Beating the quantum noise limit: Spatial mode optimization of squeezed vacuum field in hot ^{87}Rb vapor

M. A. Guidry[1], M. Zhang[1], D. T. Kutzke[1], R. N. Lanning[2], Z. Xiao[2], J. P. Dowling[2], I. Novikova[1], E. E. Mikhailov[1]

[1]Department of Physics, College of William & Mary, Williamsburg, VA 23185, USA || [2]Hearne Institute for Theoretical Physics, Louisiana State University, Baton Rouge, LA 70803, USA

Abstract

Squeezed states of light, *i.e.*, quantum states exhibiting reduced noise statistics, may be used to greatly enhance the sensitivity of light-based measurements. We study a squeezed vacuum field generated in hot Rb vapor via the polarization self-rotation effect. By propagating a strong pump beam through an atomic vapor cell, we were able to achieve a noise suppression of 2.7 dB below shot noise. Our previous work revealed that this amount of noise suppression may be limited by the excitement of higher order modes in the squeezed field during the atom-light interaction. Once incident on the homodyne detection scheme, these higher order modes may induce an imperfect mode match between the squeezed field and the local oscillator (LO). In this work, we used a liquid-crystal-based spatial light modulator to modify the spatial mode structure of the pump and LO beams. We demonstrate that optimization of the spatial modes can lead to higher detected noise suppression.

Quantum fluctuations

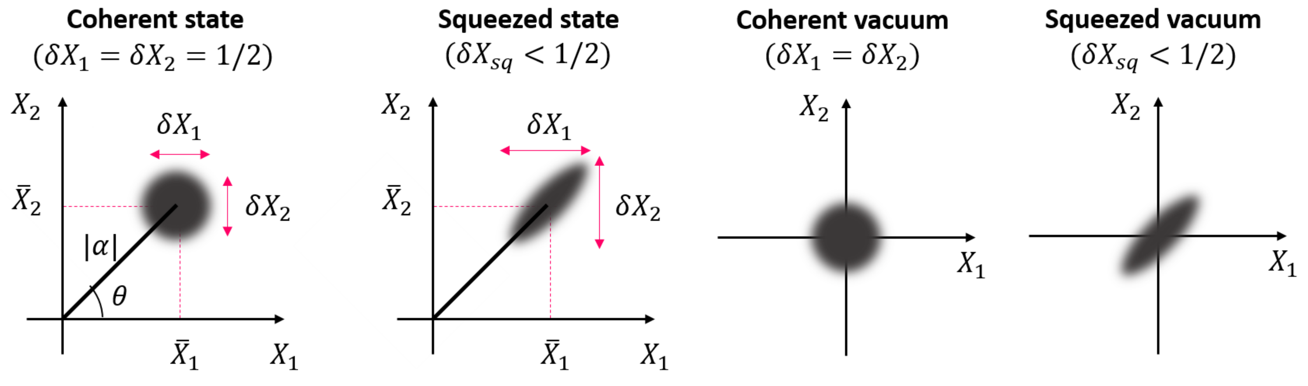
Quadrature operators

$$\hat{X}_1 \equiv \frac{1}{2}(\hat{a} + \hat{a}^\dagger), \quad \hat{X}_2 \equiv \frac{1}{2i}(\hat{a} - \hat{a}^\dagger)$$

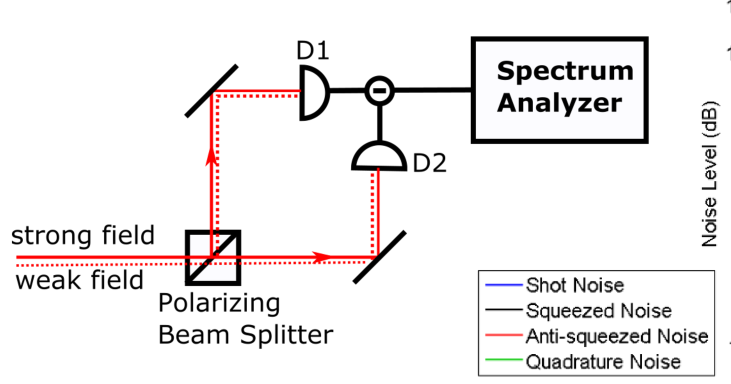
$$\hat{E} = E_0(z)\left(\hat{a}e^{-i\omega t} + \hat{a}^\dagger e^{i\omega t}\right)$$

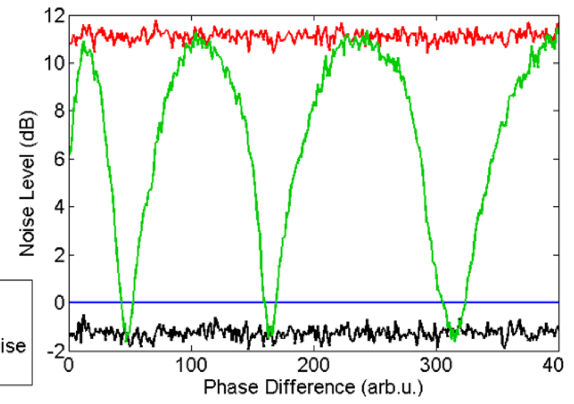
$$\hat{E} = 2E_0(z)(\hat{X}_1 cos\omega t + \hat{X}_2 sin\omega t)$$

$$\left\langle(\Delta\hat{X}_1)^2\right\rangle\left\langle(\Delta\hat{X}_2)^2\right\rangle \geq \frac{1}{16}$$



Homodyne detection





Left: Balanced homodyne detection scheme. **Right:** Quadrature noise measurements versus phase difference.

Incident on 50/50 BS

$$\mathcal{E}_s(t) = \mathcal{E}_s + \delta X_{1s}(t) + \delta X_{2s}(t)$$
$$\mathcal{E}_{LO}(t) = [\mathcal{E}_{LO} + \delta X_{1LO}(t) + \delta X_{2LO}(t)]e^{i\theta}$$

By tuning the relative phase θ, we may **select** a quadrature to be detected.

After 50/50 BS

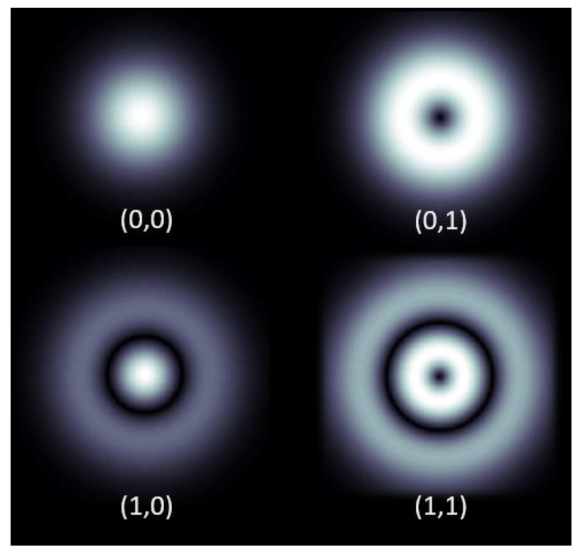
$$\mathcal{E}_1 = \sqrt{1/2}\,\mathcal{E}_{LO}(t) + \sqrt{1/2}\,\mathcal{E}_s(t)$$
$$\mathcal{E}_1 = \sqrt{1/2}\,\mathcal{E}_{LO}(t) + \sqrt{1/2}\,\mathcal{E}_s(t)$$

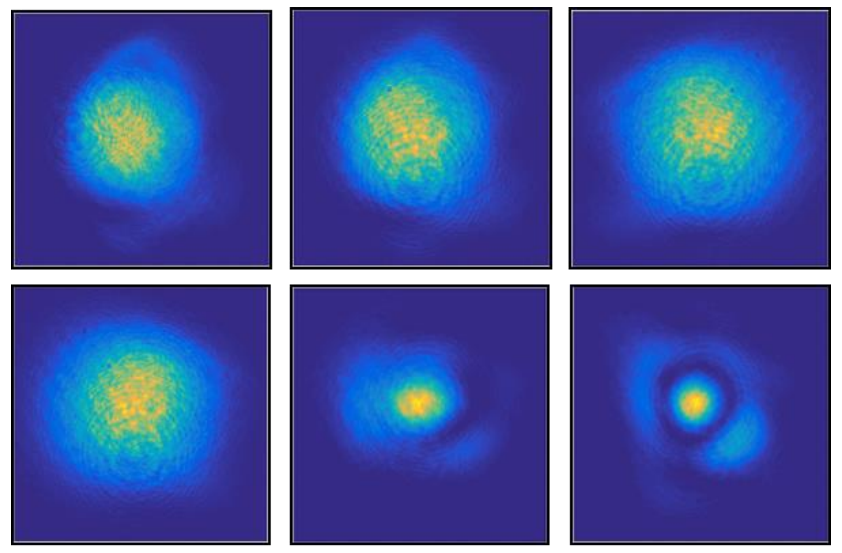
$$|\mathcal{E}_1|^2 - |\mathcal{E}_2|^2 \approx 2\mathcal{E}_{LO}(\delta X_{1s}cos\theta + \delta X_{2s}sin\theta)$$

References

[1] A. B. Matsko et al., *Phys. Rev. A* **66**, 043815 (2002).
[2] S. Barreiro et al., *Phys. Rev. A* **84**, 033851 (2011).
[3] M. Zhang et al., *Phys. Rev. A* **93**, 01385 (2016).

Multi-mode generation





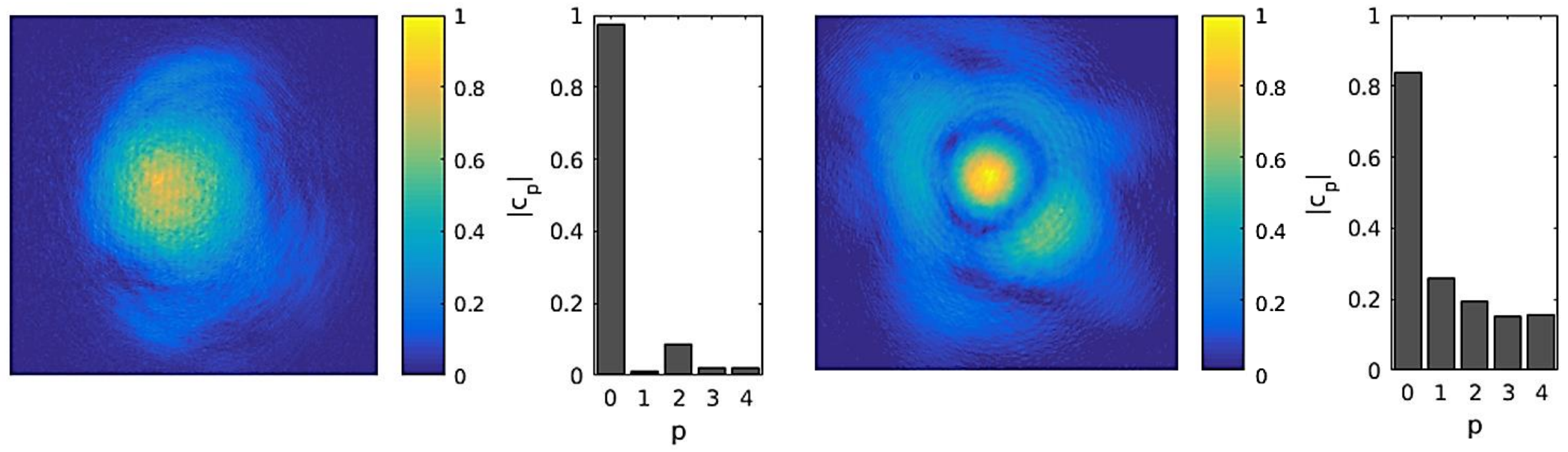
Left: Intensity profiles of the first four spatial Laguerre-Gaussian modes, where (p,l) refers to the radial and azimuthal index, respectively. **Right:** Intensity cross-section of the beam after interacting with increasing atomic density.

Polarization-self rotation (PSR)

- PSR squeezing offers a source of squeezed vacuum which is much **less complicated**, **less costly**, and potentially **more stable** than most other squeezing methods.
- Theoretical prediction [1]: -8 dB
- Experimental world record [2]: -3 dB
- Our experimental best: -2.7 dB

Squeezing degradation

- Previous experiments in our group revealed the **strong dependence of squeezing on spatial structure.**
- Our theoretical model [3] predicts that higher order modes may squeeze by different amounts and at different squeezing angles. The combination of these different squeezing angles may **degrade overall detected squeezing.**



