Ghost Imaging Technology in Sensing Applications

Sanjit Karmakar & Yanhua H. Shih
Department of Physics, University of Maryland, Baltimore, MD 21250
e-mail: sanjitk1@umbc.edu

The two peculiar features of quantum imaging: (1) reproduction of nonlocal "ghost" images and (2) improvement of imaging spatial resolution beyond the classical limit were demonstrated so far in "ghost" imaging experiments and lithography types of measurements respectively. This article reports an experimental study on two-color ghost imaging with enhanced angular resolving power by means of greater field of view compared with that of classical imaging. An approach to resolve the problem of enhancing the angular resolution in space imaging by using entangled photon pairs of two colors is also reported in this article. These reported features of ghost imaging are very important and useful in the area of sensing as well as imaging applications.

1. Introduction

Quantum imaging is one of the important exciting areas in practical engineering applications. Quantum imaging was first demonstrated experimentally by Pittman et al [1] in 1995, following by the idea of Klyshko [2]. Later, non-degenerate quantum imaging was performed by Pittman et al by using a lens before the nonlinear crystal to demonstrate the dependence of the two-photon spherical mirror equation on the wavelengths of the down-converted photons [4]. Recently resolution of non-degenerate ghost imaging was also studied theoretically [5, 6].

The quantum imaging has experimentally demonstrated two peculiar features so far: (1) reproduction of nonlocal "ghost" images and (2) improvement of imaging resolution beyond the classical diffraction limit. Both the nonlocal behavior observed in the ghost imaging experiment [1, 3] and the apparent violation of the uncertainty principle explored in the quantum lithography experiment [7] are due to the two-photon coherence effect, which involves the superposition of two-photon amplitudes, nonclassical entities corresponding to different yet indistinguishable alternative ways of triggering a joint-detection event.

In this article, we report an experimental configurations on two-color, biphoton ghost imaging which can reproduce a nonlocal ghost image and simultaneously enhance the angular resolving power of imaging by means of a greater field of view compared to that of classical imaging [8–10]. We also report an approach to resolve the problem of enhancing the angular resolution in space imaging by using entangled photon pairs of two colors.

2. An Experimental Study

With the help of an entangled photon pair of $\omega_i > \omega_s$, generated from spontaneous parametric down-conversion (SPDC), we observe a ghost image with enhanced resolving power by a factor of $\omega_i/\omega_s = 1.25$ by means of a field of view, which is

$$\left(d_1 + d_2\left(\omega_i/\omega_s\right)\right)/\left(d_1 + d_2\right) = 1.16$$

times greater than that of the one-color ghost imaging as well as the classical imaging set up, where ω_s is the angular frequency of the radiation that illuminates the object, ω_i is the angular frequency of idler beam, d_1 and d_2 are the optical distance from output plane of SPDC source to the imaging lens and the object plane respectively. In this experiment, we choose $d_1 = 345$ mm, $d_2 = 715$ mm.

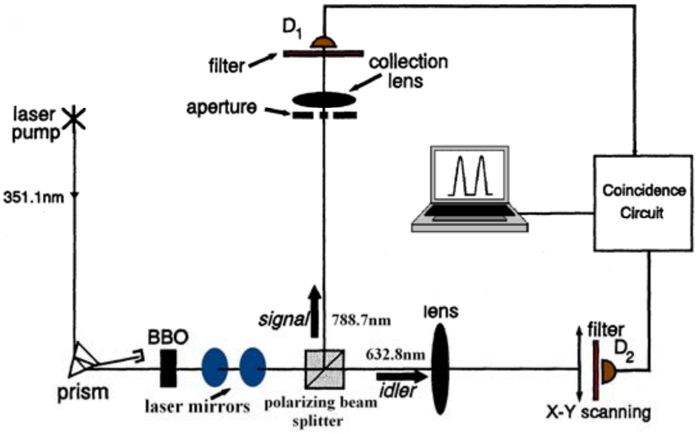

Fig. 1. Schematic of our experimental setup. The detector D_2 is scanned on the *x-y* transverse plane to observe the image of the object aperture. The prism is used to separate the residuals from 351.1 nm laser line. The laser mirrors are used to reflect 351.1 nm and to transmit 788.7 nm and 632.8 nm wavelengths.

The schematic of this experimental configuration is shown in Fig. 1. A light beam of wavelength the 351.1 nm from an argon ion laser is used to pump a nonlinear beta barium borate (BBO) crystal to generate orthogonally polarized signal ($\lambda_s = 788.7$ nm) and idler ($\lambda_i = 632.8$ nm) photons, where λ_s and λ_i are the wavelengths of the signal and idler respectively. The detector D_2 is scanned on the transverse plane of the idler beam and the output pulses from both detectors are sent to coincidence counting circuit for joint detection. By recording the coincidence counts as a function of the transverse plane coordinates of the detector D_2 in the idler beam, the image of the double slit aperture is observed with a magnification factor of 0.26, even though the single counting rates at both detectors remain constant and it is reported in Fig. 2. The slit width and center-to-center distance between the slits of the double slit aperture are 1 mm and 2.75 mm respectively.

