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

Ryan S. Bennink
Vincent Wong
David L. Aronstein
Robert W. Boyd
Svetlana G. Lukishova
Alberto M. Marino
Carlos R. Stroud, Jr.

Institute of Optics, University of Rochester

Daniel J. Gauthier

Department of Physics, Duke University

Phys. Rev. Lett. 88, 113901 (2002).

Interests and Motivation

Non-classical states of light

Theoretical interest

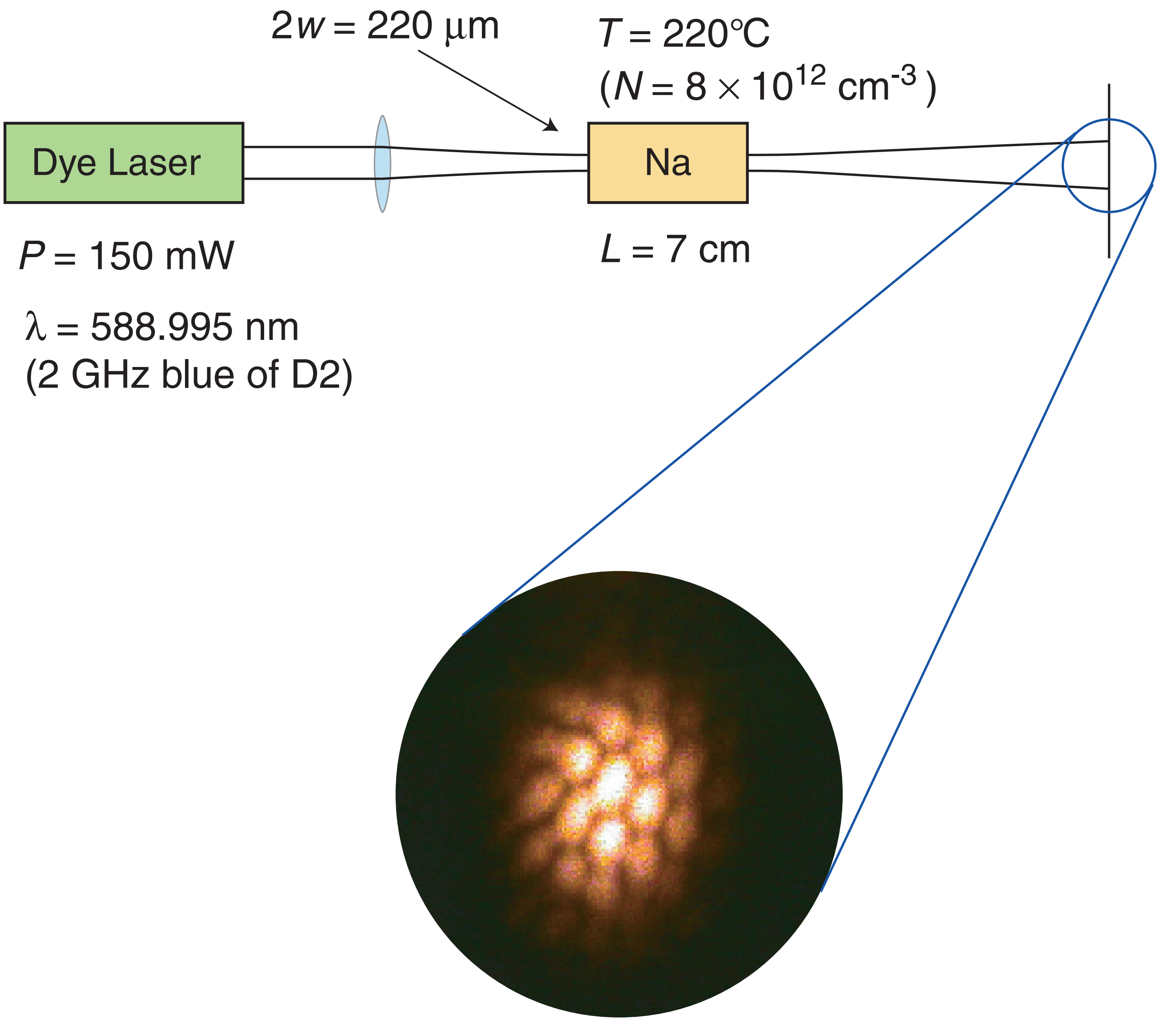
- fundamentals of Quantum Mechanics
- quantum information

Potential applications

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

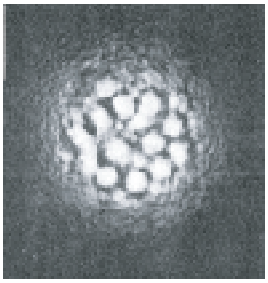
Generation of quantum states of light using coherently prepared atomic vapor

Initial Observation



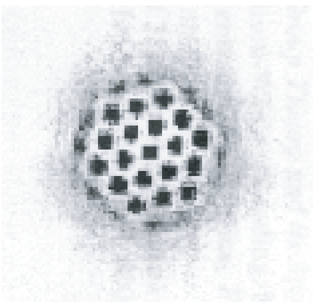
Spontaneous pattern formation with 6-fold symmetry was observed

Some Related Findings



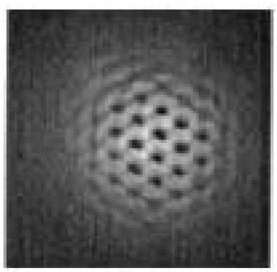
- spontaneous pattern formation in nematic LC with mirror feedback

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



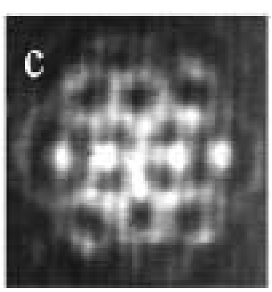
- simulation of pattern formation in a Kerr slice with mirror feedback

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



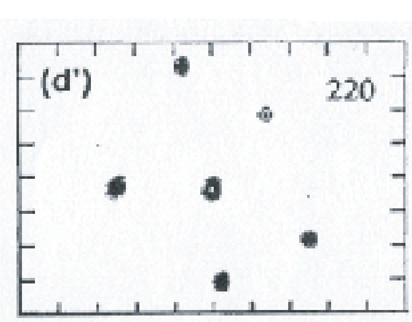
- spontaneous pattern formation in sodium vapor with a feedback mirror

  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

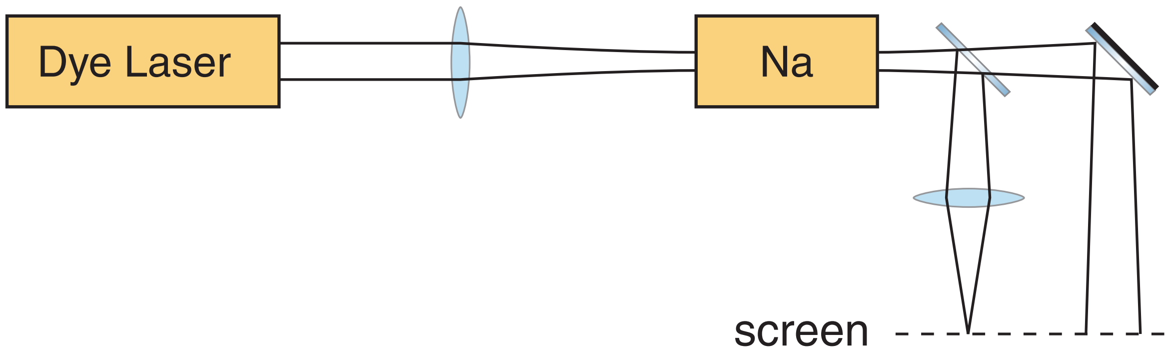
  M. Vaupel, A. Maitre, and C. Fabre, Phys. Rev. Lett. **83** (1999) 5278.



