Shack-Hartmann Tomography for Multimode Optical Beam Propagation

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Motivation

We experimentally show that wavefront detection combined with tomography processing can be used for the complete characterization of the second-order coherence and hence 3D imaging of partially coherent vortex beams. A standard Shack-Hartmann single-shot measurement is used in the method.

3D imaging

To be able to propagate intensity, mutual coherence function G must be known at the input:

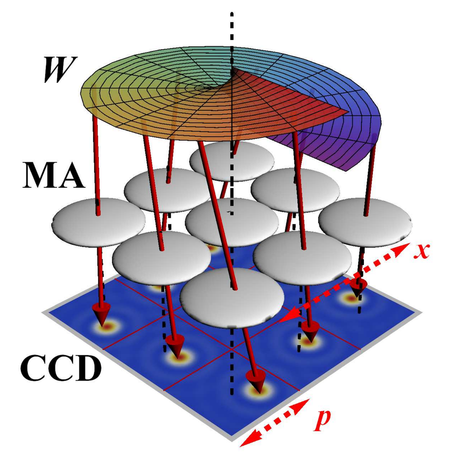
$$I(x) = \int_{-\infty}^{\infty} h(x,x')h^*(x,x'')G(x',x'')dx'dx''$$

Let ρ be a coherence matrix, a discrete version of function $G(x',x'')$:

$$G(x',x'') = \langle x'|\rho|x''\rangle = \mathrm{Tr}(\rho|x'\rangle\langle x''|)$$

If basis for the problem is labeled by $|k\rangle$ ($k = 1,\ldots,d$, with d being the dimension), the complex amplitudes are $\langle x|k\rangle = \psi_k(x)$. Therefore, the coherence matrix ρ is given by $d \times d$ non-negative matrix.

Principle of SH tomography



If a SH sensor is illuminated with a coherent signal $U(x)$, and the ith microlens is Δx_i apart from the SH axis, this microlens feels the field $U(x-\Delta x_i) = \langle x|\exp(-i\Delta x_i P)|U\rangle$. This field is truncated and filtered by the aperture (or pupil) function $A(x) = \langle x|A\rangle$ and Fourier transformed by the microlens:

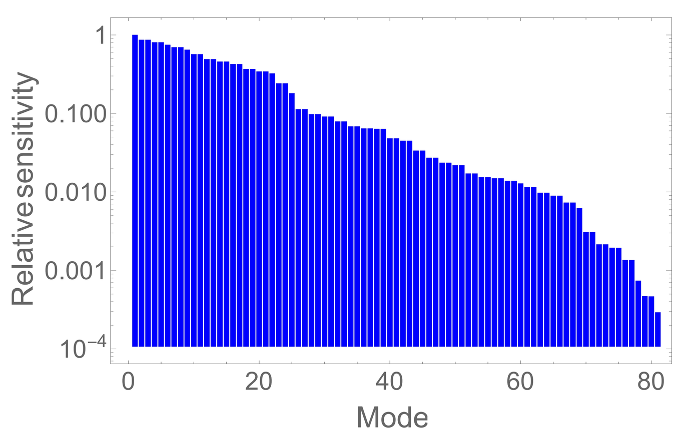
$$U'(\Delta p_j) = \langle A|\exp(-i\Delta p_i X)\exp(-i\Delta x_i P)|U\rangle\,.$$

The intensity measured at the jth pixel behind the ith lens is then governed by a Born-like rule

$$I(\Delta x_i, \Delta p_j) = \mathrm{Tr}(\rho\,|\pi_{ij}\rangle\langle\pi_{ij}|)\,,$$

with $|\pi_{ij}\rangle = \exp(i\Delta x_i P)\exp(i\Delta p_i X)|A\rangle$.

Mode decomposition of SH tomography



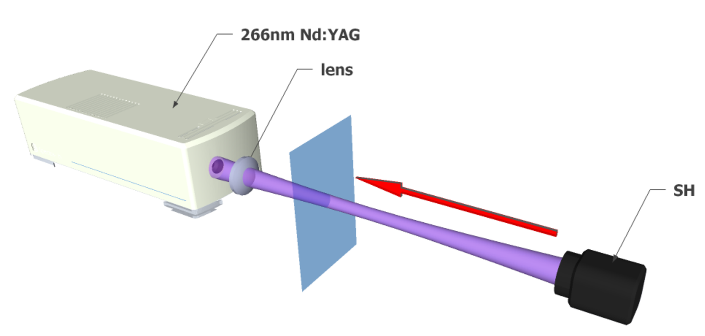
We define the dynamical range (or field of view) of the SH tomography as the set of normal modes of measuring matrix with singular values exceeding a given threshold.

