Honeycomb Pattern Formation by Laser-Beam Filamentation in Atomic Sodium Vapor

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Interests and Motivation

Non-classical states of light

Theoretical interest

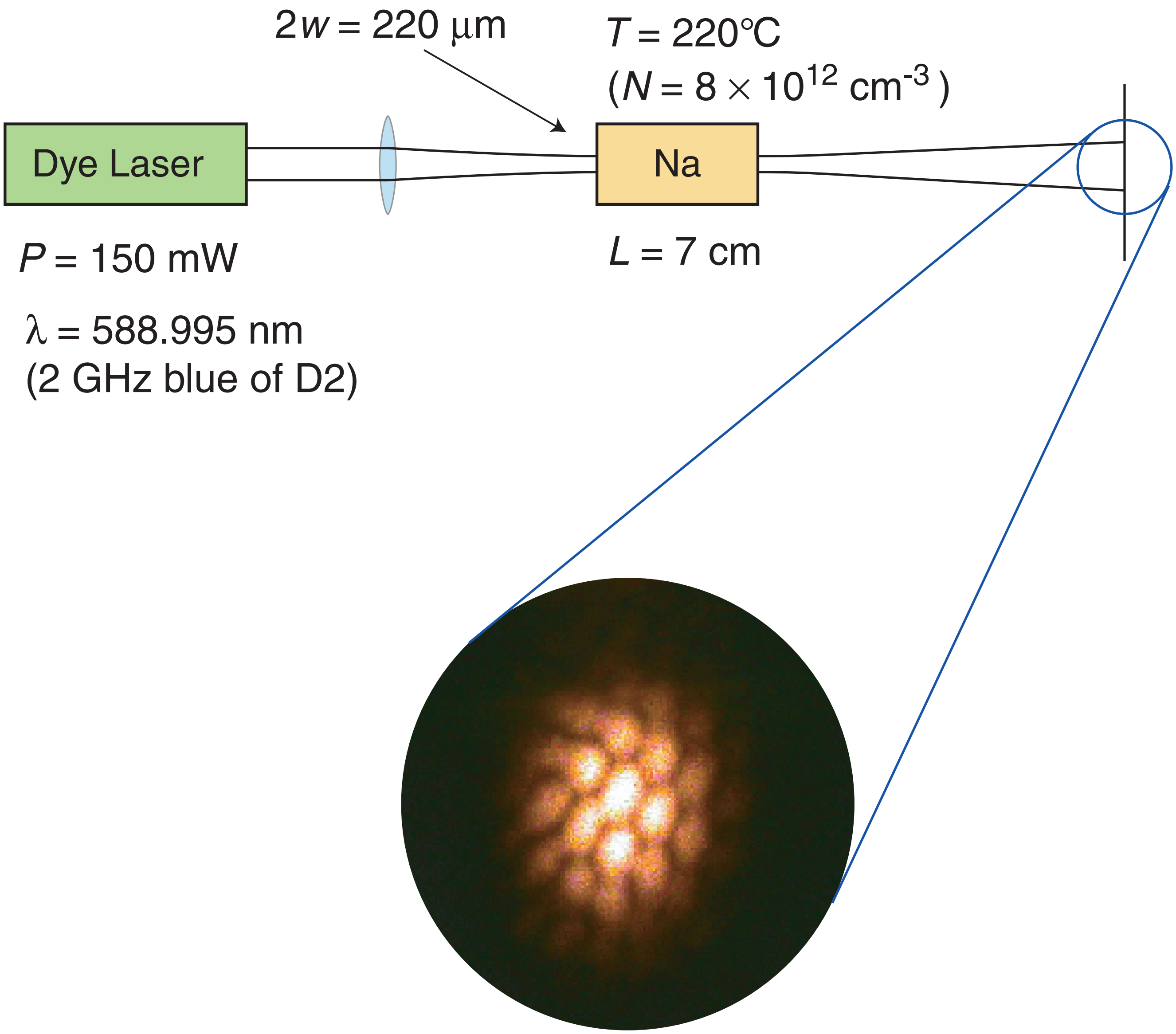
- fundamentals of Quantum Mechanics
- quantum information

