Spatial Profile of the Squeezed Quantum Noise Generated and Modified by Resonant Atomic Ensembles

Mi Zhang, Irina Novikova, Eugeniy E. Mikhailov

*College of William & Mary*

R. Nicholas Lanning, Jonathan P. Dowling

*Louisiana State Univ.*
Quantum Fluctuations in Light field:

\[ E(\phi) = |a|e^{-i\phi} = |a|\sin(\phi) + i|a|\cos(\phi) = X_1 + iX_2 \]

Coherent State
Standard Quantum Limit
\[ \delta X_1 = \delta X_2 \]
\[ \delta X_1 \delta X_2 = \frac{1}{4} \]

Squeezed State
Squeezed Quantum Noise
\[ \delta X_1 \neq \delta X_2 \]
\[ \delta X_1 \delta X_2 \geq \frac{1}{4} \]
Squeezed Vacuum State

Squeezed State

Squeezed Vacuum State
A.B. Matsko et al., PRA 66, 043815 (2002):
theoretically prediction of 4-6 dB noise suppression

\[ a_{out} = a_{in} + \frac{igL}{2} (a_{in}^\dagger - a_{in}) \]
A.B. Matsko et al., PRA 66, 043815 (2002): theoretically prediction of 4-6 dB noise suppression

\[ a_{out} = a_{in} + \frac{igL}{2} (a^+_in - a_{in}) \]
SMPM fiber - single-mode polarization-maintaining fiber
λ/2 - half-wave plate
GP - Glan-laser polarizer
PBS - polarizing beam splitter
PhR - phase-retarding wave plate
BPD - balanced photodetector
Development of Squeezing in atomic vapors
Expansion caused by Self-defocusing is irrelevant to squeezing amount.

Spatial structure of beam after interaction

Spatial Mask – Sharp Edge

Blocking beams from the same sides is equivalent to modification before splitter.

Beams blocked from opposite sides.
Laguerre Gaussian modes

\[ u_{p l}^{LG} = \frac{C_{p l}^{LG}}{w(z)} \left( \frac{r}{w(z)} \right)^{|l|} \exp \left[ -\frac{r^2}{w^2(z)} \right] L_p^{|l|} \exp \left[ -\frac{ikr^2z}{2(z^2 + z_R^2)} \right] (-i\phi) \exp \left[ i(2p + |l| + 1)\tan^{-1} \frac{z}{z_R} \right] \]

\( l \): azimuthal index
\( p \): radial index

Guoy Phase \( \zeta(z) = \arctan \left( \frac{z}{z_R} \right) \), has a \( \pi \) shift across the focus

L Allen, M.J Padgett, Optics Communications, Volume 184, Issues 1–4, 1 October 2000
Spatial Mask – Ring Mask

[Diagram of experimental setup with labels: Magnetic Shield, Rb Cell, Collimated beam, Mask, PBS]

[Graphs showing noise level vs. transmission with different noise levels and theoretical curves for comparison]
Spatial Mask – Circular Mask

Center block = 8% total power

Center block = 25% total power

Graphs showing the relationship between transmission and noise level with different center block settings.
Instead of sending in higher LG modes, we might be generating them.

Propagation function: $\hat{L}\Omega_x = -i \left( \frac{\kappa}{\Delta} \right) (u^*u)^2 \Omega_x$

Solution: $\Omega_x = \Omega_{x0} + \sum_p u_{0p} \int dz' c_p(z'), \quad c_p(z') = \int r'dr'u_{0p}^*(r',z') \rho_x(r',z')$

Q: How Many Modes Should We Add?
A: 5.

An analysis reveals we must keep up to $p=5$ in our superposition.
Evolution of multimode beam

Intensity at Edge of Iris: \( \frac{I(0,Z)}{I(0,0)} = \nu_{0,0} \text{ mode} \)

Intensity at Edge of Iris: \( \frac{I(0,Z)}{I(0,0)} = \Omega_x \text{ cell} \)

Intensity at Edge of Iris: \( \frac{I(0,Z)}{I(0,0)} = \Omega_x \)

Abs[ \( c(Z) \) ]

Abs[ \( c(Z) \) ]

Longer cell?
Fixed Iris Size

![Diagram of an optical setup with labeled components: Collimated Beam, Mask, Magnetic Shield, Rb Cell, PBS.]

Intensity at Edge of Iris: \( \frac{I(0,z)}{I(0,0)} - \Omega_s \)

\[ R = \frac{r}{w_0} \]

\[ Z = \frac{z}{z_p} \]

(a) Minimum Noise (dB)

- 96%
- 93%
- 86%
- 83%
- 74%

(b) Transmission

- 96%
- 93%
- 86%
- 83%
- 74%

Position of Iris (cm)
Guoy Phase $\zeta(z) = \arctan \left( \frac{z}{z_R} \right)$, has a $\pi$ shift across the focus.
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• We generated a squeezed vacuum state from polarization self-rotation.
• The squeezed vacuum state consists of high order Laguerre Gaussian modes with different squeezing parameters.