Conservation of orbital angular momentum in stimulated down-conversion

D. P. Caetano [1]***, M. P. Almeida***[1]***, P. H. Souto Ribeiro***[1]***, J. A. O. Huguenin***[2]***, B. Coutinho dos Santos***[2]
and A. Z. Khoury[2]

[1]**Instituto de Física, Universidade Federal do Rio de Janeiro, CP 68528, Rio de Janeiro, RJ 21945-970, Brazil**
[2]**Instituto de Física, Universidade Federal Fluminense, BR-24210-340 Niterói, RJ, Brazil**
dilson@if.ufrj.br

Abstract

We report on an experiment demonstrating the conservation of the orbital angular momentum in stimulated down-conversion. It has been demonstrated that the orbital angular momentum is not transferred to the individual beams of the spontaneous down-conversion. It is also known that 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.

Introduction

The cavity-free stimulated down-conversion, studied by Mandel and co-workers[1], has been subject of interest of others authors[2-4]. Signals obtained in stimulated parametric down-conversion are much larger than those obtained in the spontaneous process and carries information about the details of the parametric interaction. This allows us to use the stimulated parametric down-conversion as a useful tool for understanding the entanglement properties of the twin photons from the parametric down-conversion. We have recently demonstrated the transfer of the angular spectrum and images from the pump and auxiliary lasers to the stimulated down-conversion field[4] in direct connection with the analogous process in the context of the quantum correlations observed in coincidence measurements[5].

The possibility of preparing twin photons entangled in different degrees of freedom has also become subject of interest, in particular, the orbital angular momentum (OAM). Conservation of OAM in the up-conversion process[6], optical pumping of cold atoms[7] and quantum entanglement[8] 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[9]. This is a consequence of the fact that signal and idler beams are incoherent when considered individually[10].

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 process, besides the pump, a second auxiliary laser is aligned with one of the down-conversion modes, inducing emission. Our results demonstrate conservation of the topological charge, which can be written as $m_p = m_s + m_i$, where p,s,i stands for pump, signal and idler respectively.

Orbital angular Momentum in Stimulated Down-Conversion

Light beams with OAM are described by Laguerre-Gauss $LG_{l,m}$ modes, where l and m are radial and azimuthal mode numbers. The angular momentum of the beam is given by $m\hbar$ per photon[9]. Therefore, the conservation of topological charge may be read as a statement of OAM conservation. In our experiment, $LG_{0,1}$ modes are produced by diffraction on computer generated holograms as in Ref[11], 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[11]. 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.

From the theory developed in Ref. [3] the spatial intensity distribution of the idler beam in the stimulated down-conversion for thin crystals is given by:

$$I(r_i) = |C|^2 \left\{ \int d\rho \left|W_p(\rho)\right|^2 + \left| \int d\rho W_p(\rho) W_s^*(\rho) \exp\left[i \left|\rho_i - \rho\right|^2 \frac{k_i}{2z} \right] \right|^2 \right\} \tag{1}$$

For special cases, where spontaneous emission is negligible and the transverse amplitude of one of the laser fields can be considered constant, the intensity profile of the idler beam is given by:

$$I(r_i) \propto \left| \int d\rho W_p(\rho) \exp\left[i|\rho_i - \rho|^2 \frac{k_i}{2z} \right] \right|^2 \qquad \text{;auxiliary constant, (2)}$$

$$I(r_i) \propto \left| \int d\rho W_s^*(\rho) \exp\left[i|\rho_i - \rho|^2 \frac{k_i}{2z} \right] \right|^2 \qquad \text{; pump constant. (3)}$$

It shows that if the pump or the auxiliary laser is prepared in a $LG_{0,m}(m)$ mode the intensity profile of the idler beam will look like a doughnut. This is indeed an indication that the idler beam is also a $LG_{0,m}$ mode, but rigorously speaking, is not sufficient. In Refs. [3,4], 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 the pump or the auxiliary laser is prepared in LG modes, within the same formalism, ut it is not done here.

Experiment

The experimental set-up is sketched in Fig. 1. A 200mW He-Cd laser pumps a type II, 3mm long BBO non-linear crystal, with a c.w. 442 nm wavelength beam. Non-degenerate twin beams are generated with signal and idler wavelengths around 845nm and 925nm, respectively. An auxiliary beam is obtained from a diode laser oscillating around 845nm. The diode laser power is about 150mW. 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. [1-4]. 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 $LG_{0,m}$ ($m\neq 0$) 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 is related to the sign of the topological charge and the number of derivations in the fork is related to the absolute value of the charge. For example, the fork on the left pointing up and fork on the right pointing down means that the topological charge is negative. A rotation of the pattern does not change this configuration, only a reflection would change it, but a reflection implies in changing the sense of propagation. Those are signatures of the LG mode, which can be easily identified by comparing the measured interference patterns with calculated ones.

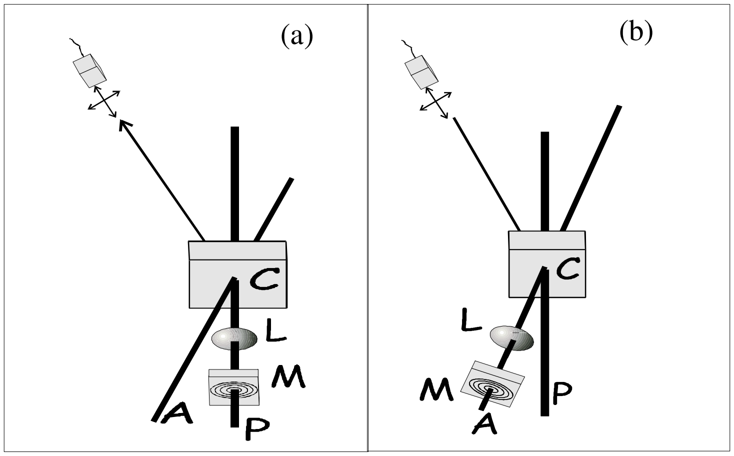

Figure 1: Schematic representation of the experiment. P is the pump beam, A is the auxiliary beam, L is the lens, C is the nonlinear crystal, M is a diffraction mask. a) The pump beam is prepared in the $LG_{0,1}$ mode. b) The auxiliary beam is prepared in the $LG_{0,1}$ mode.

Results and Discussions

Firstly the pump beam is prepared in a $LG_{0,1}$ mode, Fig. 1a. Auxiliary laser power is high enough to ensure that the spontaneous emission is negligible compared to the stimulated one (signal to noise ratio is about 300). As a result the idler beam propagates as a $LG_{0,1}$ mode and its intensity distribution looks like a doughnut, Fig. 2a. The idler beam is then analyzed with the Michelson interferometer as described in the previous section. In Fig. 3a we show the interference pattern, where the upper plot correspond to a theoretical simulation. In a second step, the auxiliary beam is prepared in a $LG_{0,1}$ mode, Fig. 1b. The results are showed in Fig 2b and Fig 3b, for intensity distribution and interference pattern, respectively, of the idler beam. