Super-charging nonlinear optical processes through collective effects

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Introduction

• Long-term goal:
  – Realize few-photon nonlinear optical (NLO) effects (for quantum/optical info. networks)

• Short-term goal:
  – Study nonlinear wave mixing processes

• Approach:
  – use collective (rather than single atom) effects to ‘super charge’ NLO processes
    • reduce instability thresholds, enhanced scalings, etc.
Optical FWM

- Optical four-wave mixing (FWM) involves the exchange of energy between four optical fields.

\[ E_{\text{in}} \rightarrow E_{\text{s}} \rightarrow E_{\text{pc}} \rightarrow E_{\text{in}} \]

\[ \hbar \Delta \]

To occur efficiently, energy and momentum must be conserved in the optical fields.

Boyd, *Nonlinear optics.*
Ultracold Atoms

2D Rb Magneto-optical Trap (MOT)

Experimental Scheme

Cooling and Trapping → FWM Experiment

Long. Optical path length = 50-100
Temp = 20-40 µK
Dimensions: R = 150 µm, L = 3 cm

FWM with Cold Atoms

Initial homogenous distribution of cold atoms
Initial homogenous distribution of cold atoms

Dipole force begins to spatially organize atoms

Gattobigio et al., PRA 74, 043407 (2006)
Collective FWM (CFWM)

- Grating self-phase-matches additional FWM processes (Bunching allows higher order wave mixing processes to occur)

- Lamb-Dicke effect enhances CFWM through
  - Confining atoms $\Delta x \ll \lambda$ (enhances bunching gain)
  - Reducing inelastic scattering while allowing elastic scattering (increases coherence time)
Investigate importance of bunching by comparing phase-conjugate reflectivity (PCR) for different pump polarizations

\[ \theta = 10 \, \text{deg} \]
\[ \Delta = -6 \, \Gamma \]
\[ |R|^2 = \frac{I_{PC}}{I_{probe}} \]
PCR Results: No Bunching

Counter-rotating pumps

$|R|^2 = \tan(\beta I_p)^2$

Self-oscillation ($|R|=\infty$) for $\beta I_p = \pi/2$

$I_s = 1.6 \text{ mW/cm}^2$

PCR Results: With Bunching

Co-rotating pumps

\[ |R|^2 = \tan(\beta I_p)^2 \]

- exp. data

Diagram showing the relationship between \( |R|^2 \) and \( I_p/I_s \). The red line represents the theoretical model, and the purple dots represent experimental data.
**PCR Results: With Bunching**

Co-rotating pumps

\[ |R|^2 = \tan(\beta I_p)^2 \]

- exp. data

\[ |R|^2 = \tan(\beta (1+b(I_p) I_p)^2 \]

\[ \frac{I_p}{I_s} \]

bunching
Degree of Bunching

- semi-classical, 1D model
- only pump-pump grating
- phenomenological rethermalization rate
PCR Results: With Bunching

Co-rotating pumps

$|R|^2 = \tan(\beta I_p)^2$

$|R|^2 = \tan(\beta (1+b(I_p)) I_p)^2$

Exp. data

Predicted threshold

Observed threshold

Bunching
Observation of Self-oscillation

Pump beams
MOT beams

Forward
Backward

$I_{SF}$ (mW/cm²)

$t$ (µs)
Collective Instability

Initial homogenous distribution of cold atoms

Dipole force begins to spatially organize atoms

Generated light acts back on atoms to self-organize atoms and further enhance scattering
Experimental Results

![Diagram showing SF, Pump, Forward, Backward, F/B Pumps, and MOT beams](image)

**Graph:**
- **Y-axis:** $I_{SF}$ (mW/cm²)
- **X-axis:** t (μs)
- **Lines:**
  - Blue: Forward
  - Red: Backward

**Legend:**
- **On/off**: F/B Pumps
- **MOT beams**
Experimental Results

Cloud expansion terminates self-oscillation

$I_{SF}$ (mW/cm$^2$)

- Blue: Forward
- Red: Backward

$t$ (μs)

F/B Pumps

MOT beams
Persistent CFWM via Trapping

\[ g^{(2)}(\tau) = \frac{\langle I^2 \rangle}{\langle I \rangle^2} \]

\( \tau_c \sim 300 \mu s \)
Decoherence Mechanisms

Atomic Motion

• Expect gratings to decay due to ballistic atomic motion in a time $\tau_c$

$$\tau_c = \frac{1}{\Lambda_g v_{av}} = 0.76 \, \mu s \text{ for } T=30 \, \mu K, \, \Lambda_g \sim 400\, \text{nm}$$

$\Lambda_g$ = grating wavelength
$v_{av}$ = av. velocity

Atoms confined to wells diffuse much more slowly

Incoherent Scattering

• Free atom scattering rate of $\Gamma_{\text{free}} \sim 300 \, \text{kHz}$

$$\frac{\Gamma_{\text{free}}}{\Gamma_{\text{bound}}} = \frac{E_r}{\hbar \Omega_{\text{vib}}} \sim 50 - 100 \rightarrow \Gamma_{\text{bound}} \sim 3 - 6 \, \text{kHz}$$

$L$ = recoil energy
$\Omega_{\text{vib}}$ = vibrational frequency
Conclusion: Self-organization can reduce NLO instability thresholds and give rise to new, more sensitive parameter dependences.

Future: Study how collective effects may enhance other NLO processes
  - quantum correlated photon pair generation
  - quantum memories