Bessel-type interference patterns detected in single photon regime

R. Grunwald and M. Bock

Application Note

Introduction

- Many Interference experiments for proving the quantum mechanical nature of single photons are based on the well-known ***Young's double slit*** [1]. In this case, an attenuated spherical or plane wave passes through a multiple diffracting structure.
- In our novel approach, modified setups with beam-shaping axicons were utilized to study for the first time the quantum interference ***non diffracting*** beams [2].
- Single-photon statistics in space was analyzed with a high-resolution ***EMCCD camera*** of large quantum efficency.

Experimental techniques

Photon source:

- diode laser, 822.7 nm, 2.58 mW
- 10^{15} photons/0.05 s

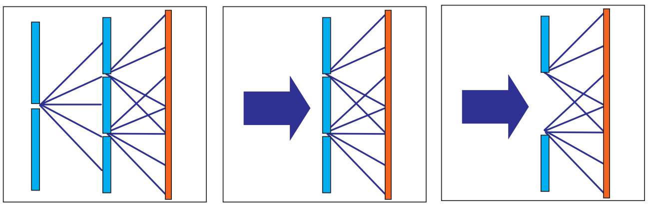
Attenuation:

- set of calibrated filters ($>10^{10}$)
- number of channels (10^6)
- intensity profile (up to 10)
- in total 10^{16}-10^{17}

Beam shaping element:

- thin film microaxicon array [3] (SiO_2 on silica, hexagonal Gaussian, 5.7 µm height)

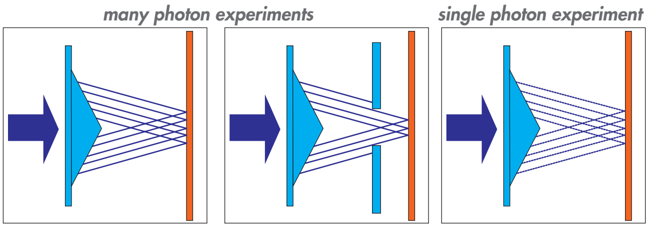
Modified Young-type setups – diffractive



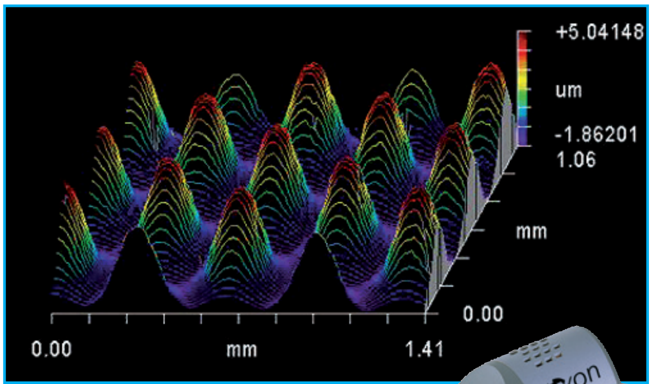
Young | double slit | rims

-non diffractive

many photon experiments | *single photon experiment*



Bessel beam | truncated Bessel beam | attenuated Bessel beam

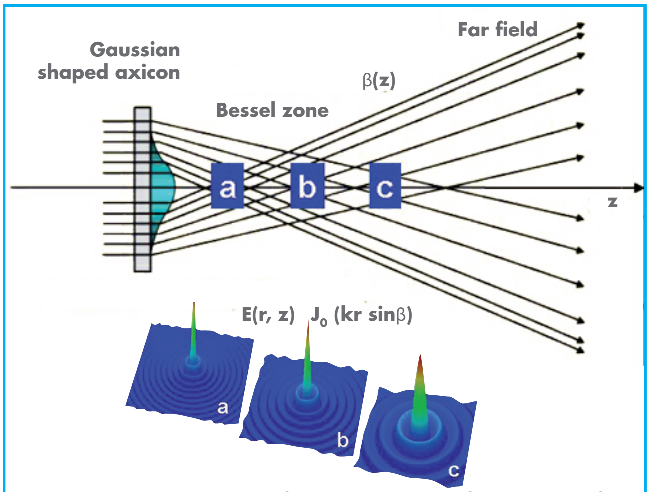


Microaxicon array

Detecting systems:

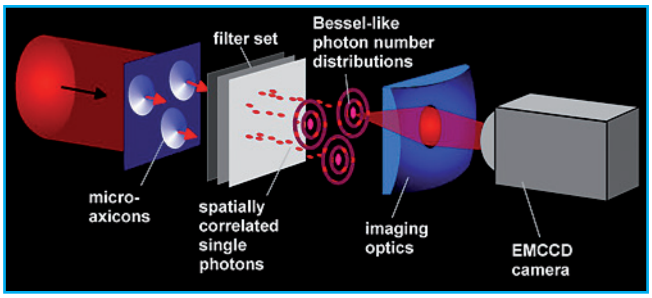
- EMCCD, iXon, Andor
- cooled (-70 °C)
- 1 MegaPixels
- quantum efficiency 0.43 @ 800 nm
- $>10^4$ grey levels
- accumulating mode
- minimum exposure time: 0.05s

Bessel-like beams



Physical approximation of Bessel beams by finite zones of quasi- non diffracting propagation [3].