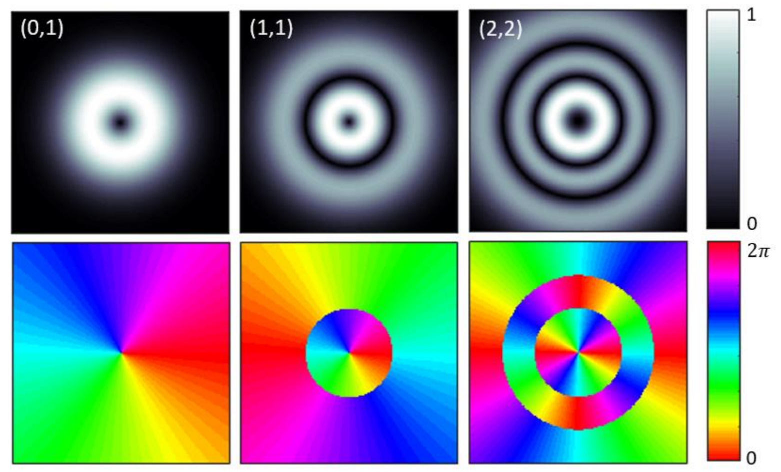
Intensity cross section and mode decomposition of a beam directly after interacting with Rb vapor. **Left:** Low atomic density (1.4×10^{10} cm^{-3}). **Right:** High atomic density (1.1×10^{13} cm^{-3}).

Poor mode match

A poor mode match between the LO and the squeezed field will degrade detected squeezing on the homodyne.

$$\Delta I_-^2 \approx \mathcal{E}_{LO}^2\delta X_{1s}^2\left[\iint[u_{LO}u_s^* + u_{LO}^*u_s]\cos(\phi+\theta)\,dxdy\right]^2 + \mathcal{E}_{LO}^2\delta X_{2s}^2\left[\iint[u_{LO}u_s^* + u_{LO}^*u_s]\sin(\phi+\theta)\,dxdy\right]^2 + \mathcal{E}_{LO}^2\delta X_{1,2v}^2\left(1 - \frac{1}{2}\iint[u_{LO}u_s^* + u_{LO}^*u_s]dxdy\right)$$