Potential applications

- precision measurements
- sub-Rayleigh lithography
- low noise communication, imaging
- quantum computing

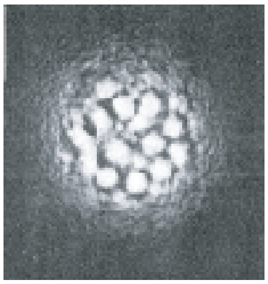
Generation of quantum states of light using coherently prepared atomic vapor

Initial Observation



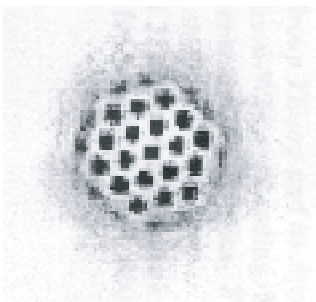
Spontaneous pattern formation with 6-fold symmetry was observed

Some Related Findings



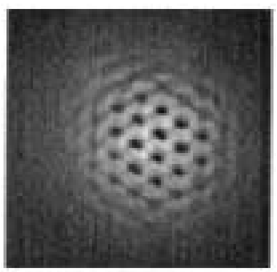
- spontaneous pattern formation in nematic LC with mirror feedback

R. MacDonald and H.J. Eichler, Opt. Comm. **89** (1992) 289-295.



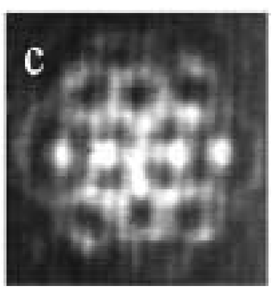
- simulation of pattern formation in a Kerr slice with mirror feedback

F. Papoff, G. D'Alessandro, G.-L. Oppo, and W.J. Firth, Phys. Rev. A **48** (1993) 634.



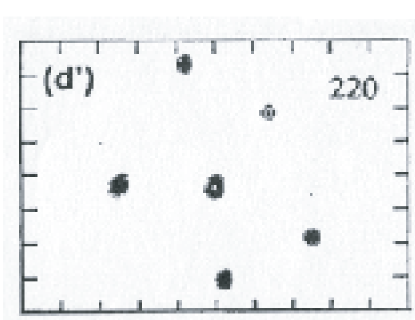
- spontaneous pattern formation in sodium vapor with a feedback mirror

R. Herrero, E. Grosse Westhoff, A. Aumann, T. Ackemann, Y. A. Logvin, and W. Lange, Phys. Rev. Lett. **82** (1999) 4627.



- spontaneous pattern formation in a near-degenerate OPO

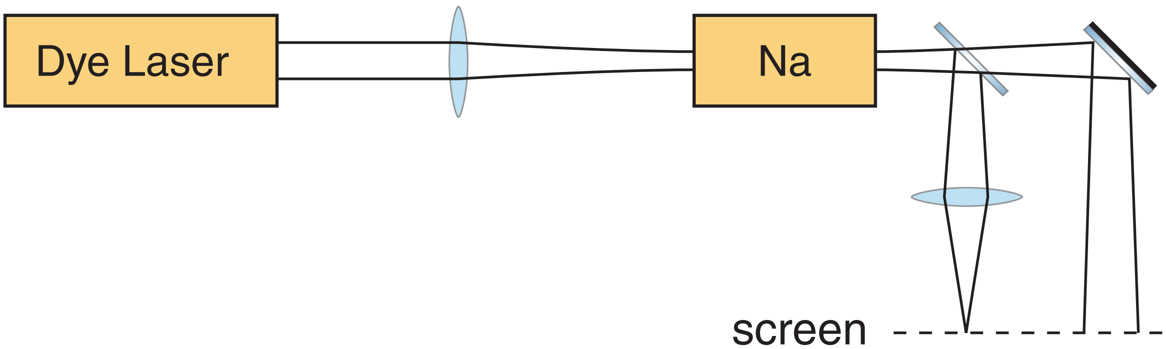
M. Vaupel, A. Maitre, and C. Fabre, Phys. Rev. Lett. **83** (1999) 5278.



