope} \]

Rotation response (V)

Magnetic field (G)

1 mW

2 mW

4 mW

6 mW

8 mW

12 mW
Light group velocity

Group velocity \( v_g = \frac{c}{\omega} \frac{\partial n}{\partial \omega} \)

Delay \( \tau = \frac{L}{v_g} \sim \frac{\partial n}{\partial \omega} \sim \frac{\partial R}{\partial B} \)
Light group velocity

Group velocity $v_g = \frac{c}{\omega \frac{\partial n}{\partial \omega}}$

Delay $\tau = \frac{L}{v_g} \sim \frac{\partial n}{\partial \omega} \sim \frac{\partial R}{\partial B}$
Heisenberg uncertainty principle and its optics equivalent

Heisenberg uncertainty principle
\[ \Delta p \Delta x \geq \frac{\hbar}{2} \]
The more precisely the POSITION is determined, the less precisely the MOMENTUM is known, and vice versa

Optics equivalent
\[ \Delta \phi \Delta N \geq 1 \]
The more precisely the PHASE is determined, the less precisely the AMPLITUDE is known, and vice versa

Optics equivalent strict definition
\[ \Delta X_1 \Delta X_2 \geq \frac{1}{4} \]
Minimum uncertainty (coherent) states

Coherent state

\[ X^2 \]

\[ X^1 \]

\[ \phi \]

Squeezed state

\[ \Delta X_1 \Delta X_2 \geq \frac{1}{4} \]
Minimum uncertainty (coherent) states

Coherent state

Squeezed state

\[ \Delta X_1 \Delta X_2 \geq \frac{1}{4} \]
Self-rotation of elliptical polarization in atomic medium

\[ a_{\text{out}} = a_{\text{in}} + \frac{igL}{2} (a_{\text{in}}^\dagger - a_{\text{in}}) \]

- **theory**: A.B. Matsko et al., PRA 66, 043815 (2002)
Setup

LASER

SMPM FIBER

LENS

GP

λ/2

MAGNETIC SHIELDING

87 Rb

SCOPE

BPD

PBS

LENS

λ/2

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superluminal squeezing

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Maximally squeezed spectrum with $^{87}$Rb

W&M team. $^{87}$Rb $F_g = 2 \rightarrow F_e = 2$, laser power 7 mW, $T=65^\circ$ C

Lezama et. al report 3 dB squeezing in similar setup
Squeezing vs magnetic field

Spectrum analyzer settings: Central frequency = 1 MHz, VBW = 3 MHz, RBW = 100 kHz

![Diagram of experimental setup]

Squeezing vs magnetic field

Spectrum analyzer settings: Central frequency = 1 MHz, VBW = 3 MHz, RBW = 100 kHz

Time advancement setup

Squeezer
- Diode Laser
- Optical Fiber
- $\lambda/2$
- Rb Cell
- $F=2$
- $F=1$
- $F'=2$
- $F'=1$

Interaction
- Bypass
- $B_z$
- Rb Cell

Detection
- $\lambda/4$
- $\lambda/2$
- Balanced photodetector
- Spectrum Analyzer
Squeezing modulation and time advancement

![Graph showing noise power vs. time](image)

- Time, ms
- Noise power, dB

(a) Superluminal squeezing

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Squeezing modulation and time advancement

Noise (dB) vs. Time (ms)

- Noise levels are plotted along the y-axis (ranging from -1.6 to 0 dB).
- Time duration is marked along the x-axis (ranging from -3 to 2.5 ms).
- Two curves are shown: one for bypass and one for cell.

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superluminal squeezing

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Advancement vs power

![Graph showing advancement vs power](image-url)
Advancement vs power

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Squeezing level before and after advancement cell

![Graph showing noise power versus pump power, with two curves labeled (a) and (b).](image-url)
Vacuum cell vs coated cell

Vacuum cell

Coated cell
Vacuum cell vs coated cell

Vacuum cell

![Graph showing noise power vs magnetic field for vacuum cell with antisqueezed and squeezed states.](image)

Coated cell

![Graph showing noise level vs magnetic field for coated cell with superluminal squeezing.](image)
First demonstration of superluminal squeezing propagation with $v_g = -c/16000$ or time advancement of 4 $\mu$S