Spatial mode optimization

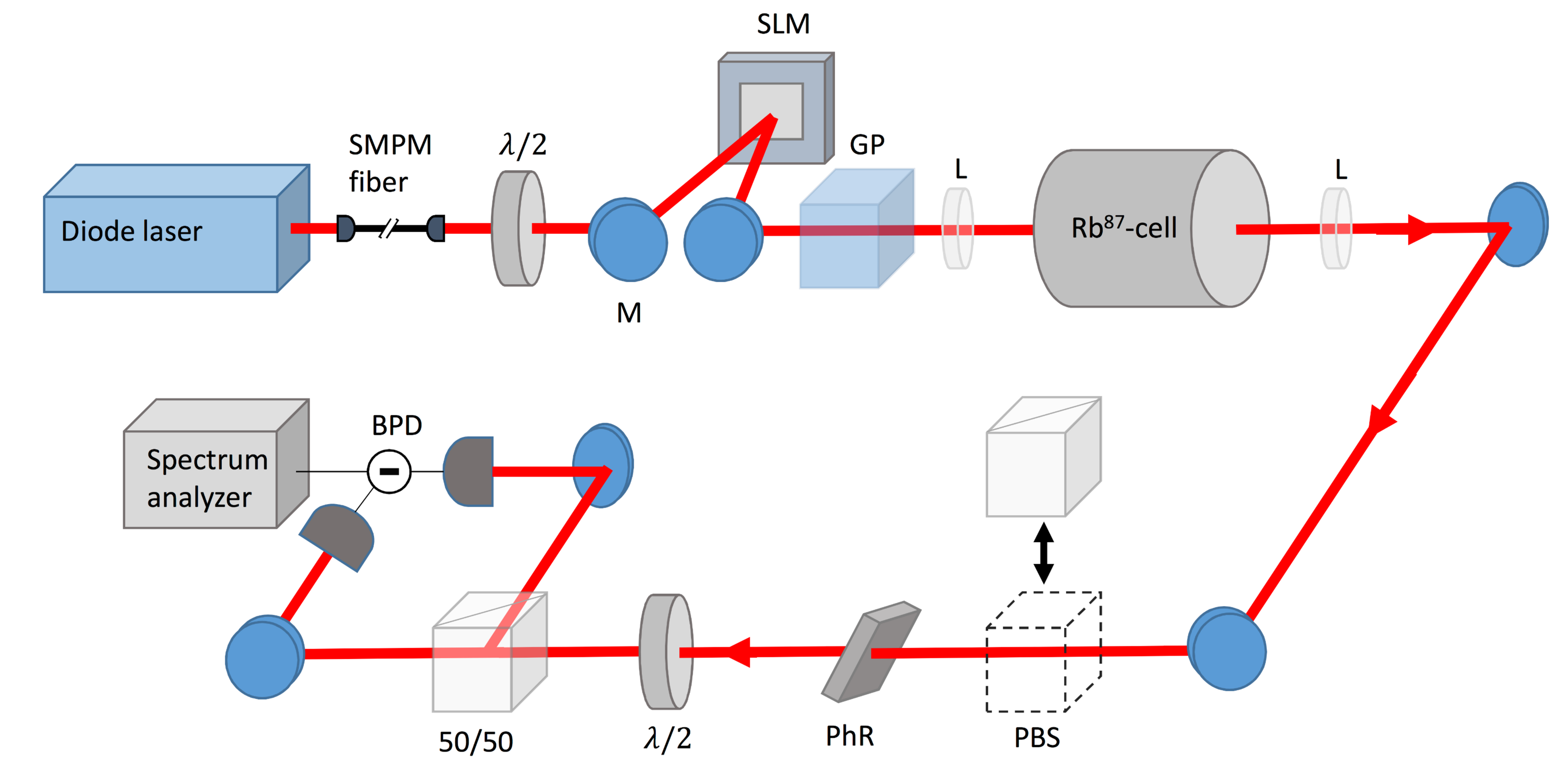


- By projecting the phase distribution of the LG mode equation onto an SLM, we may recreate the phase distribution in the beam associated with that mode.
- The phase mask applied to the beam is

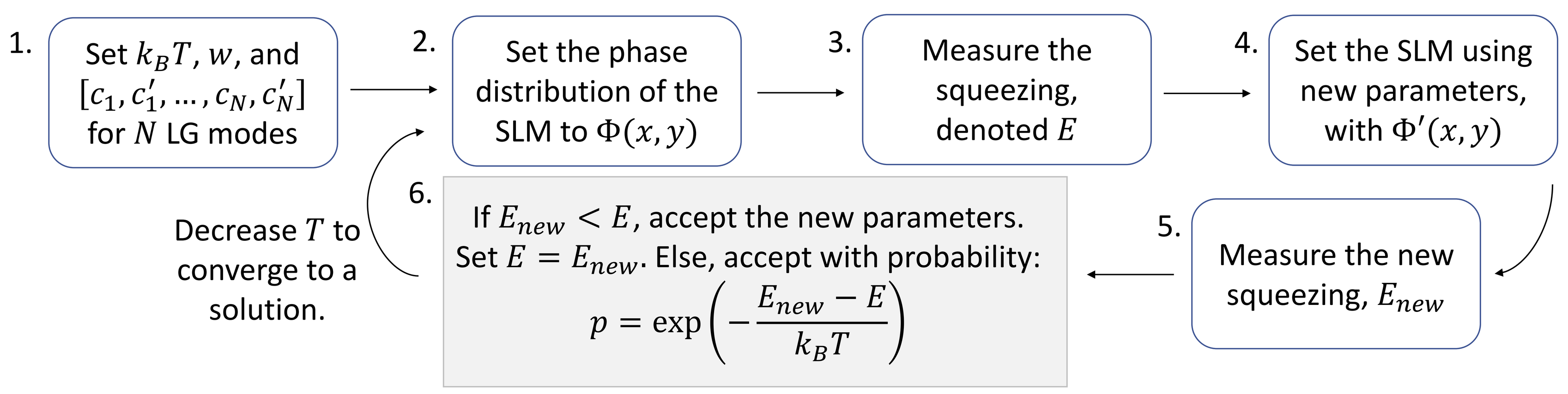
$$\Phi(x,y) = \arg\left(\sum_{p,l}^{N}(c_{pl} + ic'_{pl})LG_{pl}(w,x,y)\right)$$

where LG_{pl} is the mode distribution, w is the beam waist, and c_{pl}, c_{pl}' are coefficients for mode (p,l).