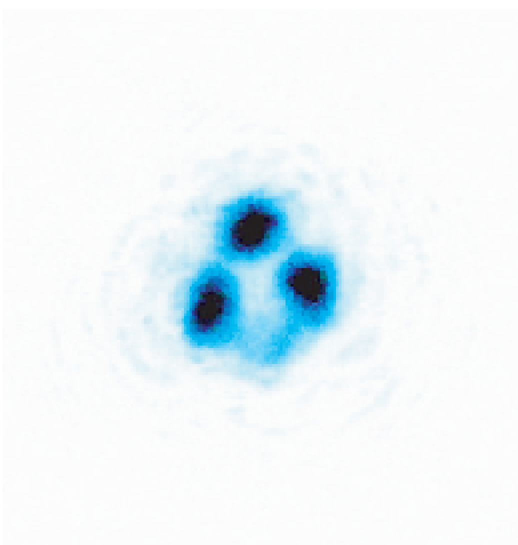
- filementation of an aberrated beam in sodium vapor

J.W. Grantham, H.M. Gibbs, G. Khitrova, J.F. Valley, and Xu Jiajin, Phys Rev. Lett. **66** (1991) 1422.

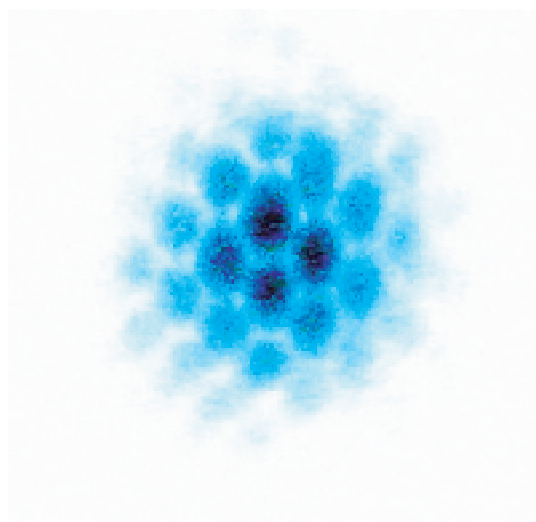
Experimental Results



