Conservation of Orbital Angular Momentum in Stimulated Down-Conversion

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We report on an experiment demonstrating the conservation of orbital angular momentum in stimulated down-conversion. The orbital angular momentum is not transferred to the individual beams of the spontaneous down-conversion, but it is conserved when twin photons are taken individually. We observe the conservation law for an individual beam of the down-conversion through cavity-free stimulated emission.

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The cavity-free stimulated parametric down-conversion was first studied by Mandel and co-workers [1] and more recently it has been explored by other authors [2,3]. One important aspect of this process is its connection with the spontaneous parametric down-conversion, where entangled states for two photons can be easily prepared. Signals obtained in stimulated down-conversion are much larger than those obtained in the spontaneous process and carries information about the details of the parametric interaction, like phase matching conditions. This information is preserved thanks to the stimulation without optical cavities, where the optical mode properties are determined mainly by the cavity configuration. Therefore, studying stimulated down-conversion is useful for understanding entanglement properties of the twin photons from the parametric down-conversion. We have recently demonstrated the transfer of coherence and images from the pump and auxiliary lasers to the stimulated down-conversion field [3] in direct connection with the analogous process in the context of the quantum formalism, observed in coincidence measurements [4].

The possibility of preparing entangled photons in different degrees of freedom, has also become subject of interest. Particularly, the orbital angular momentum (OAM) of the light, has been studied in the context of the classical [5] and quantum optics [6]. Conservation of OAM in the up-conversion process [4], optical pumping of cold atoms [9] and quantum entanglement [10] have been observed experimentally for this degree of freedom. However, in the spontaneous parametric down-conversion process, the OAM is not transferred from the pump to each individual signal or idler beam [11]. This is a consequence of the fact that signal and idler beams are incoherent when taken individually [12].

In this work, we observe experimentally the manifestation of the conservation law for the OAM in the stimulated down-conversion process, for the idler beam. In this case, besides the pump, a second auxiliary laser is aligned with one of the down-conversion modes inducing emission. Conservation of the topological charge, can be written as $m_p = m_s + m_i$, where p,s,i stands for pump, signal and idler respectively.

Light beams with OAM can be described by Laguerre-Gauss $LG_{l,m}$ modes, where $l$ and $m$ are azimuthal and radial mode numbers, and the OAM is given by $ml$ per photon. In our experiment, $LG_{0,1}$ modes are produced by diffraction on computer generated holograms as in Ref. [13], for example. The identification of the modes, was made in our experiment by the passage of each beam through a Michelson interferometer, operating with a small misalignment [13]. The resulting interference pattern shows the sign and the absolute value of the topological charge in the mode. This method is very simple and presents some advantages compared to other most common ones, where a coherent reference field is needed, or where a Dove prism is inserted inside a Mach-Zhender interferometer.

The spatial intensity distribution of the idler beam in the stimulated down-conversion for thin crystals can be predicted by Eq. 10 of Ref. [4]. Special cases, where spontaneous emission is negligible and the transverse amplitude of one of the laser fields can be considered constant, result in Eqs. 2 and 3 of Ref. [3]. From these equations it is seen that the intensity profile of the idler beam will look like a doughnut if the pump or the auxiliary laser is prepared in a $LG_{0,m}(m \neq 0)$ mode. This is indeed an indication that the idler beam is also a $LG_{0,m}$ mode, but rigorously this is not enough. In Refs. [13], the quantum treatment used has shown to be useful in describing the stimulated down-conversion process and it would be interesting to derive the state of the idler field when either the pump or the auxiliary laser is prepared in LG modes, within the same formalism. However, this calculation is not straightforward and it is beyond the scope of the present work. In the following, we will present experimental results supporting the predictions in Ref. [4] concerning the intensity distributions and supporting the intuition that if the idler presents a doughnut shape it “should” posses some OAM.

The experimental set-up is sketched in Fig. 1. A He-Cd laser pumps a BBO non-linear crystal 3nm long, with a c.w. 442 nm wavelength beam. Non-degenerate twin beams with signal and idler wavelengths around 845nm and 925nm respectively, are generated. An auxiliary...
beam is obtained from a diode laser oscillating around 845nm. It is aligned with the signal beam, so that their modes have good overlap and emission is stimulated in this down-conversion mode by the laser. As a result, the idler beam is completely changed with respect to its intensity and spectral properties, as described in Refs. [1–5]. The goal of the experiment is to prepare the pump beam in a LG_{0,1} mode and to measure the OAM of the idler beam. The same procedure is repeated preparing the auxiliary beam in a LG_{0,1} mode and measuring the OAM of the idler beam. The idler beam is directed onto a Michelson interferometer, before it is detected by an avalanche photodiode single photon counting module. The Michelson interferometer is slightly misaligned along the horizontal axis, so that for a plane wave input, the resulting interference pattern presents vertical parallel stripes. The larger the misalignment, the narrower the stripes. When a LG_{0,m} (m ≠ 0) mode enters the interferometer, the beam with doughnut shape is divided in two and the misalignment works to make the side of one beam interfere with the center of the other and vice-versa. Two opposed bifurcations appear in the interference pattern. The orientation of the bifurcations are related to the sign of the topological charge, or the sense of rotation of the phase in the transverse plane and the number of derivations in the fork is related to the absolute value of the charge.