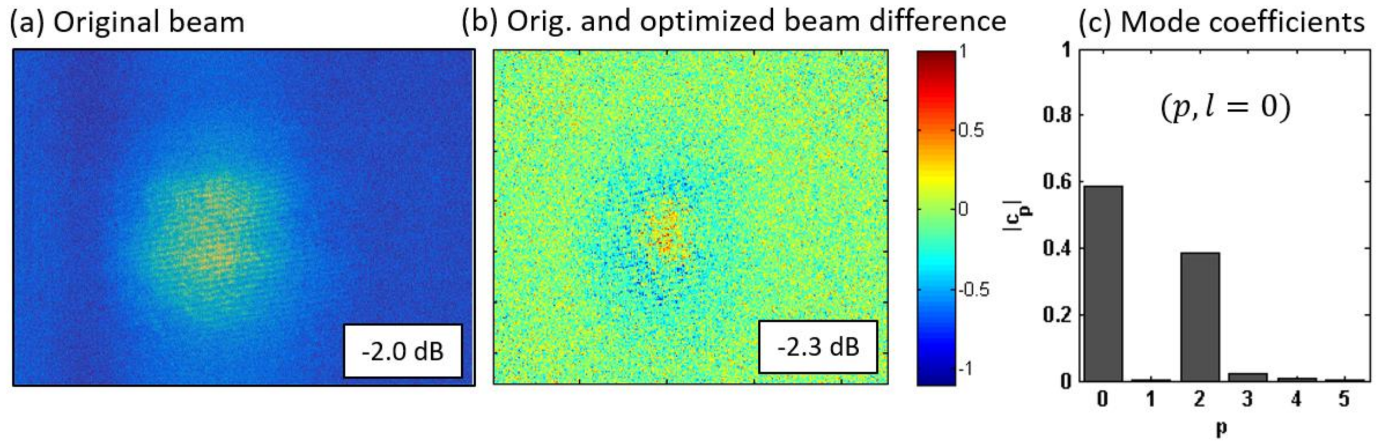
Experimental detection scheme

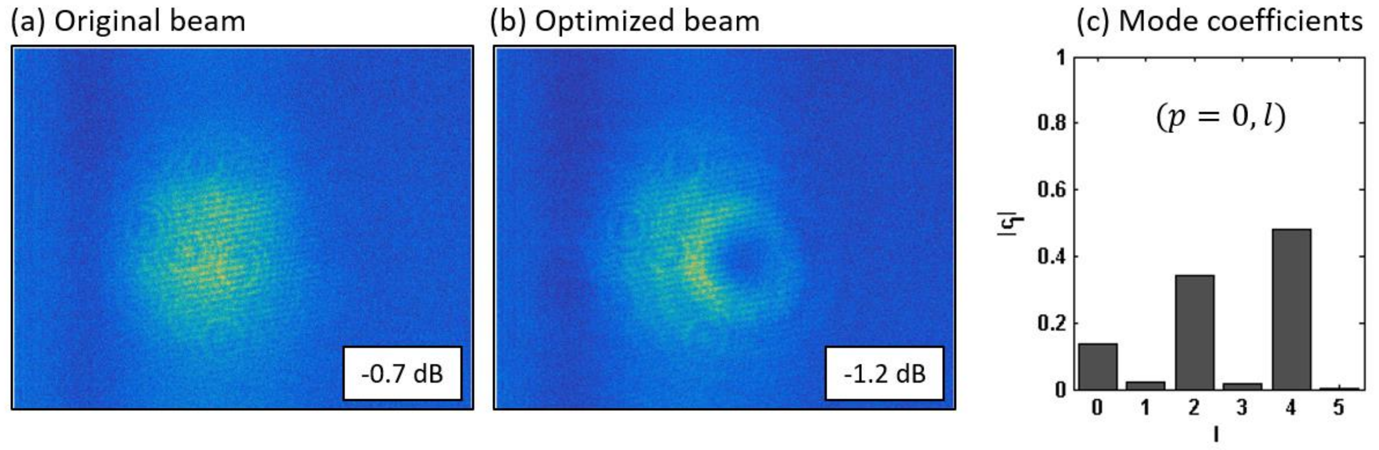


Optimization via the Metropolis algorithm



Pump beam optimization results





Top: Optimization run with optimal squeezing conditions. (a) Pump beam subject to a flat phase mask. (b) The residuals between the original beam and the optimized beam. (c) The LG mode coefficients used to create the optimized beam. **Bottom:** Optimization run with suboptimal squeezing conditions. (a) Flat phase beam. (b) The optimized beam. (c) LG mode coefficients.

Conclusion

- **We have demonstrated improved squeezing through optimization of the pump beam spatial mode structure.**
- The power of the strong beam is **redistributed from the Gaussian mode into higher order modes** during the nonlinear light-atom interaction.
- Initial optimization of the local oscillator was unsuccessful due to the oscillatory nature of the liquid crystal display. We continue to investigate this.

Outlook

- Using a quantum noise-limited camera, we are beginning to directly probe the spatial structure of the squeezed field.

This project is supported by AFOSR grant FA9550-13-1-0098. Funding from the VSGC is gratefully acknowledged.

Mail: maguidry@email.wm.edu

VSGC Conference 2017, April 19, Williamsburg, VA, USA