At cell exit



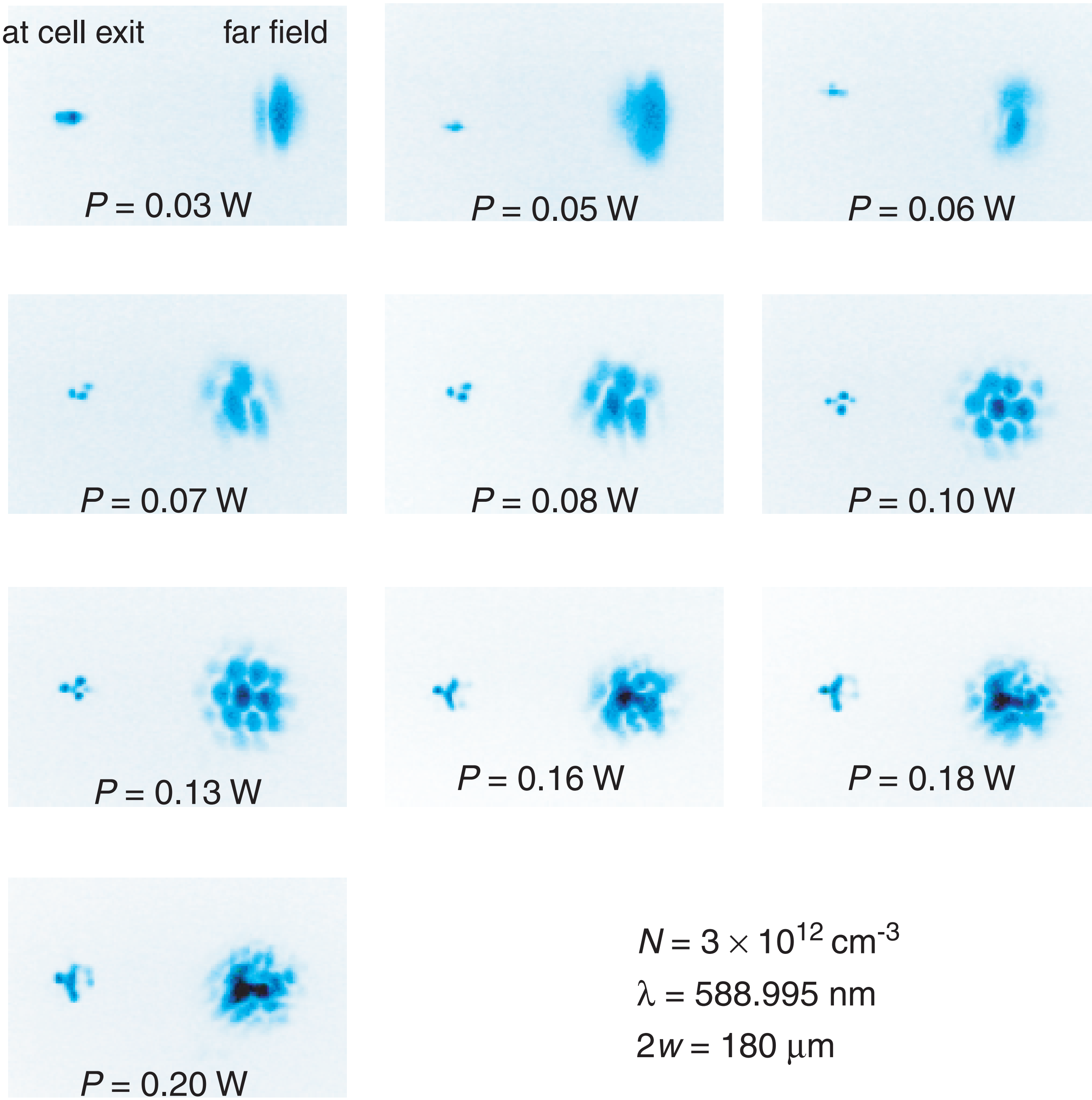
Far-field pattern



Honeycomb pattern results from orderly filamentation

Experimental Results

Power dependence



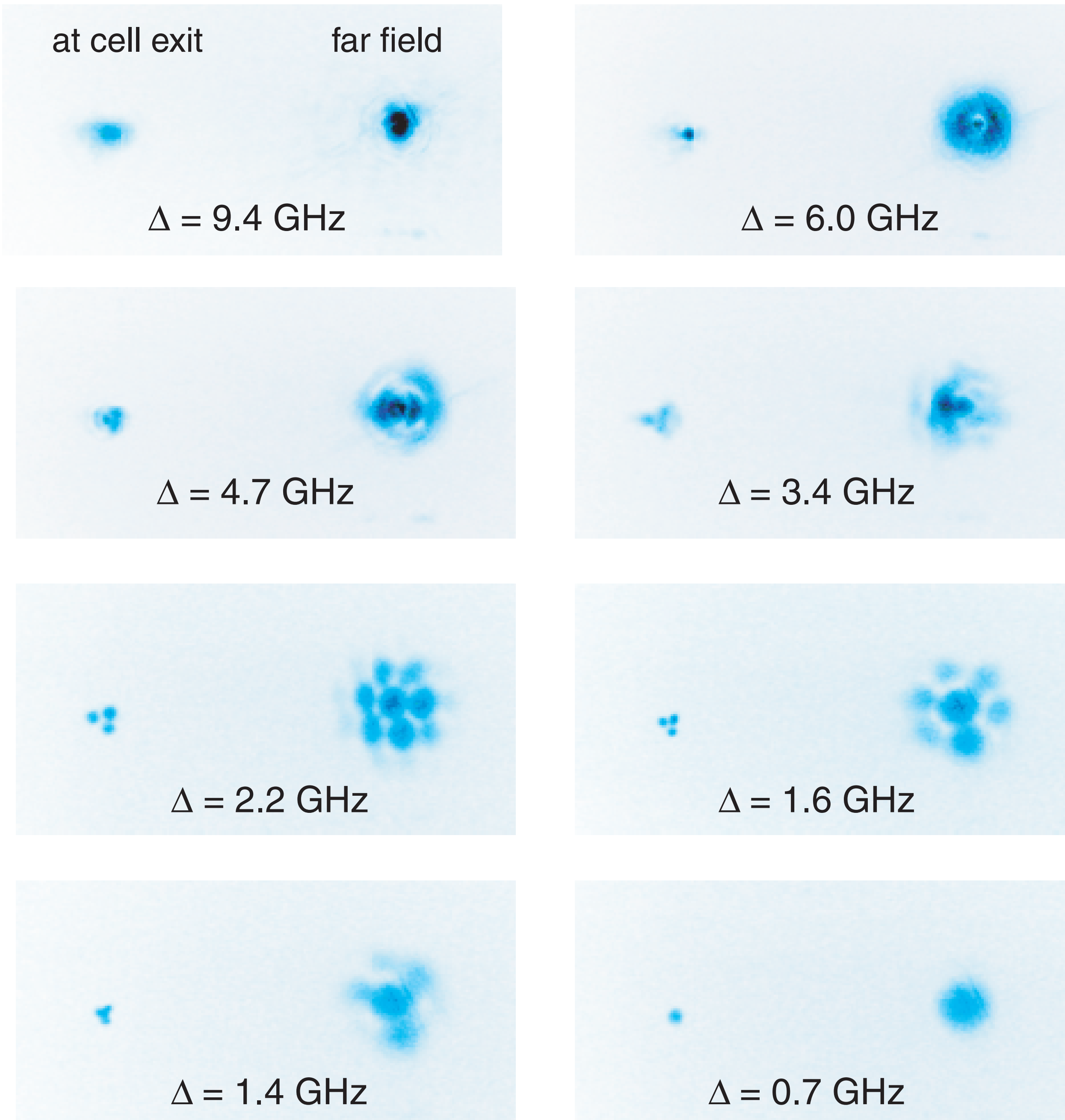
$N = 3 \times 10^{12}$ cm^{-3}

$\lambda = 588.995$ nm