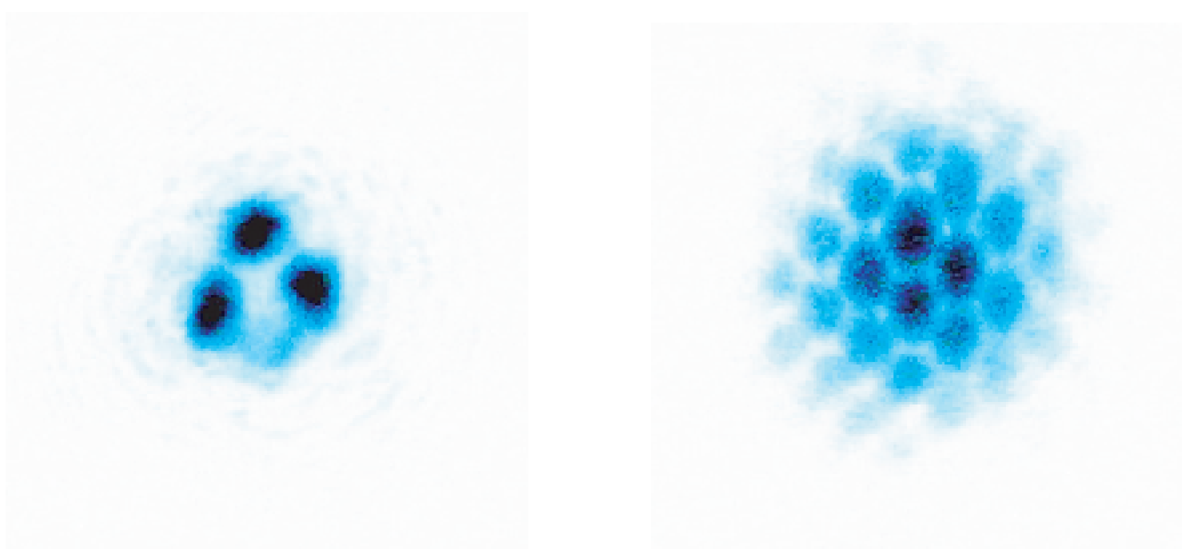
- filementation of an aberrated beam in sodium vapor

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

Experimental Results



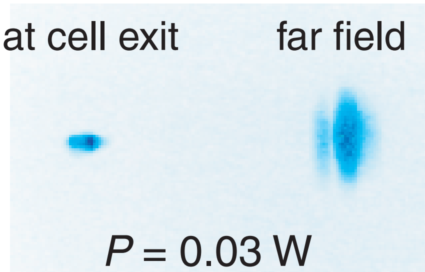
At cell exit | Far-field pattern

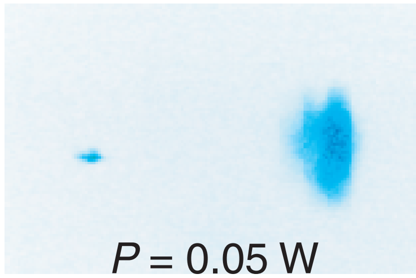


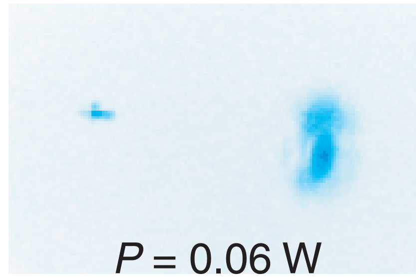
Honeycomb pattern results from orderly filamentation