The observed field of view for this two-color ghost imaging case is 23.24o whereas the field of view for the above condition of one-color case is 20.00o. This means the field of view for the two-color case improves by a factor of 1.16 than that of the one-color case. A greater field of view under the enhanced resolving power of an imaging system is a useful and important feature in certain applications. For example, in the semiconductor industry, the feature sizes on microchips continue to shrink with each new generation of manufacturing equipment. That is why the need of sensor with higher resolving power and a larger field of view increases for the inspection purpose.

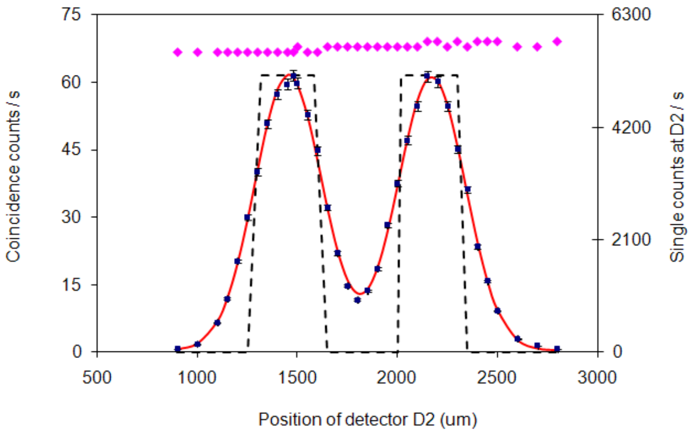

Fig. 2. Image of the double slit aperture in terms of coincidence counts as function of transverse plane coordinates of detector D_2. The pink color diamond and the blue color square on the figure represent the single counts per sec at detector D_2 and coincidence counts per sec respectively. The red line is the fitting for coincidence counts experimental data. The dashed line shows the image of the double slit in an ideal situation.

3. An Approach to Enhance the Angular Resolution in Space Imaging

There is another application of two-color ghost imaging under certain specific condition. The shorter wavelength provides better spatial resolution of imaging system. But in space the shorter wavelength have more chances to be absorbed in atmosphere. That creates the problem of enhancing angular resolution of imaging system in space. Under certain specific condition in which $d_1 \gg d_2$, the angular resolution limit is calculated as

$$\Delta\theta_{\min} = 1.22\frac{\lambda_i}{D}$$

where D is the diameter of the imaging system.

Under this condition, one can send the longer wavelength signal to the target to achieve better angular resolution limit with the shorter wavelength idler. This simple approach can be easily achieved in a space application. One may send the longer wavelength signal to the ground target from a space station and send the corresponding shorter wavelength idler to a satellite imaging system to record the image. This configuration is able to take advantage of sending the longer wavelength signal through the atmosphere to avoid absorption of shorter wavelengths in the atmosphere. However, it is also able to achieve a higher angular resolution with the shorter wavelength of the idler, propagated in the vacuum.

4. Conclusion

We have successfully performed optical imaging experiment with the help of a quantum-mechanical non- degenerate, two-color entangled source. The reported experiment is demonstrated here as a quantum mechanical two-photon geometrical effect for the non-degenerate, two-color case. From the fundamental point of view, the Einstein-Podolsky-Rosen (EPR) correlation [11] for the entangled signal-idler pair in the non-degenerate, two-color SPDC case is also demonstrated by this reported experiment and it is used to produce higher angular resolving power images that can be interpreted by a "two-photon modified Gaussian thin lens equation" [5]. By increasing the ratio of ωi /ωs , we can also improve the angular resolving power as well as the field of view. The reported features of two-color ghost imaging move forward the progress of the sensing as well as the imaging technologies.

References

[1] T. B. Pittman, Y. H. Shih, D. V. Strekalov, & A. V. Sergienko, *Phys. Rev. A* **52**: R3429 (1995).

[2] D.N. Klyshko, *Usp. Fiz.* **154**: 133 (1988); *Sov. Phys. Usp.* **31**: 74 (1988); *Phys. Lett. A* **132**: 299 (1988).

[3] Y. H. Shih, *IEEE J. of Selected Topics in Quantum Electronics* **9**: 1455 (2003).

[4] T. B. Pittman, D. V. Strekalov, D. N. Klyshko, M. H. Rubin, A. V. Sergienko, & Y. H. Shih, *Phys. Rev. A* **53**: 2804 (1996).

[5] M. H. Rubin & Y. H. Shih, *Phys. Rev. A* **78**: 033836 (2008).

[6] K. W. C. Chan, M. N. O'Sullivan, & R. W. Boyd, *Phys. Rev. A* **79**: 033808 (2009).

[7] A. N. Boto, P. Kok, D. S. Abrams, S. L. Braunstein, C. P. Williams & J. P. Dowling, *Phys. Rev. Lett.* **85**: 2733 (2000); M. D'Angelo, M. V. Chekova & Y. H. Shih, *Phys. Rev. Lett.* **87**: 013603 (2001).

[8] S. Karmakar & Y. H. Shih, *Phys. Rev. A* **81**: 033845 (2010).

[9] S. Karmakar & Y. H. Shih, *Proc. SPIE* **7702**: 770204 (2010).

[10] S. Karmakar & Y. H. Shih, in **Frontiers in Optics** (OSA Technical Digest CD, 2010), paper PDPC8.

[11] A. Einstein, B. Podolsky, & N. Rosen, *Phys. Rev.* **47**: 777 (1935).