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Quantum interference and diffraction of parametric down-converted biphotons

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Abstract. We present two-photon diffraction and interference experiments utilizing parametric down-converted photon pairs (biphotons) and a transmission grating. The biphoton exhibits a diffraction-interference pattern equivalent to an effective single particle with half wavelength of the constituent photons.

Keywords. Quantum interference; quantum lithography; parametric down-conversion.

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1. Introduction

Developments of micro-fabrication techniques of semiconductors depend on the improvement of spatial resolution in optical lithography. Recently, 'quantum lithography' using a multiphoton state has attracted much attention as a novel method to improve optical spatial resolution beyond the classical diffraction limit [1]. According to this proposal, the diffraction limit of a quantum N-photon state is better than that of a single photon by a factor of N. D'Angelo *et al* [2] demonstrated a Young's double-slit experiment utilizing parametric down-converted photons as a proof-of-principle of quantum lithography. Although the interferometric behavior of the multiphoton state can be explained by the standard quantum treatment of light, it is also interpreted as the characteristic of the 'photonic de Broglie wave' proposed by Jacobson and others [3,4].

In this report, we demonstrate a proof-of-principle experiment of quantum lithography utilizing spontaneous parametric down-converted photon pairs (biphotons) and a transmission grating, and show that the diffraction of the multiphoton state can be explained by the concept of the photonic de Broglie wave. We also discuss the diffraction-interference pattern of the biphotons in comparison with that of classical light.

2. The experiment

Figure 1 gives the schematic view of our experimental set-up. Pairs of frequency-degenerate photons were collinearly generated by spontaneous parametric down-conversion (SPDC) in a 5 mm long $KNbO_3$ (KN) crystal pumped by the second harmonic

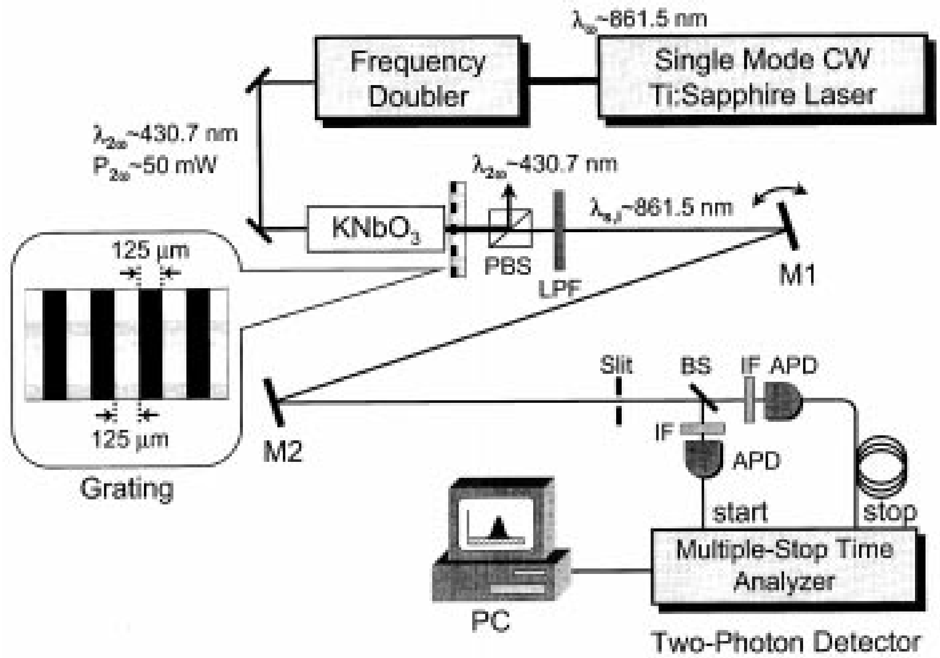

Figure 1. Schematic of the experimental set-up to observe the biphoton diffraction and interference. PBS: polarizing beamsplitter, LPF: long-pass filter, M1, M2: mirrors, BS: non-polarizing beam splitter, IF: interference filters, APD: avalanche photodiodes.

light of a single longitudinal mode Ti:sapphire laser operating at 861.5 nm. The photon pairs were diffracted by a transmission grating (slit width: 125 μm, period: 250 μm), placed just after the KN crystal. In this geometry, each photon pair passes together through one of the grating slits [2]. By rotating a mirror (M1), we recorded spatial diffraction-interference patterns at a two-photon detector consisting of two avalanche photodiodes (APDs) followed by a multiple-stop time analyzer. To measure the two-photon coincidence counting rate, we recorded the number of start-stop events from the two APDs within a certain time window (1 ns). We simultaneously recorded the number of start pulses as the one-photon counting rate. For comparison, we also observed diffraction-interference patterns of a chaotic light from a halogen lamp using the same apparatus.