$2w = 180$ μm

Experimental Results

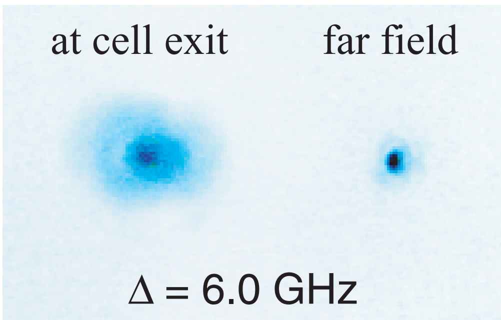
Frequency dependence

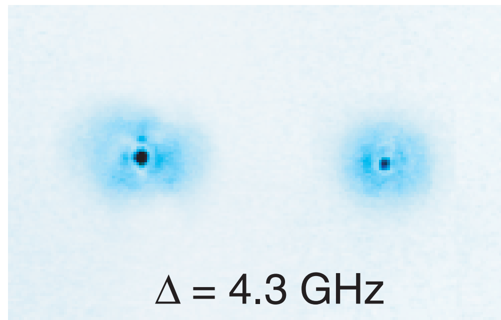


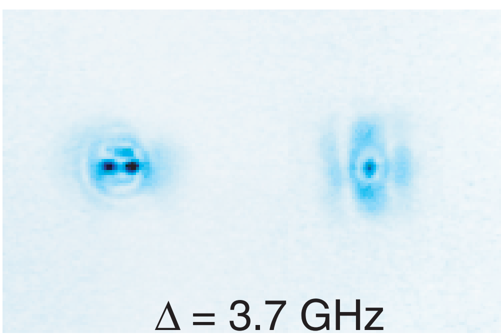
$N = 3 \times 10^{12}\ \mathrm{cm}^{-3}$, $P = 110$ mW, $2w = 180\ \mu\mathrm{m}$