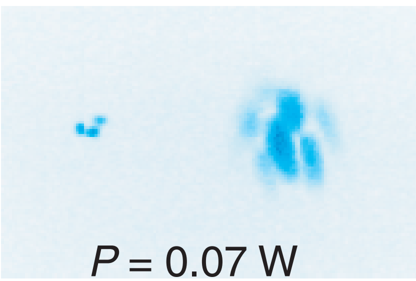
Experimental Results

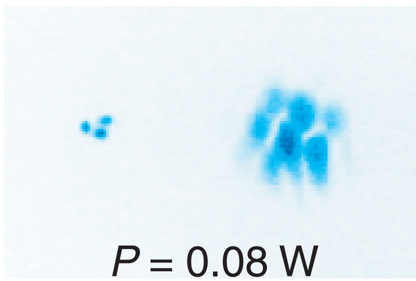
Power dependence

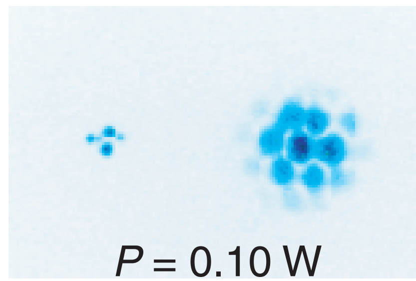


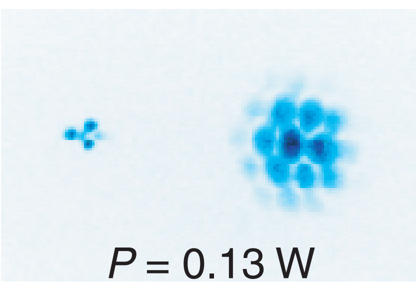


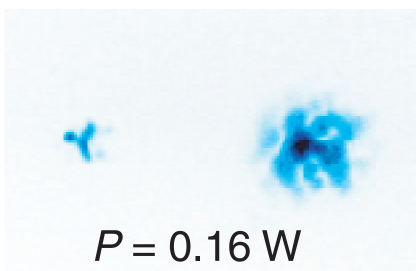


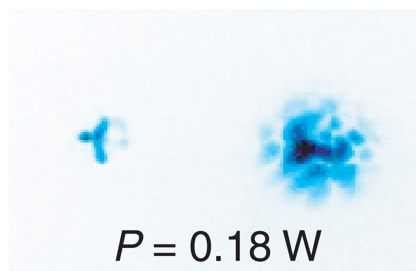


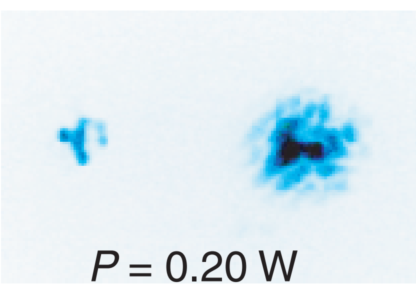












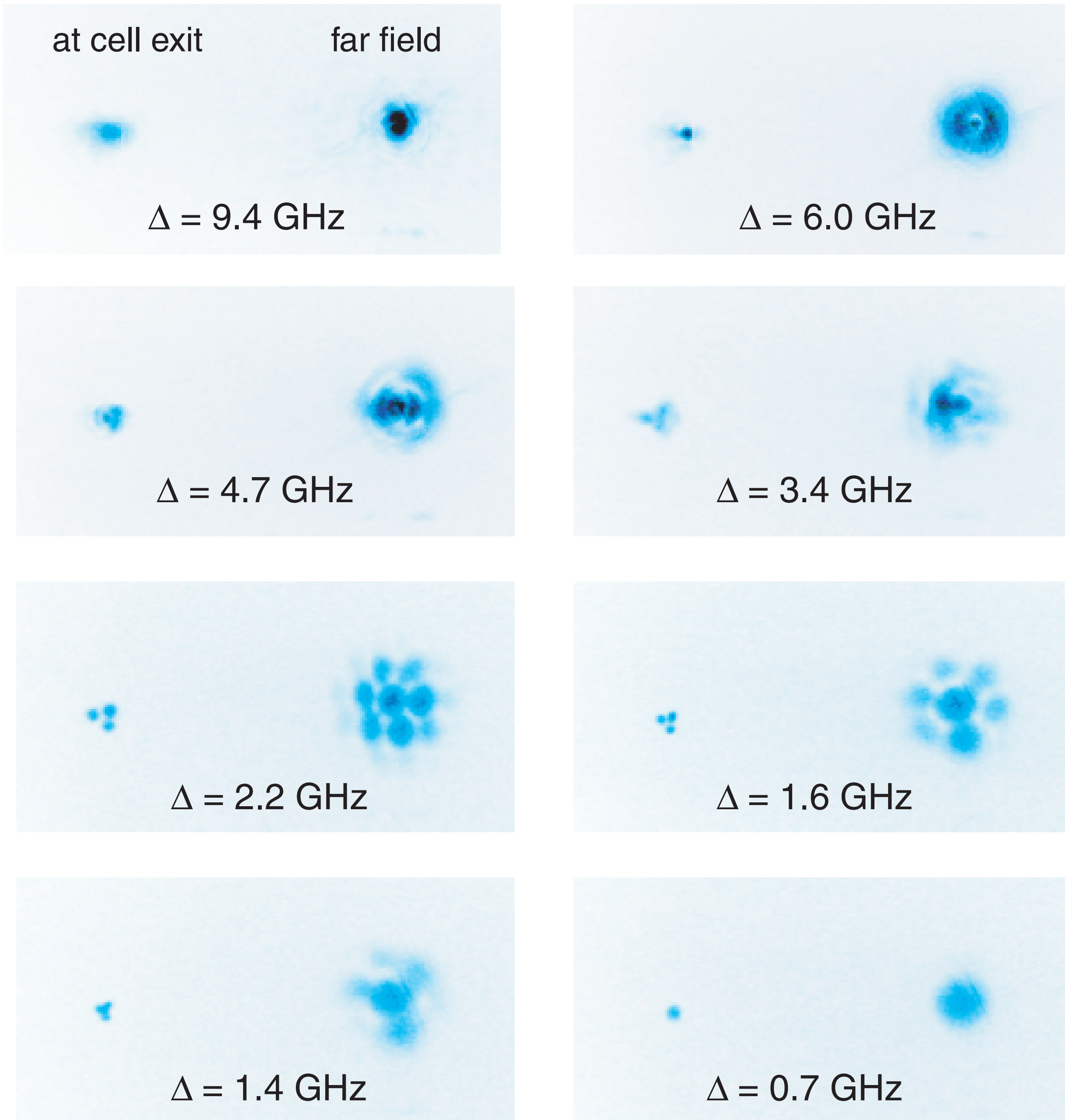
$N = 3 \times 10^{12}$ cm^{-3}

$\lambda = 588.995$ nm

$2w = 180$ μm

Experimental Results

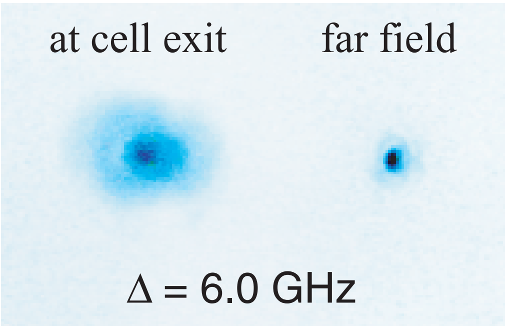
Frequency dependence

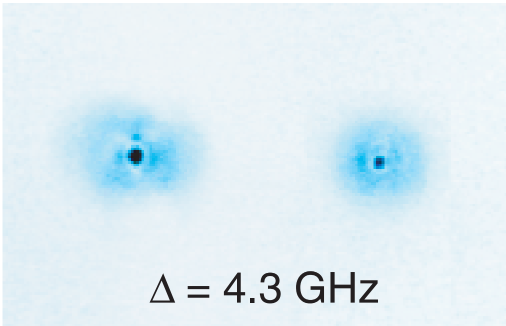


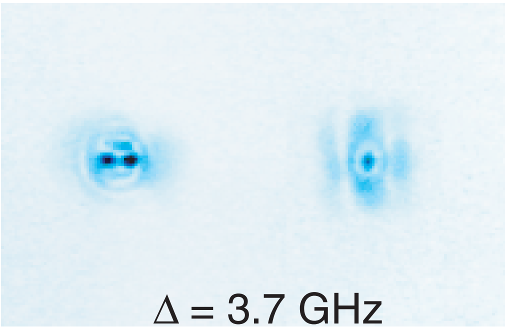
$N = 3 \times 10^{12}\ \mathrm{cm}^{-3}$, $P = 110$ mW, $2w = 180\ \mu$m