The pump beam was prepared in a LG mode with m_p=+1. After crossing the crystal, the beam is directed to a Michelson interferometer, in the same fashion as described above for the idler, in order to be able to compare the interference patterns for pump and idler. All interference patterns are measured by scanning the detector in the transverse plane. The resulting matrix with the intensities at different positions is converted into a grey scale bitmap where the higher intensities are white and the lower ones are black. The interference pattern measured for the pump beam is shown in Fig. 2. The two forks would be oriented along the vertical axis if the misalignment were only in the horizontal direction. Due to a small vertical misalignment, the forks are oriented along an axis making an angle with the vertical direction. From the orientation of the forks it is possible to identify the topological charge, m_p=+1. As a consequence of the OAM conservation, when the pump is prepared with m_p=+1 and the auxiliary laser with m_s=0, the idler must have m_i=+1. On the other hand, when the auxiliary laser is prepared with m_i=+1 and the pump with m_p=0, the idler must have m_i=-1.

The idler beam obtained in the stimulated down-conversion is then analyzed with the Michelson interferometer in the same way as described above for the pump. Pump and auxiliary laser powers are high enough to ensure that the spontaneous emission is negligible compared to the stimulated one. As a result, when either the pump or the auxiliary laser is prepared in a LG_{0,m} (m ≠ 0) mode, the idler beam also propagates as a LG_{0,m} (m ≠ 0) mode and its intensity distribution looks like a doughnut. Idler intensity distributions are shown in Fig. 3, when a) m_p=+1 and m_s=0 and b) m_p=0 and m_s=+1. In Fig. 3 we have the interference patterns, again for a) m_p=+1 and m_s=0, and b) m_p=0 and m_s=+1, where the upper plots correspond to theoretical simulations and the lower ones correspond to the experimental results for the idler beam. Note that the orientation of the forks of the idler in a) (m_i=+1) is inverted (mirror image) when compared to the idler in b) (m_i=-1).

In the results presented above, the OAM was actually transferred from the pump and auxiliary lasers to the stimulated idler beam. When the OAM comes from the pump with m_p=+1, the idler is changed into a m_i=+1 LG_{0,1} mode. When the OAM comes from the auxiliary lasers with m_s=+1, the idler is changed into a m_i=-1 LG_{0,-1} mode. This is compatible with the conservation of the total topological charge m_i = m_s + m_i. Since pump, signal and idler beams are not collinear, the conservation of the OAM requires that part of the momentum is absorbed by the crystal. The relation, m_i = - m_s when m_p = 0, can be understood in terms of the phase conjugation of the idler in comparison with the auxiliary laser, as a LG beam with m=-1 looks like a LG beam with m=-1 propagating backwards.

In conclusion, we have observed experimentally the transfer of orbital angular momentum from the pump and auxiliary lasers to the stimulated parametric down-conversion idler beam. This transfer implies in the conservation of the topological charge. For concluding that the orbital angular momentum vector is conserved it is necessary the crystal absorbing part of the momentum, since pump, signal and idler beams are not collinear.

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The interference pattern for the pump beam can be easily controlled, so that we have intentionally introduced a small vertical misalignment in order to demonstrate its effect. For the idler beam it is harder to control as it is a weak infra-red beam.

FIG. 1. Sketch of the experiment. P is the pump beam, A is the auxiliary beam, L is the lens, C is the nonlinear crystal, M is a diffraction mask. a) The pump beam is prepared in the LG$_{0,1}$ mode $m_p=+1$ and b) The auxiliary beam is prepared in the LG$_{0,1}$ mode $m_s=+1$.

FIG. 2. Gray scale bitmap plotted from a 30x30 matrix with the transverse interference pattern of the pump beam. a) Pump LG$_{0,1}$ mode $m_p=+1$ and b) Auxiliary LG$_{0,1}$ mode $m_s=+1$.

FIG. 3. Gray scale bitmap plotted from a 20x20 matrix with the transverse intensity of the idler beam. a) Pump LG$_{0,1}$ mode $m_p=+1$ and b) Auxiliary LG$_{0,1}$ mode $m_s=+1$.

FIG. 4. Gray scale bitmap plotted from a 20x20 matrix with the transverse interference pattern of the idler beam. a) Pump LG$_{0,1}$ mode $m_p=+1$. Theoretical simulation (top), experimental result (bottom). b) Auxiliary LG$_{0,1}$ mode $m_s=+1$. Theoretical simulation (top), experimental result (bottom).