$$I_{ij} = \sum_k p_k^{ij} r_k\,.$$

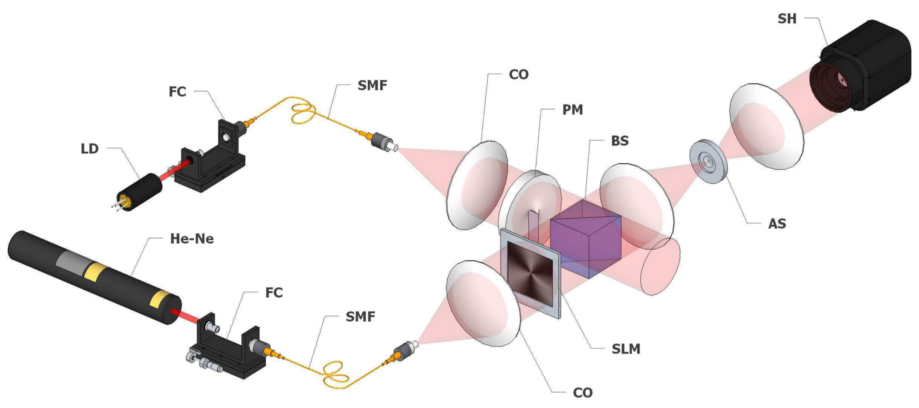
Conclusion

Applying quantum tomography to Shack-Hartmann data, the coherence matrix carrying complete information about the 3D intensity distribution of the signal can be reconstructed. As the method is a single-shot measurement and the Shack-Hartmann sensor is easy to build cost effective device, there is a great potential for implementing this technique in general 3-D imaging problems.

Experimental setups



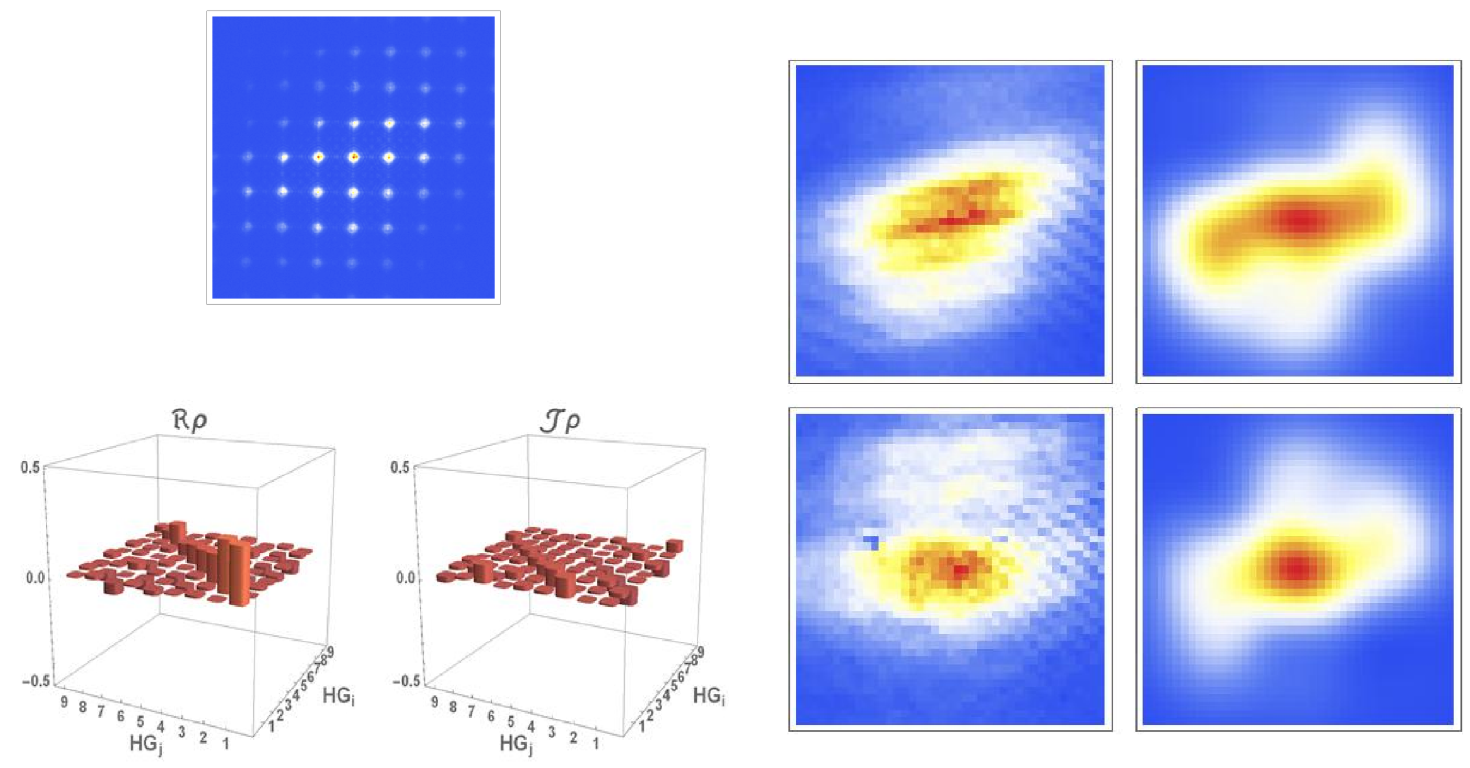
Deep UV Nd:YAG 266nm setup.



