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Quantum entanglement with a Hermite-Gaussian pump

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ABSTRACT

Typically, a Gaussian mode is used to pump a non-linear crystal to produce pairs of entangled photons. We demonstrate orbital angular momentum (OAM) entanglement when a non-fundamental mode is used to pump a non-linear crystal. An approximation to an HG_{10} Hermite-Gaussian beam is produced by introducing a phase step into the transverse profile of the pump beam. We show both OAM and angular position correlations between the entangled pair of photons, by using two separate spatial light modulators to perform the measurements. The transfer of the OAM spectrum of the pump beam to the entangled photons is clearly illustrated and corresponds well with previous results demonstrating OAM conservation. This is the first step towards tailoring the entangled quantum states.

PUMP SHAPE AND SPDC

Spontaneous parametric down-conversion (SPDC) is a commonly used technique to generate pairs of entangled photons. Within SPDC, a pump beam is usually approximated as a plane wave incident on a nonlinear crystal, which results in the emission of two correlated photons in definite directions. Phase matching allows the amplitude and phase structure of the pump to be transferred to the two-photon field. The transfer of the plane-wave spectrum of the pump to the two-photon field leads to conservation of OAM in both stimulated and spontaneous parametric down-conversion. Thus, for near-collinear SPDC, the following selection rule,

$$m = \ell_A + \ell_B \tag{1}$$

holds, where $m\hbar$ is the OAM per photon of the pump beam and $\ell_A\hbar$ and $\ell_B\hbar$ are the OAM of the modes into which the pair of entangled photons are projected. The entangled two-photon state generated in this case is

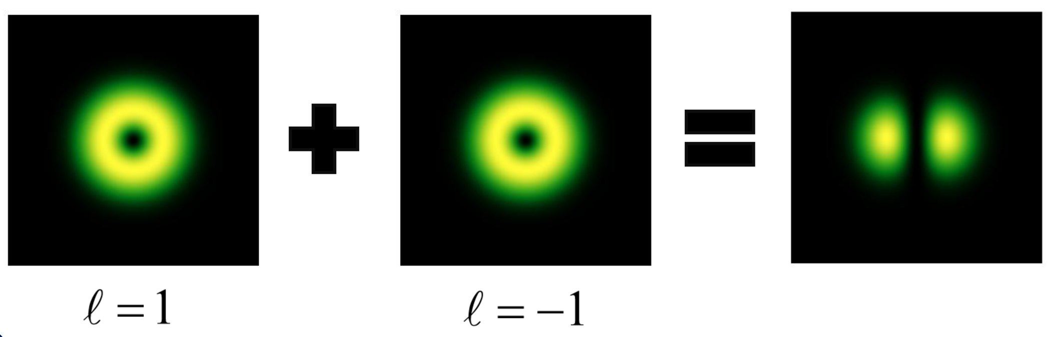
$$|\Psi\rangle = \sum_{\ell=-\infty}^{\infty} c_\ell |m-\ell\rangle|\ell\rangle, \tag{2}$$

where $|c_\ell|^2$ is the probability of finding one photon in state $|m-\ell\rangle$ and the other in state $|\ell\rangle$. The use of a cover slip introduces a π -phase shift to half of the area of the usual Gaussian output of a laser beam. This introduces a phase flip to one half of the beam, hence the name 'flipped mode'. This mode is composed of an infinite sum of odd HG modes, where the first order HG_{10} mode contributes 80% to the 'flipped mode'. Since the Laguerre-Gaussian (LG) modes form a convenient basis for OAM-carrying beams, the flipped mode can be decomposed into the LG modes, shown in Table 1.

ℓ	$\langle LG^{\ell,0} \| u_{f,0}\rangle$
± 5	$\frac{1}{8}\sqrt{\frac{3}{10\pi}} = 0.0386$
± 3	$\frac{-1}{2}\sqrt{\frac{1}{6\pi}} = -0.1151$
± 1	$\sqrt{\frac{1}{\pi}} = 0.5642$
0	0

Table.1: The "flipped mode" created by the cover slip is composed of only odd-value OAM states. The +/- 1 OAM modes contribute the most to the HG-like mode.

