Smart Quantum Statistical Imaging beyond the Abbe-Rayleigh Criterion

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Spectroscopy with non-classical light

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S. Corona-Aquino, RJLM et al., J. Phys. Chem. A 126, 2185 (2022)
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Quantum transport in complex systems

M. A. Quiroz-Juárez, RJLM, et al., EPJ Plus 138, 775 (2023)
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Multiphoton quantum-state engineering and quantum simulation

M. Hong, RJLM et al., Laser & Photonics Reviews 23001117 (2023)
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C. You, RJLM et al., Nature Communications 12, 5161 (2021)

Smart quantum (and classical) optics experiments

M. L. J. Lollie, RJLM, et al., Mach. Learn.: Sci. Technol. 3, 035006 (2022)
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Smart Quantum Statistical Imaging
(Quantum Smart Camera)

Omar Magaña-Loaiza
Chenglong You
Mario A. Quiroz-Juarez
Smart Quantum Statistical Imaging  
(Quantum Smart Camera)

• **Identification of light sources using machine learning**  
  Applied Physics Reviews **7**, 021404 (2020)

• **Observation of the modification of quantum statistics of plasmonic systems**  
  Nature Communications **12**, 5161 (2021)
Identification of light sources using machine learning
Identification of light sources using machine learning

Thermal light

Coherent Light

Photon number

Probability

\( n_0 = 5 \)

\( n_0 = 5 \)
Identification of light sources using machine learning

Thermal light

Probability

Photon number

Coherent Light

Probability

Photon number
Identification of light sources using machine learning

We need 1,000,000 measurements to distinguish one source from the other!
Identification of light sources using machine learning

We need 1 000 000 measurements to distinguish one source from the other!

1 s measurement for a correct identification of the light sources
ADALINE = ADAptive LINear Element
ADALINE = ADAptive LINear Element

~20 microseconds

50 000 times faster!!

Applied Physics Reviews 7, 021404 (2020)
Modification of photon statistics of plasmonic systems

Indistinguishable sources:
\[ P_{\text{det}}(\alpha) = \int P_1(\alpha - \alpha')P_2(\alpha')d^2\alpha' \Rightarrow p_{\text{det}}(n) = \langle n | \rho_{\text{det}} | n \rangle, \quad \text{with} \quad \rho_{\text{det}} = \int P_{\text{det}}(\alpha) |\alpha\rangle \langle \alpha| d^2\alpha \]

Distinguishable sources:
\[ p_{\text{det}}(n) = \sum_{m=0}^{n} p_1(n-m)p_2(m) \]

R. J. Glauber, Phys. Rev. 131, 2766 (1963)
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Observation of the modification of quantum statistics of plasmonic systems

Chenglong You 1,6, Mingyuan Hong 1,6, Narayan Bhusal 1, Jinnan Chen 2, Mario A. Quiroz-Juárez 3, Joshua Fabre 1, Fatemeh Mostafavi 1, Junpeng Guo 2, Israel De Leon 4, Roberto de J. León-Montiel 5 & Omar S. Magaña-Loaiza 1,8

Nature Communications 12, 5161 (2021)
Smart Quantum Statistical Imaging beyond the Abbe-Rayleigh Criterion
E. Sezgin, J. Phys.: Condens. Matter 29, 273001 (2017)
Smart Quantum Statistical Imaging beyond the Abbe-Rayleigh Criterion
Photon-number distribution of N coherent and M thermal indistinguishable, independent sources:

\[
p_{\text{th-coh}}(n) = \frac{(m_{\text{tot}})^n \exp\left(-|\alpha_{\text{tot}}|^2/m_{\text{tot}}\right) \sum_{k=0}^{n} \frac{1}{k!(n-k)!} \Gamma\left(\frac{1}{2} + n - k\right) \Gamma\left(\frac{1}{2} + k\right) \times _1F_1\left(\frac{1}{2} + n - k; \frac{1}{2}; \frac{(\text{Re}[^{\text{tot}}\alpha]^2)}{m_{\text{tot}} (m_{\text{tot}} + 1)}\right) _1F_1\left(\frac{1}{2} + k; \frac{1}{2}; \frac{(\text{Im}[\alpha_{\text{tot}}]^2)}{m_{\text{tot}} (m_{\text{tot}} + 1)}\right)}{\pi (m_{\text{tot}} + 1)^{n+1}}
\]

with \( m_{\text{tot}} = \sum_{l=1}^{M} \bar{m}_l \) and \( \alpha_{\text{tot}} = \sum_{k=1}^{N} \alpha_k \). \( \Gamma(z) \) and \( _1F_1(a; b; z) \) are the Euler gamma and the Kummer confluent hypergeometric functions, respectively.
Photon-number distribution of N coherent and M thermal indistinguishable, independent sources:

\[ p_{\text{th-coh}}(n) = \frac{(m_{\text{tot}})^n \exp \left( -|\alpha_{\text{tot}}|^2/m_{\text{tot}} \right)}{\pi (m_{\text{tot}} + 1)^{n+1}} \sum_{k=0}^{n} \frac{1}{k!(n-k)!} \Gamma \left( \frac{1}{2} + n - k \right) \Gamma \left( \frac{1}{2} + k \right) \times \text{I}_1 \left( \frac{1}{2} + n - k ; \frac{1}{2} ; \frac{|\text{Re}[\alpha_{\text{tot}}]|^2}{m_{\text{tot}} (m_{\text{tot}} + 1)} \right) \text{I}_1 \left( \frac{1}{2} + k ; \frac{1}{2} ; \frac{|\text{Im}[\alpha_{\text{tot}}]|^2}{m_{\text{tot}} (m_{\text{tot}} + 1)} \right) , \]

with \( m_{\text{tot}} = \sum_{i=1}^{M} m_i \) and \( \alpha_{\text{tot}} = \sum_{k=1}^{N} \alpha_k \). \( \Gamma(z) \) and \( \text{I}_1(a; b; z) \) are the Euler gamma and the Kummer confluent hypergeometric functions, respectively.

\[ p(n), \bar{n}, g^{(2)} \]

npj Quantum Inf. 8, 83 (2022)
Experimental super-resolving imaging
Direct Imaging vs Smart Statistical Imaging

Graph a shows the measured $s/w_0$ vs $s/w_0$ relationship for Monte Carlo and Diffraction-Limited Imaging, with Superresolving Imaging and Experimental Superresolving Imaging indicated.

Graphs b, c, and d illustrate the imaging results:
- Graph b: i)
- Graph c: ii)
- Graph d: iii)
Smart quantum statistical imaging beyond the Abbe-Rayleigh criterion

Narayan Bhushal, Mingyuan Hong, Ashe Miller, Mario A. Quiroz-Juérez, Roberto de J. León-Montiel, Chenglong You and Omar S. Magaña-Loaiza

The wave nature of light imposes limits on the resolution of optical imaging systems. For over a century, the Abbe-Rayleigh criterion has been utilized to assess the spatial resolution limits of imaging instruments. Recently, there has been interest in using spatial projective measurements to enhance the resolution of imaging systems. Unfortunately, these schemes require a priori information regarding the coherence properties of "unknown" light beams and impose stringent alignment conditions. Here, we introduce a smart quantum camera for superresolving imaging that exploits the self-learning features of artificial intelligence to identify the statistical fluctuations of unknown mixtures of light sources at each pixel. This is achieved through a universal quantum model that enables the design of artificial neural networks for the identification of photon fluctuations. Our protocol overcomes limitations of existing superresolution schemes based on spatial mode projections, and consequently provides alternative methods for microscopy, remote sensing, and astronomy.

npj Quantum Information 8, 83 (2022)
Our goal: To design and implement novel machine-learning-enabled photonic technologies!
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