Setup



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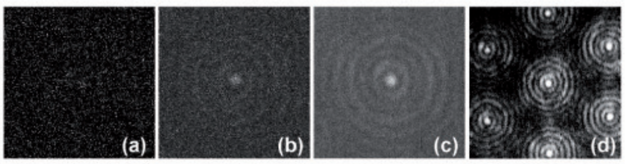
Experimental results

From Young-type interference experiments it is known that the angular distribution of diffracted quantum objects is determined by the complete double slit structure. This holds even in the case of spatio-temporally well-separated quanta (e.g. single photons). The phenomenon is interpreted as an interference of the quanta with themselves and as an expression of the statistical contribution of many possible pathways to the propagation of the quantum [1]. A more complex interference scenario is the generation of free-space interference patterns of Bessel-like structures (so-called diffraction-free or nondiffracting beams [2]) with axicons. In this case, propagation-invariant intensity distributions can be obtained over extended axial distances (pseudo-nondiffracting beams). Here we present a first experimental evidence for the generation of Bessel-like interference patterns with thin-film microaxicon arrays in single photon regime.

In the experiments, pseudo-nondiffracting Bessel-like intensity distributions were generated by refractive axicons at extremely weak illumination and detected by an electron multiplication CCD (EMCCD) camera (iXon, Andor) without an image intensifier. The light source was a cw diode laser (center wavelength 822.7 nm). The quantum efficiency of the camera in the spectral range of interest was about 0.43. The initial laser power (2.58 mW) corresponds to a photon number of 10^{15} within a time interval of 0.05 s. The camera was cooled down to -70 °C and operated at exposure times between 0.05 s and 0.2 s in accumulating mode integrating up to 100 acquisitions. With calibrated filters and a polarizer, attenuation factors of $>10^{-10}$ were obtained. The transmitted photons were spread over 1004x1002 pixels (8x8µm² area each) The dynamic range (14 bit) enabled to detect $> 10^4$ grey levels. At the chosen parameters, the setup worked in single photon regime in the most parts of the detector area.



Bessel-like interference fringes generated by an array of thin-film microaxicons (Gaussian shape, 5.7 µm, fused silica on silica, period 405 µm) in single photon regime. The light source (diode laser, wavelength 822.7 nm) was attenuated by filters. The EMCCD detector was operated in accumulating mode. The pictures correspond to an exposure time of (a) 0.2 s, (b) 10 s, and (c) 20 s (field of view 405 x 405 µm²). Picture (d) shows the hexagonal array structure of the beam for 7 selected sub-beams (period 405 µm).

Resulting patterns for different time windows are plotted in Figs 1a-c. The successive growth of Bessel-like interference fringes from noise can clearly be recognized without image processing. The beam array structure is shown in Fig. 1d (artificially overexposed).

The results of the interference experiment confirm the non-local quantum mechanical nature of single photon diffraction. In contrast to the Young's setup with a diffracting double slit, the interference from refracted beams was observed in the near-field instead of the far field. Because of their broader spectral transfer functions compared to diffractive configurations, axicon interferometers enable for experiments with polychromatic ultrashort pulses which are the subject of further investigations.

Conclusions

- The well-known fundamental statements of quantum theory about non-local photon propagation were well-confirmed by a modified Young-type interference experiment based on Bessel-like beams.
- The non diffracting nature of such beams was strongly indicated to hold even in the case of ultra low intensity.
- The spatially resolved photon statistics shows that single photons can be prepared to follow a diffraction-less path. Thus, they can be regarded to be "non diffracting single photons".

Outlook

- Single-photon characterization of few cycle wavepackets extends the quantum interference experiments to more complex spectral interference effects like X-pulses with multi-dimensional correlation information.
- The spatial correlation has to be combined with temporal auto correlation.

References

[1] R. Feynman, The Character of Physical Law (MIT, Boston, 1965), Chapter 6.
[2] J. Durnin, J. J. Miceli, and J. H. Eberly, "Diffraction-free beams," Phys. Rev. Lett. 58, 1499-1501 (1987).
[3] R. Grunwald, Thin film microoptics - new frontiers in spatio-temporal beam shaping, Elsevier, Amsterdam, 2007

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