Fig.1: The superposition of two LG beams of $\ell = 1$ and $\ell = -1$, creates an HG beam of order 1.



EXPERIMENTAL SETUP

The OAM of a beam can be measured using a spatial light modulator (SLM), which alters the phase of the incoming beam depending on the encoded phase pattern. To measure OAM, each SLM displayed a hologram with a fork dislocation of order ℓ , shown in Fig. 2(a). Angular slits of width $\Delta\theta$ were used to measure angular position. The slits were orientated at positions ϕ_A and ϕ_B on SLMs A and B, respectively (see Fig. 2(b)).

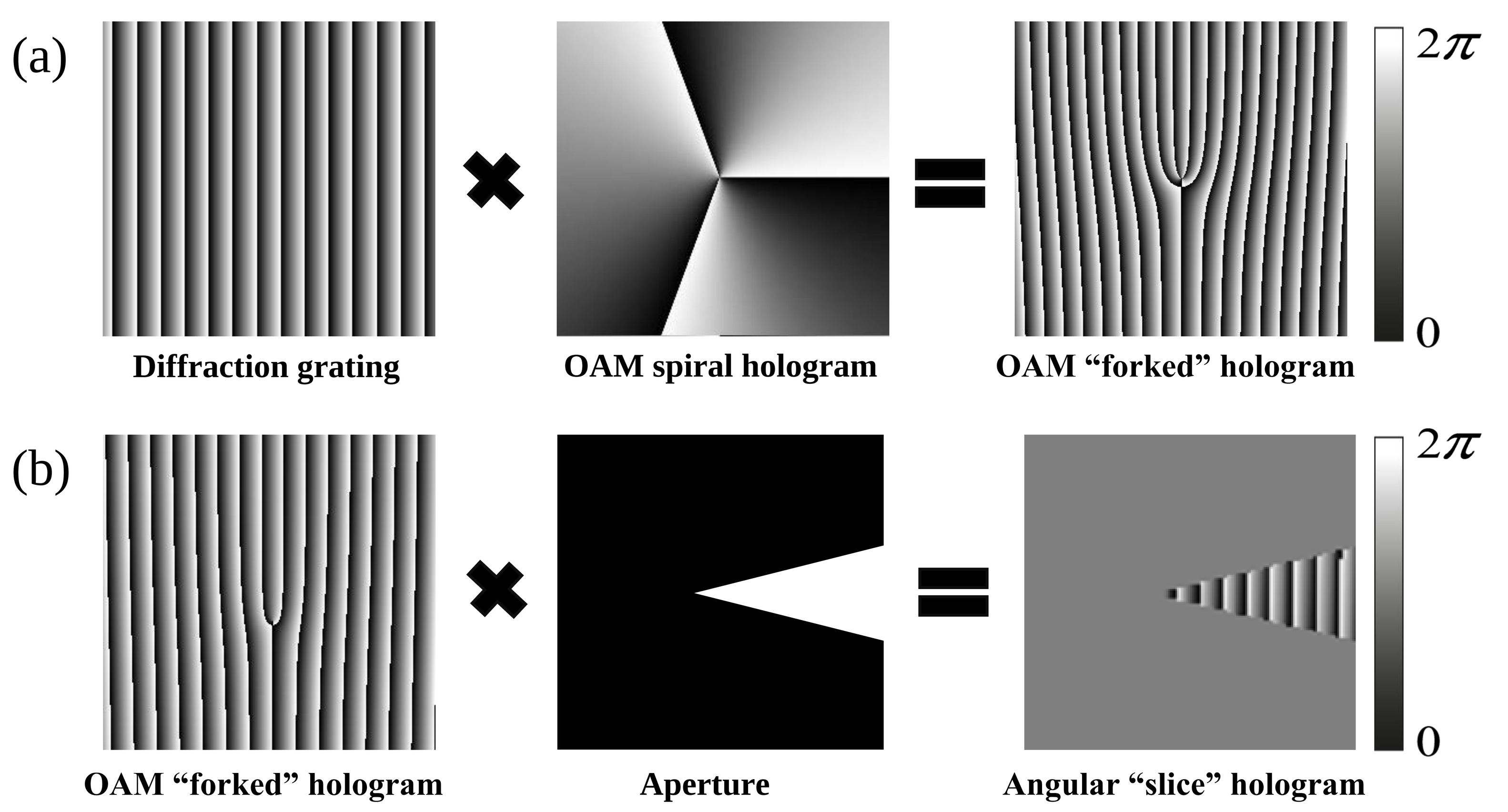


Fig.2: Spatial light modulators allow the phase of an incoming beam to be altered in a pre-determined manner. (a) The phase only component of an LG beam is created by multiplying a diffraction grating with a spiral phase pattern. This creates a "forked" hologram. (b) The angular position is measured by generating only a "slice" of the OAM hologram.

Figure 3 shows our experimental setup. A mode-locked UV laser at 355 nm was used to pump a 3 mm, type-I barium borate (BBO) crystal to produce pairs of collinear, degenerate entangled photons. A cover slip, placed on a tip-tilt mount, was placed in the path of the pump beam before the BBO crystal. The cover slip was inserted into half of the pump beam so as to generate the HG-like mode. The front plane of the crystal was imaged using lenses L1 (f1 = 200 mm) and L2 (f2 = 400 mm) onto the two separate SLMs, where the state into which each photon was projected, is specified. Each SLM plane was then imaged to the inputs of the single-mode fibres (SMFs) using L3 (f3 = 600 mm) and L4 (f4 = 3.2 mm). The single photons were detected using avalanche photo-diodes and then connected to a coincidence counter.