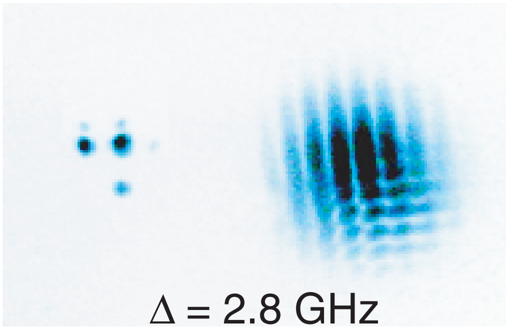
Experimental Results

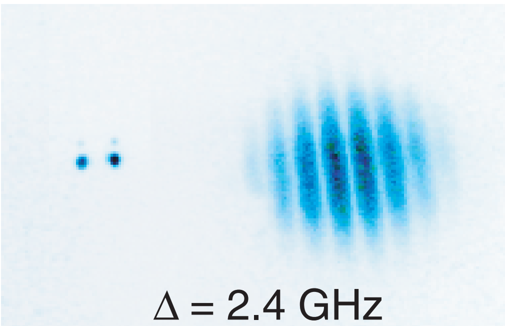
Frequency dependence









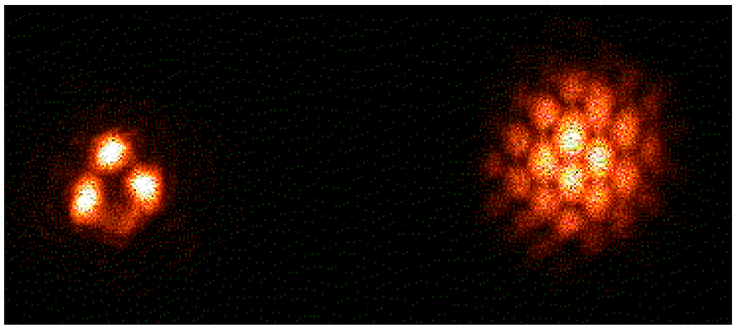


$N = 8 \times 10^{12}$ cm^{-3}

$P = 47$ mW

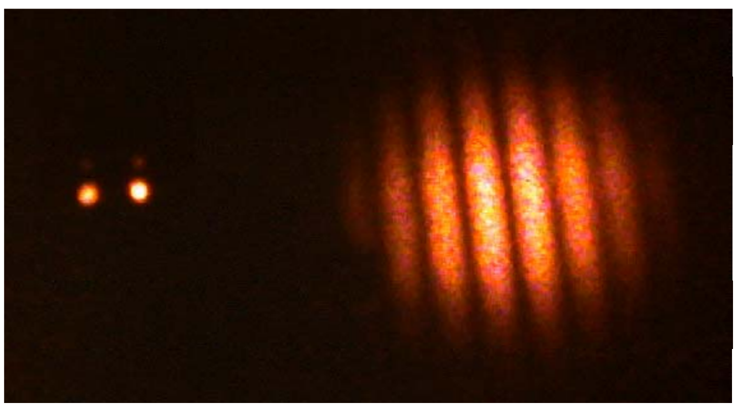
$2w = 170$ μm

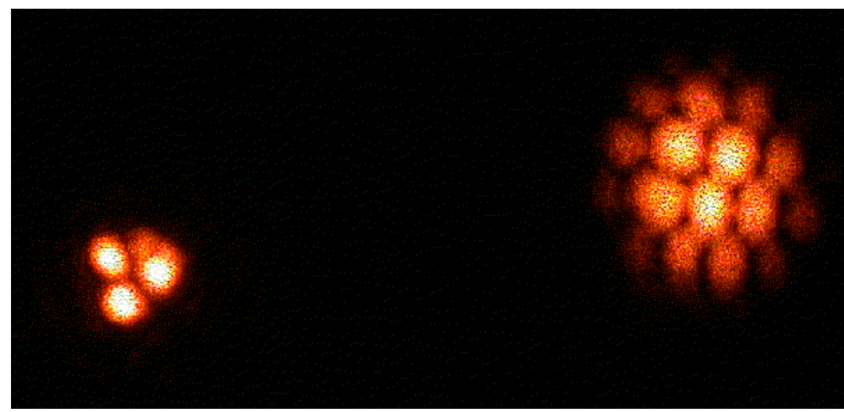
Hexagonal pattern formation in <u>a feedback-free</u> nonlinear optical system



<u>Feedback-free</u> **hexagonal (honeycomb) pattern formation was reported recently in atomic sodium vapor**

Bennink R. et al., *PRL*, 88 (11) 113901 (2002)





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

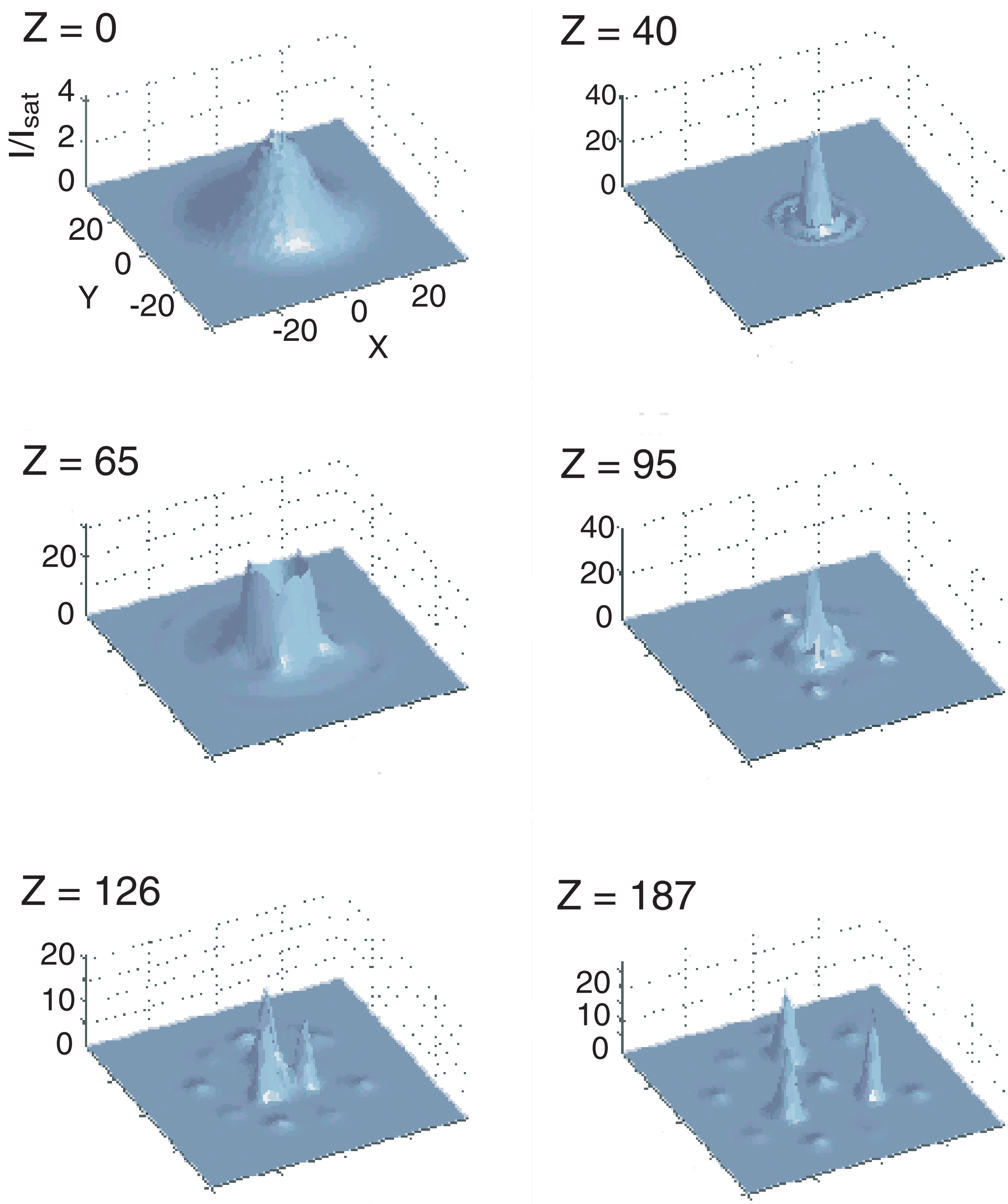
Convert to scaled variables:

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

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

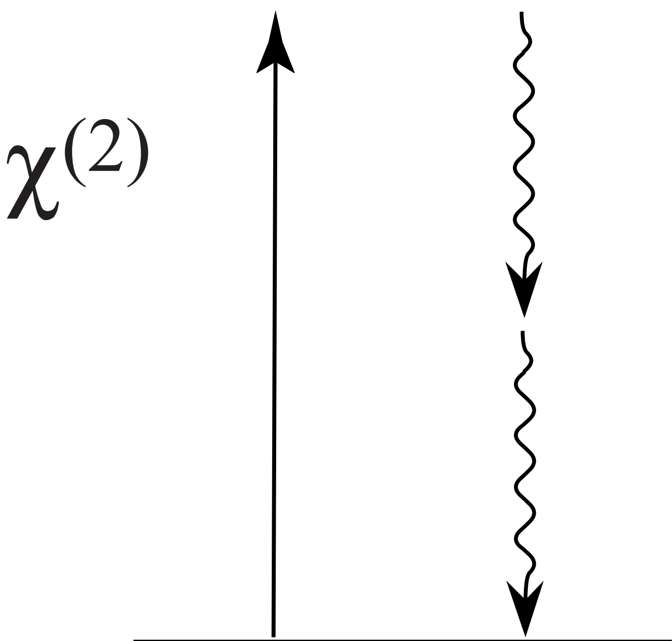
Modelling

Trifurcation occurs for appropriate initial conditions

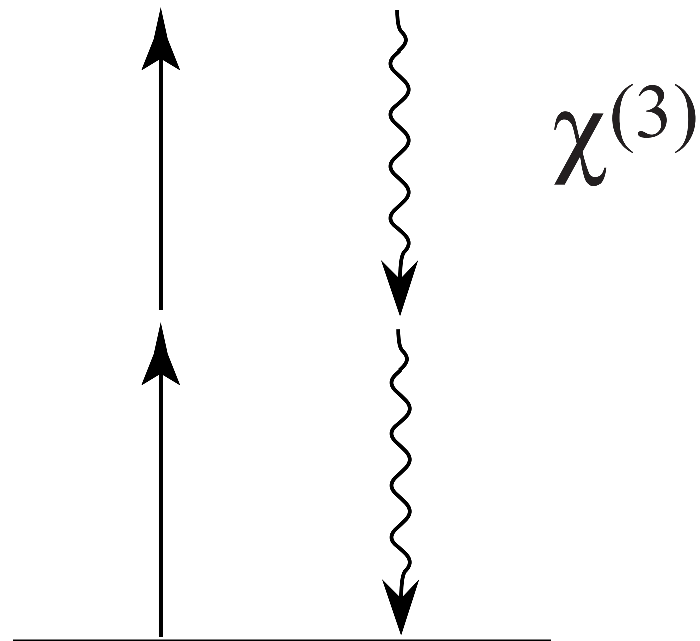


Implications of Spontaneous Pattern Formation

Two Routes to Entanglement:

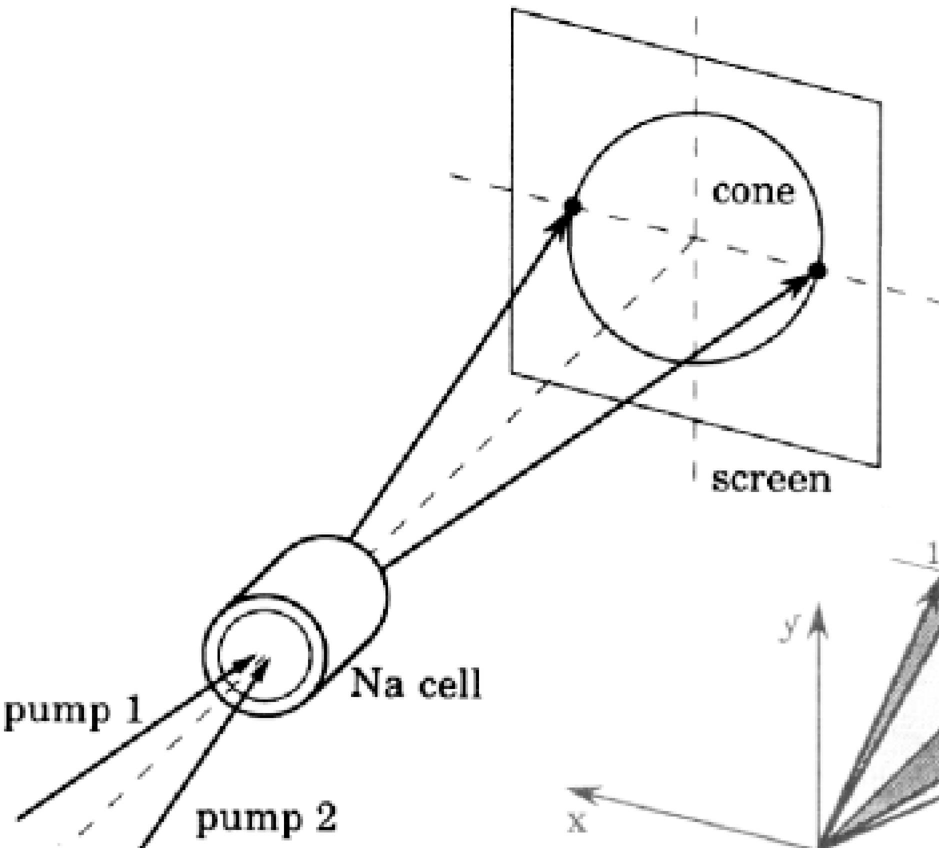


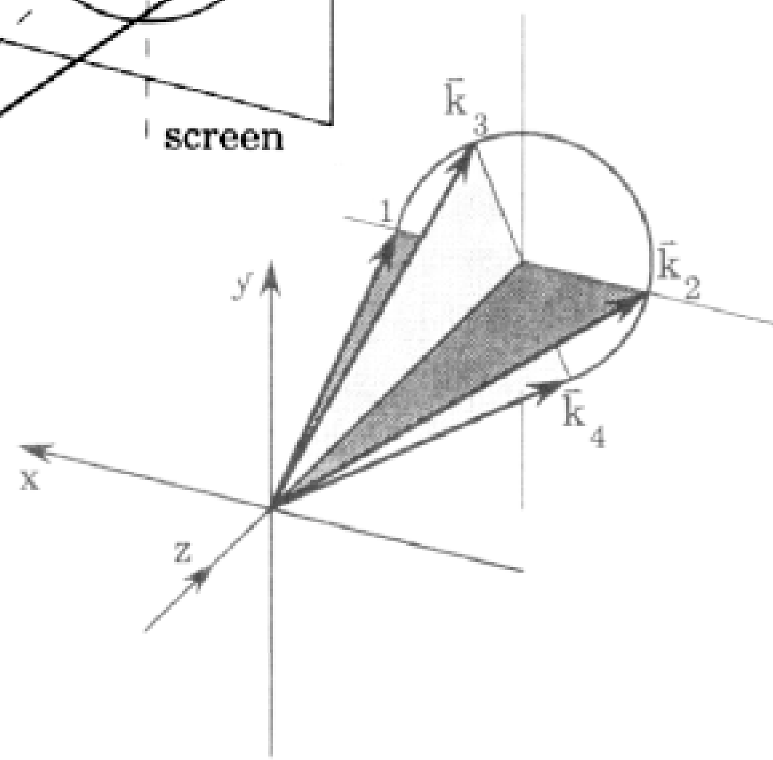
parametric downconversion

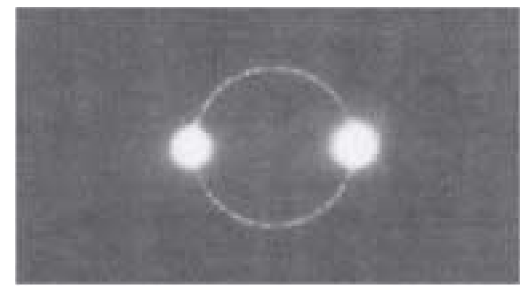


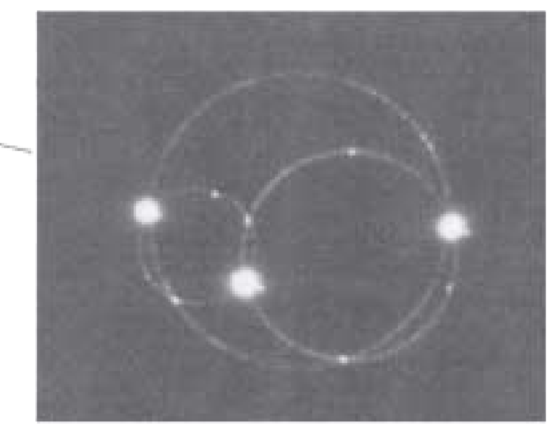
four-wave mixing

Generation of Quantum States of Light by Two-Beam Excited Conical Emission





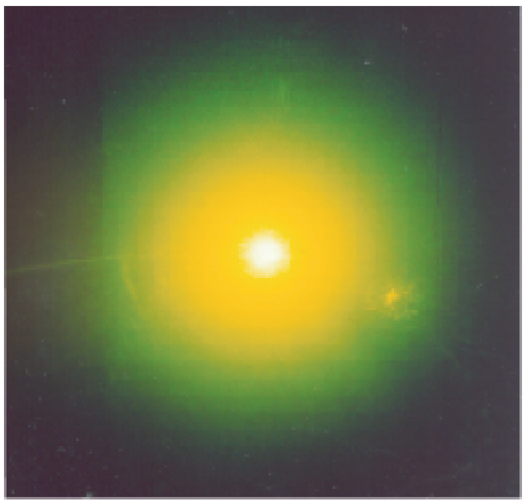




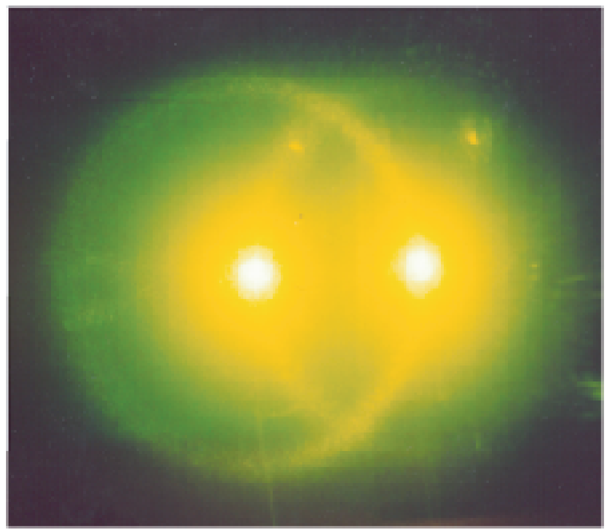
Kauranen et al, Opt. Lett. 16, 943, 1991; Kauranen and Boyd, Phys. Rev. A, 47, 4297, 1993.

Conical Emission Patterns

Single input beam

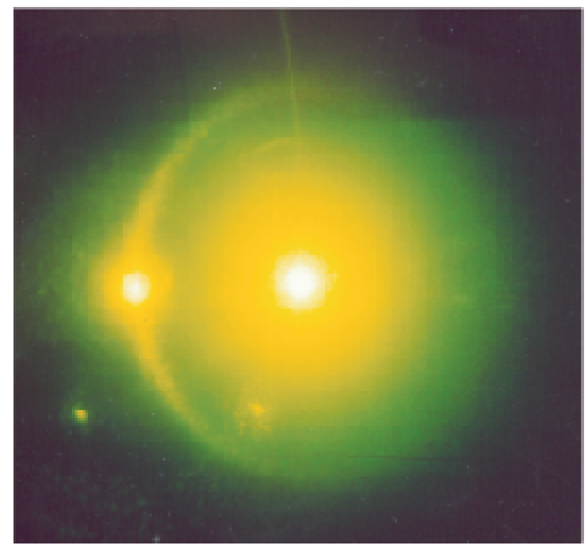


Two input beams
(equal intensity)
(parallel polarization)



Two cones formed, each centered on other beam.

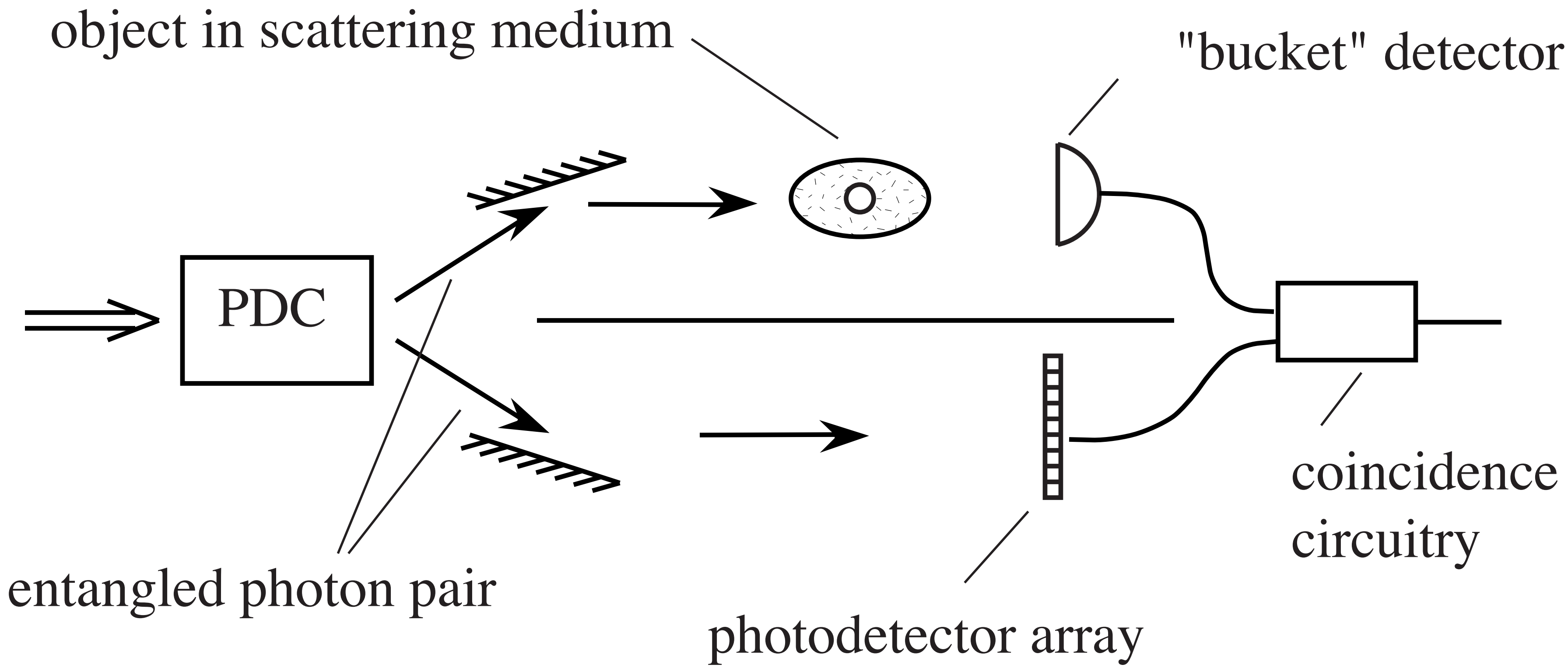
Two input beams
(unequal intensity)
(parallel polarization)



Only stronger input beam can act as pump for cone generation.