Multimode vortex beam 633nm setup.

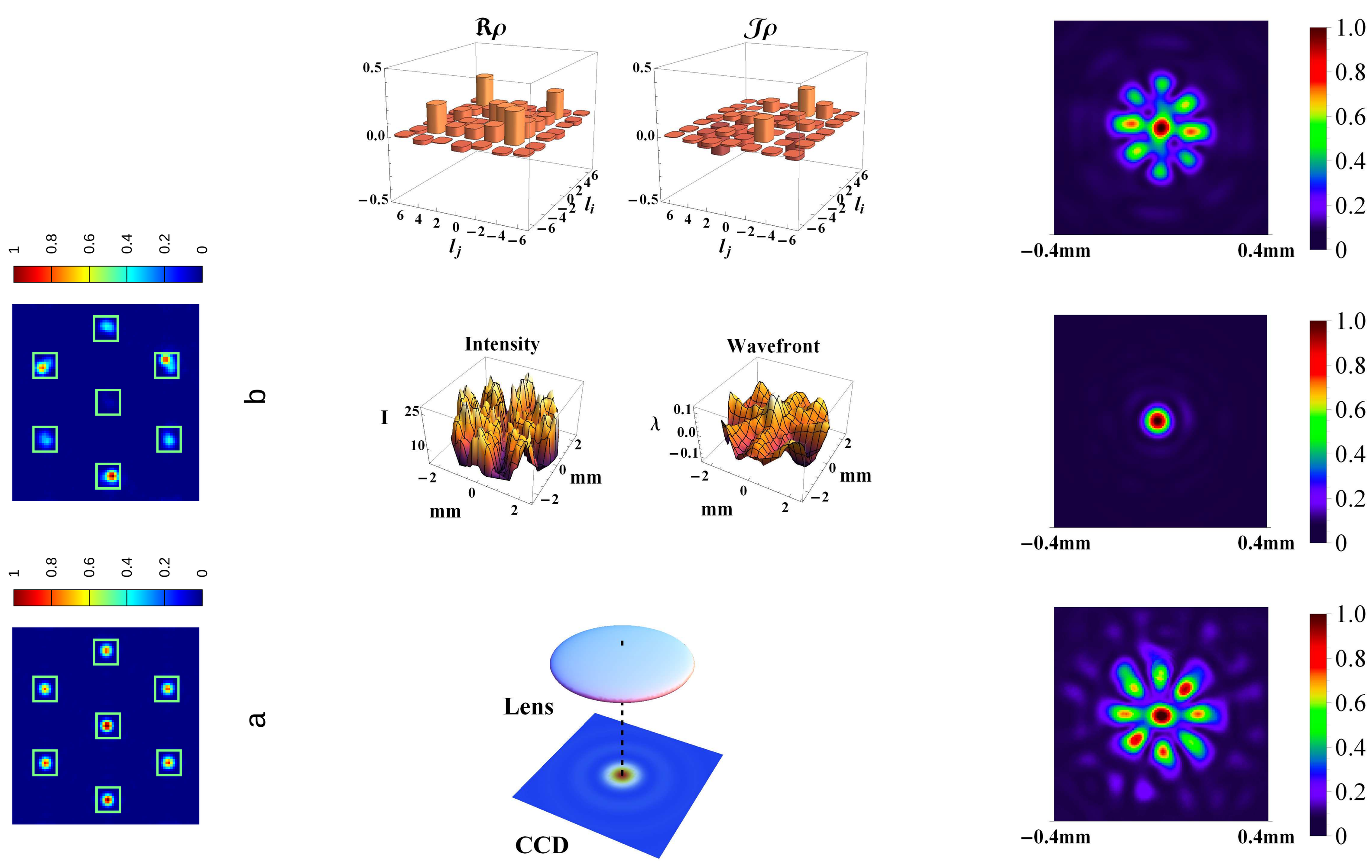
Nd:YAG beam propagation

Shack-Hartmann tomography was composed of intensity data from 11*x*11 pixels against 7*x*7 microlenses, altogether 5929 measurements



Indexes i, j label HG modes in the following order: $HG_{0,0}, HG_{1,0}, HG_{2,0}, HG_{0,1}, HG_{1,1}, HG_{2,1}, HG_{0,2}, HG_{1,2}, HG_{2,2}$

Multimode Vortex Beam



References

[1] B. Stoklasa, L. Motka, J. Rehacek, Z. Hradil and L.L. Sanchez-Soto, “Wavefront sensing reveals optical coherence," Nat. Commun. **5**, 10.1038 (2014)

[2] Z. Hradil, J. Rehacek, and L.L. Sanchez-Soto, “Quantum Reconstruction of the Mutual Coherence Function,” Phys. Rev. Lett. **105**, 010401 (2010).

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