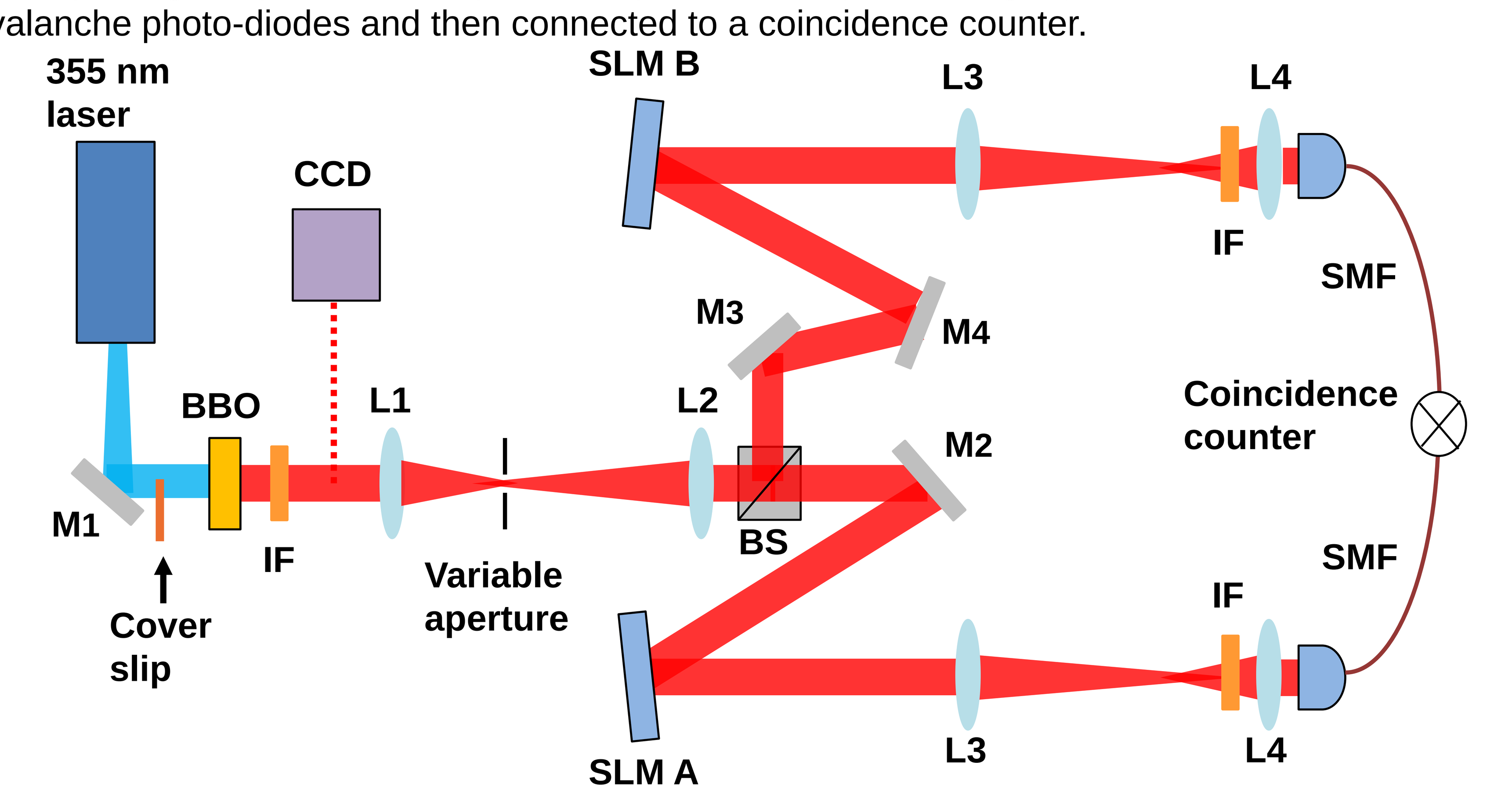


Fig.3: Experimental setup for SPDC. A π-phase shift is introduced by placing a cover slip into the pump beam before the BBO crystal. The OAM and angular position of the down-converted photons are measured by encoding onto the SLMs a forked diffraction grating or angular slit, respectively.

EXPERIMENTAL RESULTS

The pump beam consisted of superpositions of odd-valued OAM states, with $|1\rangle$ and $|-1\rangle$ making the largest contribution. Hence following the selection rule in Eq. (1), we expect high coincidences when the sum of ℓ_A and ℓ_B is 1, as shown in Fig. 4(a). We expect two diagonals symmetric about the main diagonal, in contrast to SPDC with a fundamental Gaussian pump (see Fig. 4(c)) wherein there is only one main diagonal. Figure 4(b) show the coincidences, as a function of ℓ_A and ℓ_B that we obtained from the experiment.