Generated in carbon disulfide

Quantum (?) Coincidence Imaging

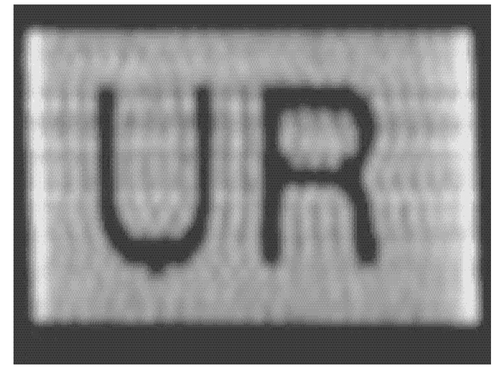


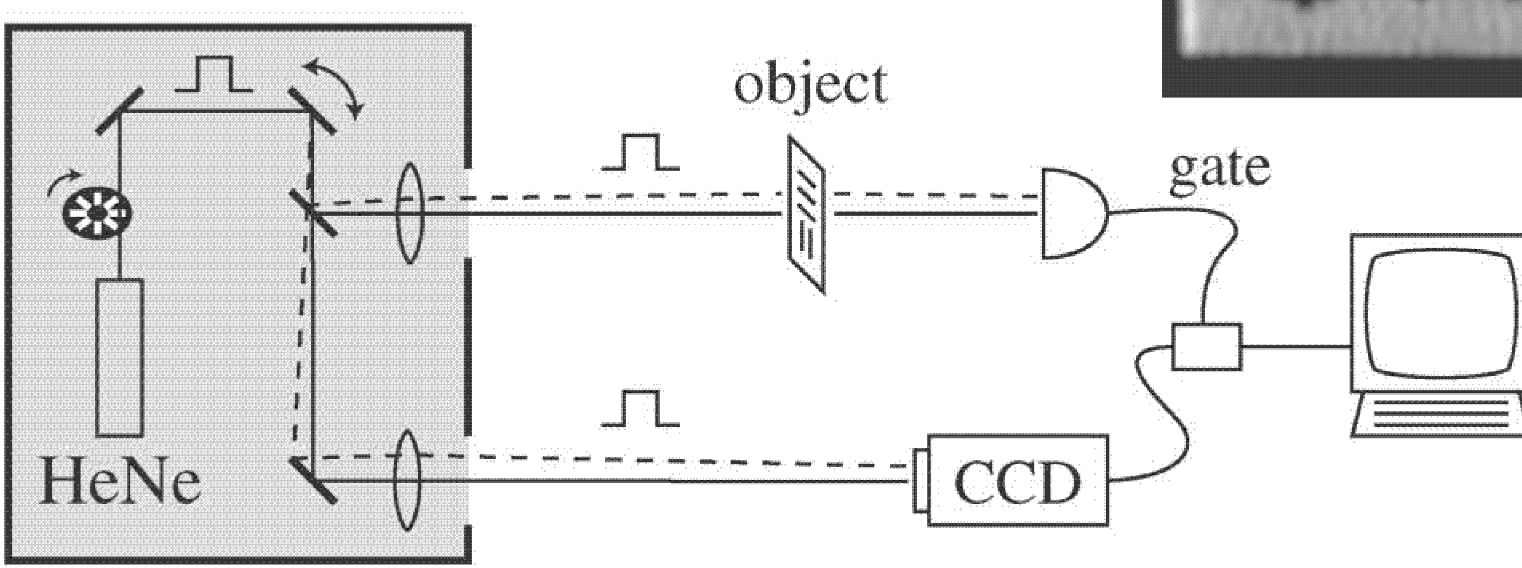
Obvious applicability to remote sensing!

Strekalov et al., Phys. Rev. Lett. **74**, 3600 (1995).
Pittman et al., Phys. Rev. A **52** R3429 (1995).
Abouraddy et al., Phys. Rev. Lett. **87**, 123602 (2001).

Classical Coincidence Imaging

We have performed coincidence imaging with a demonstrably classical source.





Bennink, Bentley, and Boyd, Phys. Rev. Lett. **89** 113601(2002).

Recent Development

VOLUME 90, NUMBER 13 PHYSICAL REVIEW LETTERS week ending 4 APRIL 2003

Entangled Imaging and Wave-Particle Duality: From the Microscopic to the Macroscopic Realm

A. Gatti, E. Brambilla, and L. A. Lugiato

INFM, Dipartimento di Scienze CC.FF.MM., Università dellíInsubria, Via Valleggio 11, 22100 Como, Italy

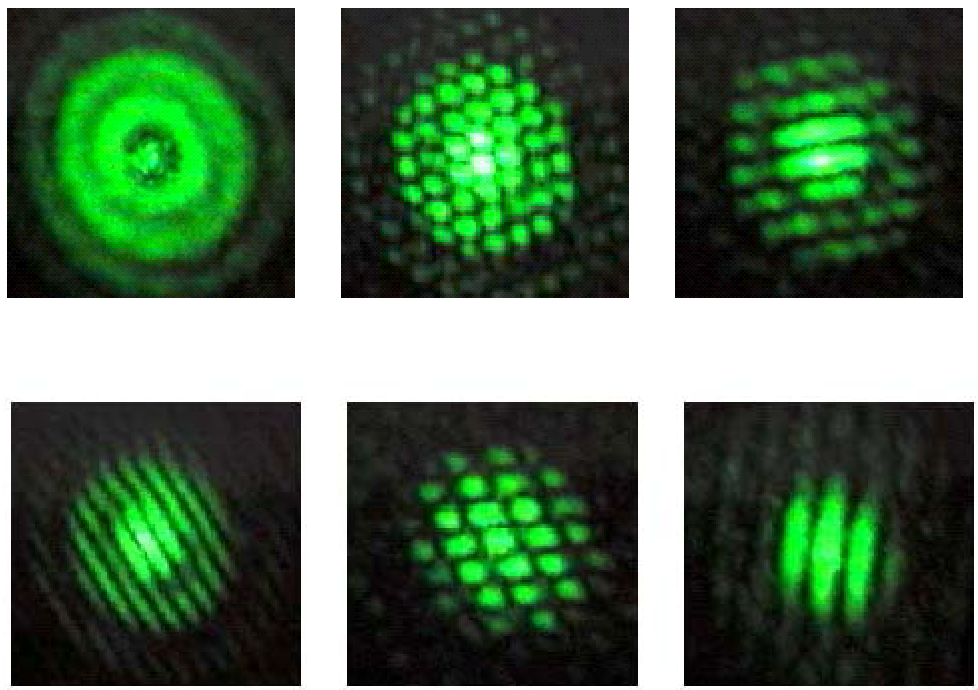
(Received 11 October 2002; published 3 April 2003)

We formulate a theory for entangled imaging, which includes also the case of a large number of photons in the two entangled beams. We show that the results for imaging and for the wave-particle duality features, which have been demonstrated in the microscopic case, persist in the macroscopic domain. We show that the quantum character of the imaging phenomena is guaranteed by the simultaneous spatial entanglement in the near and in the far field.