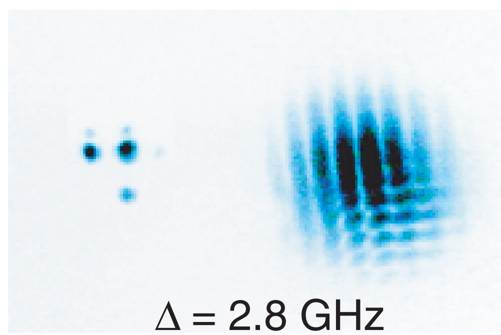
Experimental Results

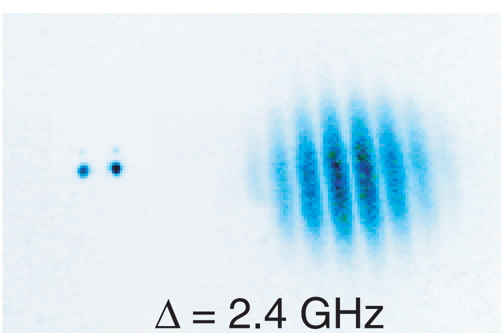
Frequency dependence











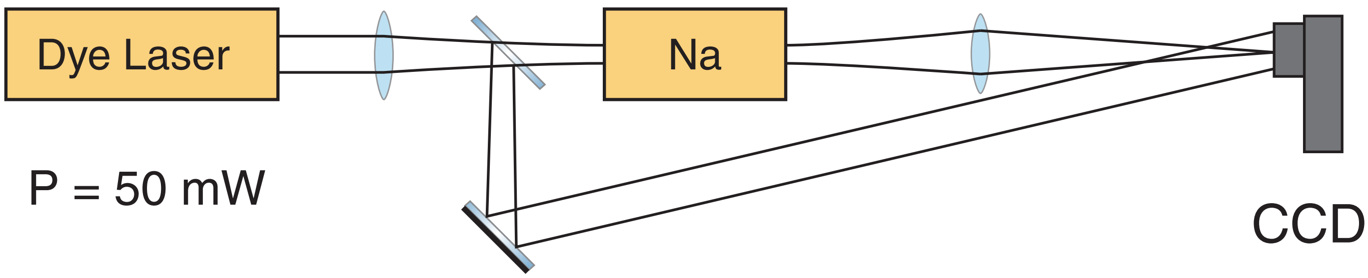
$N = 8 \times 10^{12}$ cm^{-3}

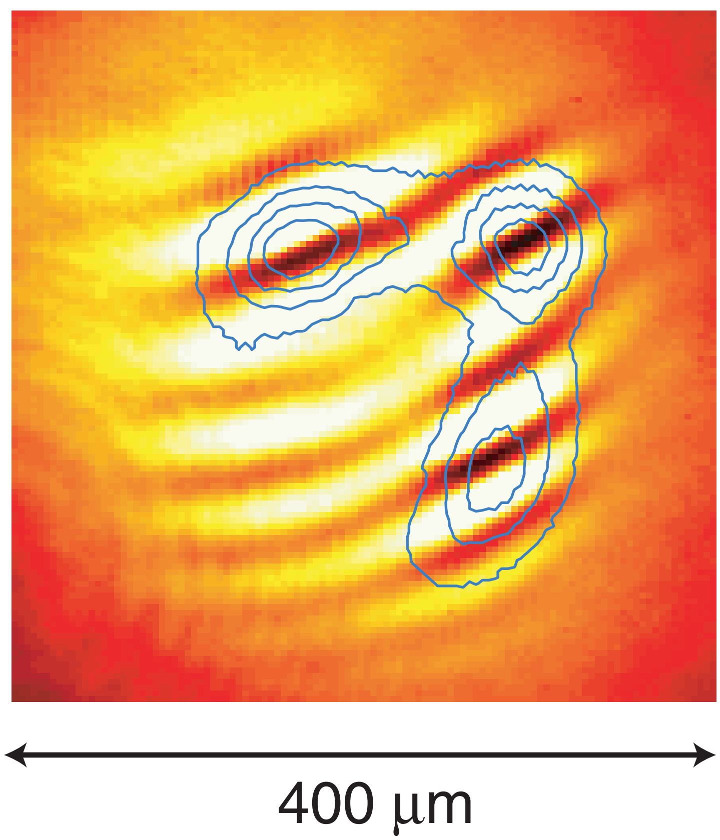
$P = 47$ mW

$2w = 170$ μm

Experimental Results

Size, power, and phase of filaments

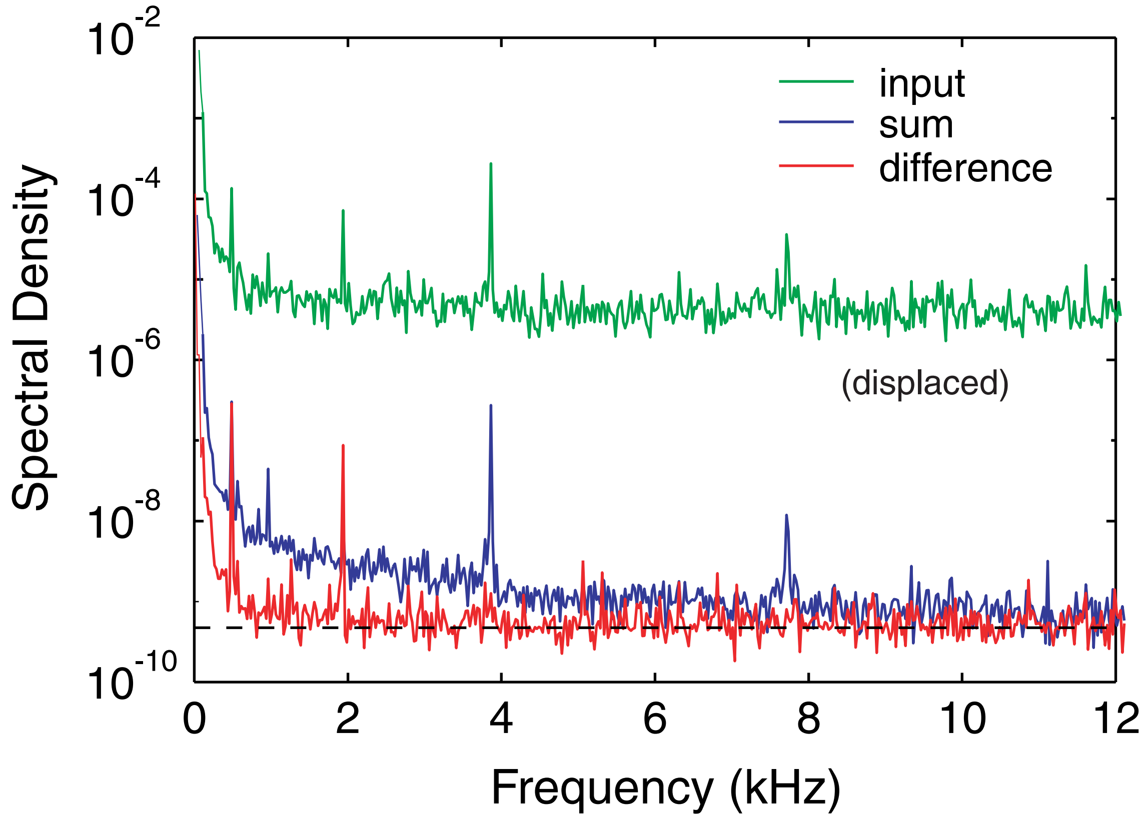




- filaments have constant and equal phase ⇒ "solitons"
- powers (~2 mW) not necessarily equal
- diameters approx. equal (~30 μm)

Experimental Results

Fluctuation statistics of a filament pair



- filaments are correlated, to within detection noise, at most frequencies

Modelling

Beam propagation in a saturable medium

small-field susceptibility

$$\left[2ik\frac{\partial}{\partial z} + \nabla_T^2\right]E(x,y,z) = -k^2 \frac{\chi_0}{1 + \left|E/E_{\text{sat}}\right|^2} E$$