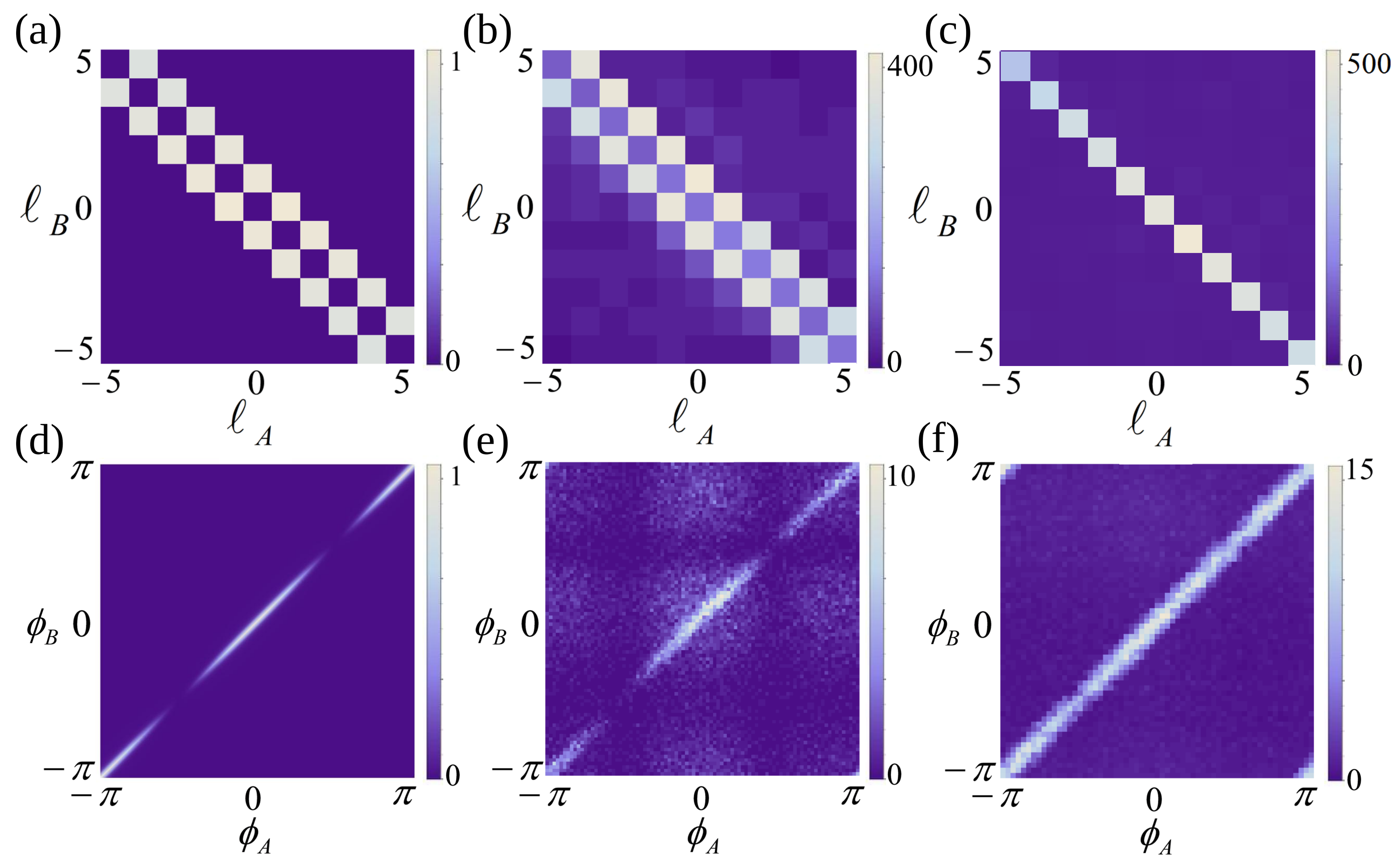


Fig. 4: OAM and angular position correlations. Theoretical predictions of the (a) OAM correlations and (d) angular position correlations for a 'phase-flipped' pump mode. Experimental measurements recorded for a 'phase-flipped' pump mode of the OAM and angular position correlations are shown in (b) and (e), respectively. A comparison of the correlations can be made to a Gaussian pump mode, shown in (c) and (f).

The expected angular position correlations are obtained from the Fourier relationship between OAM and angular position, by performing a Fourier transform on Fig. 4(a), we obtain Fig. 4(d). Because the SLMs are in the image plane of the crystal, we expect the coincidences to be high for $\phi_A = \phi_B$. In addition, due to the shape of the pump, we see a modulation wherein there are coincidence minima corresponding to the case when the slit is aligned with the phase discontinuity in the pump. Figure 4(e) shows the coincidence count rate as a function of the angular positions, ϕ_A and ϕ_B . Figure 4(f) illustrates the difference in angular position correlations when using a Gaussian pump mode.

Manipulation of the pump mode allows for possible engineering of the quantum states generated in SPDC.

REFERENCES

[1] J. Romero, D. Giovannini, M. McLaren, E.J. Galvez, A. Forbes, M.J. Padgett, "Orbital angular momentum correlations with a phase-flipped Gaussian mode pump beam". *J. Opt.*, **14**, 085401.