3. Results and discussion

Figures 2 and 3 show the measured interference patterns of light from the SPDC and the halogen lamp, respectively. In both figures, the upper graphs (a) present the interference patterns taken by one-photon detection and the lower graphs (b) are those by two-photon detection. We note that the spectrum of the SPDC emission at the detectors is almost the same as that of the halogen lamp because we detected both emissions through the same interference filters (IF) in front of the detectors. However, the measured pattern of the

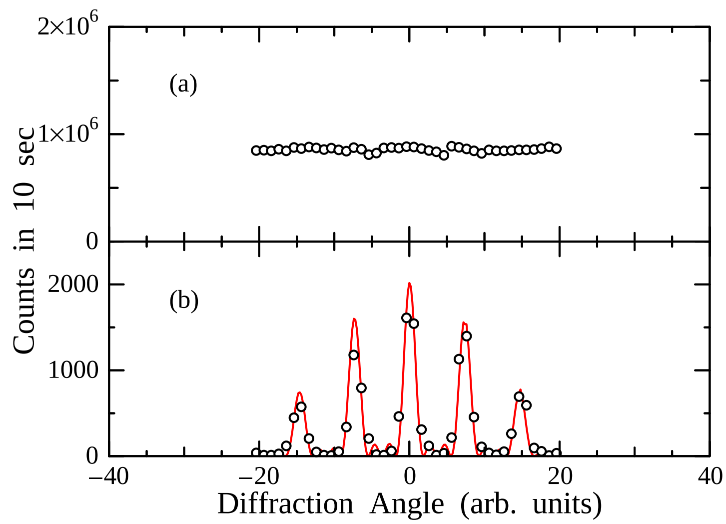

Figure 2. Diffraction-interference patterns of the parametric down-converted photons observed by (**a**) one-photon detection and (**b**) two-photon detection.

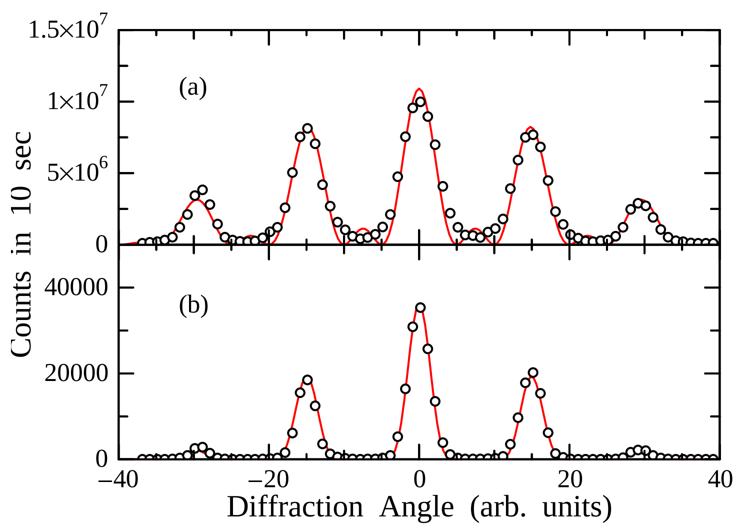

Figure 3. Diffraction-interference patterns of chaotic light from the tungsten lamp observed by (**a**) one-photon detection and (**b**) two-photon detection.

SPDC is quite different from that of the halogen lamp. The two-photon interference of the SPDC exhibits a half-modulation period compared to that of the halogen lamp. This result indicates that the biphotons generated by SPDC effectively behave as single particles with half the wavelength of the constituent photons. Our results demonstrate the proof-of-principle of quantum lithography that utilizes the multiphoton state to optical lithography beyond the classical diffraction limit [1].

It is also noteworthy that the one-photon detection of the SPDC exhibits no modulation of the interference pattern, whereas that of the halogen lamp exhibits the normal one-photon interference. The absence of the one-photon interference modulation of the SPDC can be explained only by the quantum-mechanical treatment assuming that each photon pair passes together through one of the grating slits. Thus, the one-photon interference also represents the non-classical nature of the parametric down-converted biphotons. More quantitative analysis of our results will be presented elsewhere.

4. Conclusions

In this report we presented the spatial diffraction-interference patterns of the biphotons generated by spontaneous parametric down-conversion, and showed that the biphotons exhibit half-modulation period compared to that of the classical light. Our results manifest the principle of quantum lithography and the concept of the photonic de Broglie wave of the biphoton. In addition, we showed that the one-photon interference of the biphotons exhibits no modulation. This result also represents the non-classical nature of the biphotons generated by spontaneous parametric down-conversion.

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