saturation field strength

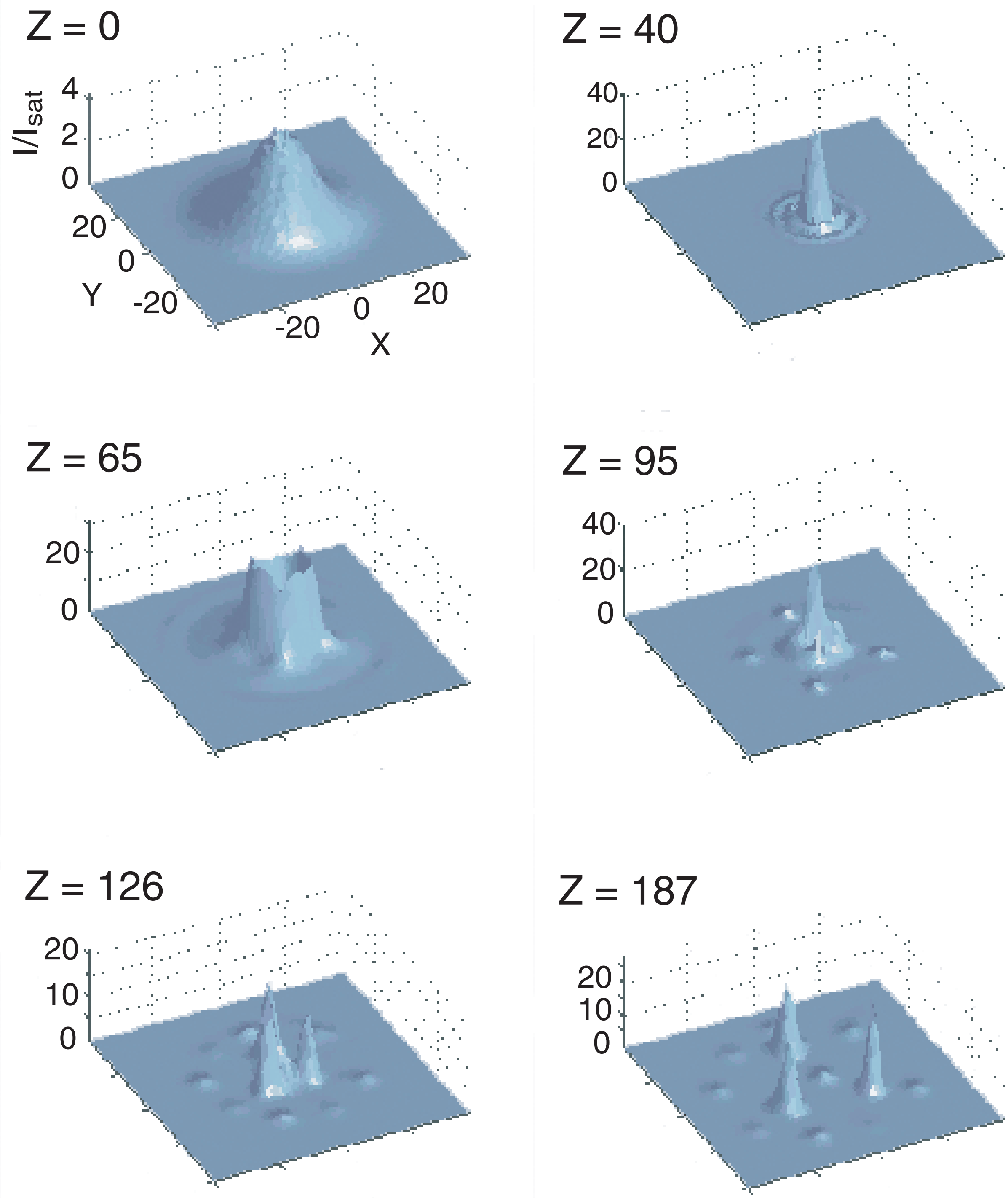
Convert to scaled variables:

$$2i\frac{\partial}{\partial Z}\psi(X,Y,Z) = \left[-\nabla_T^2 + \frac{|\psi|^2}{1 + |\psi|^2}\right]\psi$$

Only free parameters are initial conditions
(beam width, power, noise)

Modelling

Trifurcation occurs for appropriate initial conditions



Conclusions

- upon propagation through sodium vapor, patterns with hexagonal symmetry were observed

- Patterns arose spontaneously through low-order filamentation, at intensities above the saturation intensity and powers above the self-trapping power

- Filaments tend to have constant, equal phase $\Rightarrow$ "solitons"

- Filaments are stable and show strong power correlations

- Observations can be predicted qualitatively with a simple model of a saturable medium

Future directions

- Study beam evolution
- 3 separate solitons, or a higher-order soliton?
- Examine classical statistics of 3 filaments
- Examine quantum statistics
- Quantitative predictions (input power, diameter) through more accurate modelling