Imaging with spatial correlation

The Theoretical Quantum Optics Group in Como

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SPATIAL ASPECTS of QUANTUM OPTICAL FLUCTUATIONS

⇒ in the transverse distribution of light, typically in wave-mixing phenomena involving a large number of spatial modes

Reasons for interest: spatial properties of quantum states of light can be used to overcome the classical limits of imaging and to devise unconventional imaging schemes

QUANTUM IMAGING.

Quantum limits in the detection of small beam displacements (microscopy), Noiseless amplification of images, Quantum teleportation of optical images, Quantum superresolution …and much more

• Quantum spatial correlations in light beams (the fundamental resource)
• High sensitivity imaging
• Ghost-imaging: imaging without interaction
Quantum spatial correlation of twin beams and high-sensitivity imaging
**Classical spatial correlation**

Splitting by a beam splitter: two classical copies of the pattern

Speckle pattern generated by impinging a laser beam on a ground glass.

Splitting of light by the beam splitter: macroscopic process

Partition of photons in the two arms is a random process → partition noise

\[ N_\_ = N_1 - N_2 \] difference of photon numbers collected from two corresponding portions

\[ \langle \delta N^2 \rangle = \langle N_1 \rangle + \langle N_2 \rangle \] SHOT - NOISE LEVEL

Imperfect (classical) spatial correlation
Quantum Spatial correlation: the process of Parametric Down-Conversion


Microscopic process: momentum conservation creates correlation in the directions of propagation of twin photons

\[ \langle \delta N_z^2 \rangle = 0 \]

Perfect quantum correlation between any two symmetric portions
Position-momentum entanglement of twin photons

Position correlation: Position $x$ of photon 1 determined from a measurement of the position of the photon 2

Simultaneous presence of correlation in both position and momentum of the two photons

→ Entangled (nonseparable) state, similar to the original EPR (Einstein-Podolsky Rosen, 1935) state

First Experimental Demonstration of Quantum Spatial Correlation in high-gain PDC at Ultrafast Nonlinear Optics Lab in Como


Pump pulses
( 1ps @352 nm, 0.1– 0.5 mJ, 1 mm waist)

Spatial filtering

4 mm type II BBO

Portion of PDC fluorescence around collinear direction

M1

M2

f=10cm

f=10cm

Polarizing Beam-splitter

CCD

ηtot ~ 75%

η ~ 89% @704nm

Far-field images

signal

idler

⇒ evident spatial correlation
Degree of correlation: noise in the difference $N_-$ of photocounts from symmetric signal-idler pixels

$$\sigma = \frac{\langle \delta N_-^2 \rangle}{\langle N_1 + N_2 \rangle}$$

Correlation are Sub-shot-noise up to gains characterized by $\langle N_1 + N_2 \rangle \approx 15-18$

In this region: beams are spatially correlated better than two classical copies.

$\Rightarrow$ Twin beam effect over several (~4000) signal/idler spatial modes.
High-Sensitivity Imaging

A classical differential scheme suppresses the excess noise, but it is limited by the partition noise (=shot-noise in $N_2 - N_1$): a weak absorption can be hidden by noise.

The classical limit can be beaten by replacing the two classical copies with two quantum copies: twin beams with sub-shot noise spatial correlation.

\[ \chi^{(2)} \]

\[ N_1 \]

\[ \alpha(x) \]

\[ N_1' \]

\[ N_2 \]

\[ \text{reference} \]

\[ N_-' = N_1' - N_2 \]

The theoretical proposal is:

Brambilla, Caspani, Jedrkiewicz, Lugliato, Gatti, PRA 77 053807 (2008)

\[ \Rightarrow \text{Signal-to-noise ratio improved with respect to the classical limit} \]

Original Image

Classical copies

Twin beams

SNR=1.2

SNR=3.3
The regime of Como experiment is not suitable for imaging, because correlation remain sub-shot noise only for a very low photon number (background noise detrimental)

**IDEA:** WORKING at LOWER-GAIN, WITH A LONGER PUMP PULSE SHOULD MAKE CORRELATION MORE ROBUST

**Numerics:** degree of correlation $\sigma$ as a function of the detected photon number, in the presence of un unbalance $X_{\text{shift\ fixed}} = 4 \ \mu\text{m}$

$$\sigma = \frac{\langle \Delta N^2 \rangle}{\langle N_1 + N_2 \rangle}$$

**Correlation is more robust for long pump pulses, low excess noise**

$\Rightarrow$ sub-shot noise correlation at higher photon number
Second experimental demonstration of sub-shot noise spatial correlation at INRIM (Torino)

Nanosecond pump pulses ⇒ Sub-shot noise spatial correlation for higher intensities

≈2000-3000 photons per pixel, NO background noise correction
⇒ Suitable for imaging!