DOI: 10.1103/PhysRevLett.90.133603 PACS numbers: 42.50.Dv, 03.65.Ud

Our experiments are in progress

Feedback-free pattern formation in dye-doped liquid crystals and isotropic liquids



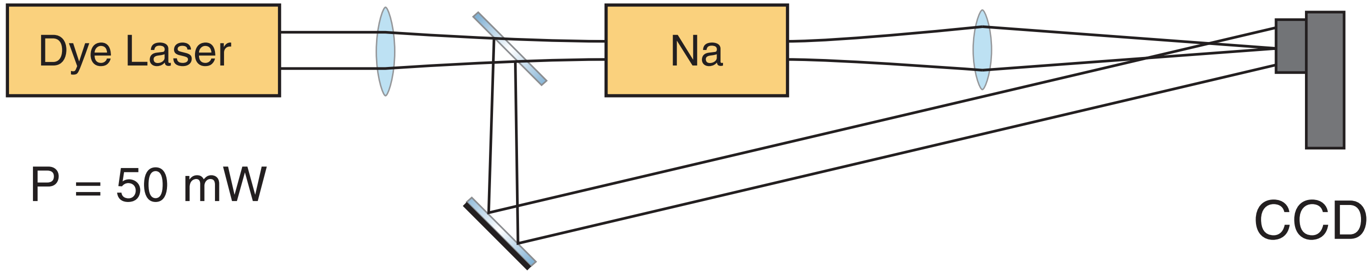
Lukishova, Boyd, Lepeshkin, Marshall and Schmid

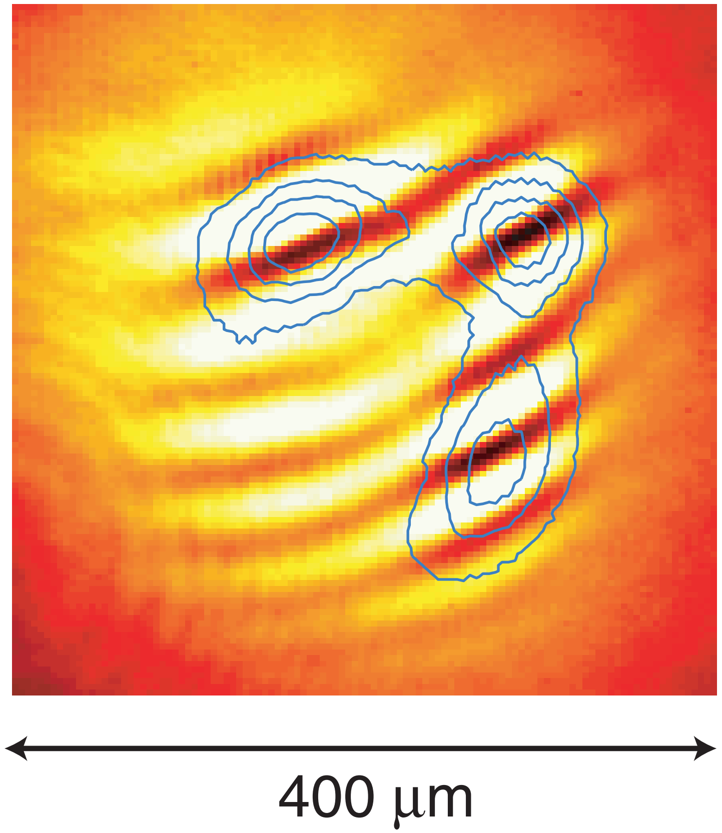
Conclusions

- 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 ⇒ "solitons"
- Filaments are stable and show strong power correlations
- Observations can be predicted qualitatively with a simple model of a saturable medium

Experimental Results

Size, power, and phase of filaments

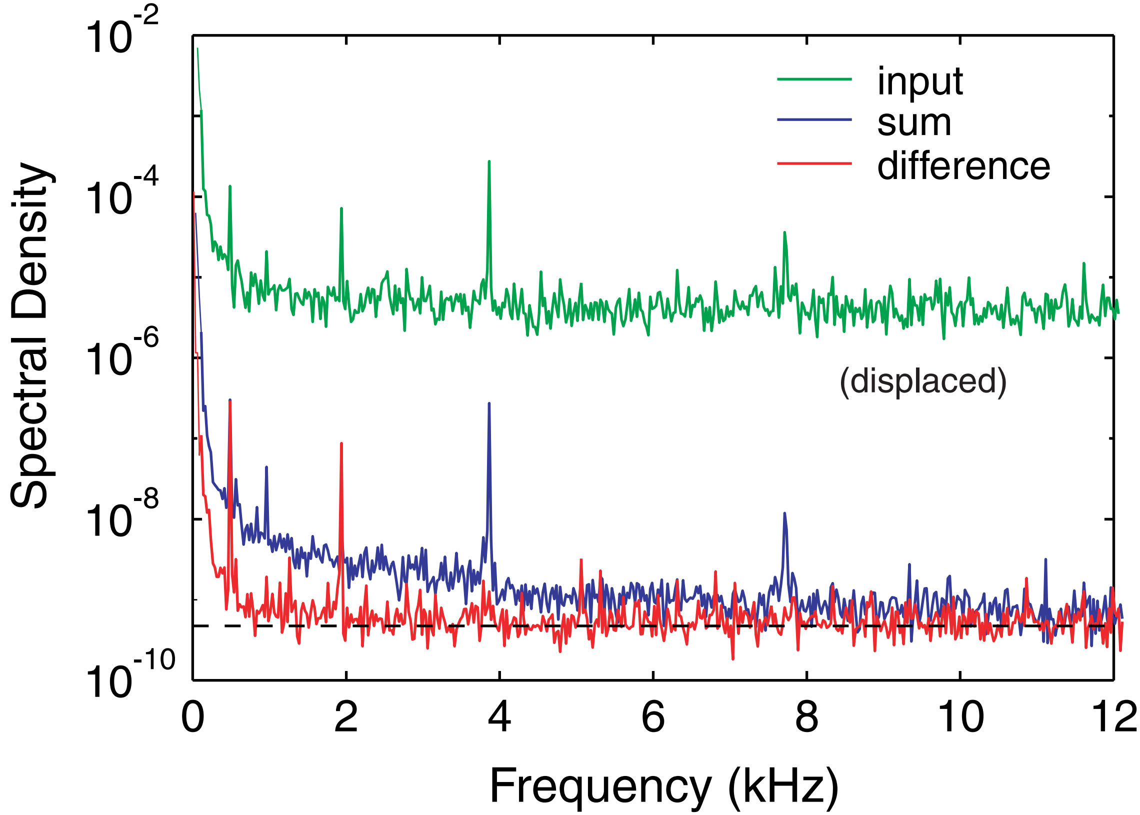




- filaments have constant and equal phase ⇒ "solitons"
- powers (~2 mW) not necessarily equal
- diameters approx. equal (~30 μm)

Experimental Results

Fluctuation statistics of a filament pair



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