Quantum correlations of light can be used to obtain higher signal-to-noise ratios than those possible through classical imaging methods.
II-Ghost imaging
Imaging without interaction

Debate about the role of the entanglement/quantum nonlocality vs classical correlation
Ghost imaging (imaging through light correlation) = unconventional way of imaging

**Light source**

**uniform illumination**

**object**

**Multi-pixel detector**

**Light source**

“**test pattern**”

**object**

**Single pixel detector (bucket detector)**

**REFERENCE ARM**

Classical or quantum copy of the test pattern

Correlation with the test pattern → object spatial information

Form the correlation as a function of position in the reference arm → object transmission function
Quantum illumination: Imaging with spatially entangled photons

The image emerges from the coincidence counts, as a function of the arrival position of photon 2, that never sees the object→ “Ghost Image” [Pittman, Shih, Strekalov and Sergienko, PRA 52, R3429 (1995)]

By simply changing the optical set-up in the path of photon 2→”Ghost Diffraction” [Ribeiro, Padua, Machado da Silva, Barbosa, PRA. 49, 4176, (1994); Strekalov, Sergienko, Klyshko and Shih, PRL 74, 3600 (1995)]
Classical illumination: Evidence of high resolution ghost image and ghost diffraction with classically correlated beams from a pseudo-thermal source


Classically correlated speckle patterns

\[ \frac{1}{q} + \frac{1}{F} = \frac{1}{F_{\text{eff}}} \]

\( F_{\text{eff}} \) focal of the two lens system
The ability to produce both the ghost image and the ghost diffraction pattern was initially attributed to the entanglement of the quantum state (simultaneous presence of position and momentum correlation)

Long debate about the need of entanglement for Ghost Imaging...

An essential literature:
- Ferri, Magatti, Sala, Gatti, Appl. Phys. Lett. 92, 261109 (2008) Etc. etc. etc…
The main message that emerged:
Caution should be taken when dealing with concepts such as “quantum nonlocality” or “entanglement”

Classical correlations are also powerful tools
Imaging in a noisy environment

Imaging through scattering media (biological tissues, fog, clouds…)

• Bio-medical imaging
• Remote sensing
Possibility of “compressive sensing”

• In conventional imaging $N$ pixels of the image are detected, being the minimum number of $N$ determined by Nyquist sampling principle.

• In ghost imaging the object is sampled by a single detector, and the image is retrieved from a statistical evaluation of the correlation with the test patterns, performed over $M$ independent patterns.

Can $M$ be significantly smaller than $N$?

Guess (inspired by researches at the The Weizmann Institute of Science on compressive imaging): Maybe yes if the image is compressible.

Fundamental issue: the signal-to-noise ratio of ghost imaging schemes
The signal-to-noise ratio of conventional ghost imaging is low
So far, imaging of simple binary objects

Recent progress:

“Differential ghost imaging” (DGI), a novel scheme that overcomes the SNR limitation (enhancement of SNR of ghost imaging by orders of magnitudes)

Bringing ghost imaging from an academic subject to “real world” applications

Measured $(\text{SNR})_{\text{DGI}} / (\text{SNR})_{\text{GI}} \sim 6.4$
Two small particles (d₁ = 400 µm, d₂ = 820 µm) in a large beam (L=5.7 mm)

The new protocol DGI allows the location and sizing of small particles (not feasible with conventional GI)

\[
\frac{(SNR)_{DGI}}{(SNR)_{GI}} = 52 \quad \text{Expected}
\]

\[
\frac{(SNR)_{DGI}}{(SNR)_{GI}} \approx 66 \quad \text{Measured}
\]

The new protocol DGI allows the location and sizing of small particles (not feasible with conventional GI)
CONCLUSIONS

Example I: High sensitivity imaging with spatially correlated twin beams
⇒ Sub-shot-noise correlations are the fundamental resource that permits to surpass the classical limit in sensitivity
⇒ useful for weakly absorbing object, whenever a low disturbance is needed

Example II: Ghost Imaging
⇒ Classical sources can completely mimic the behaviour of quantum sources
⇒ Poor signal-to-noise ratio, overcome by a novel scheme (DGI)
⇒ DGI enhances experiments not feasible with conventional GI, opens the access to the potentialities of GI

⇒ Imaging in scattering media, compressive sensing

Work in progress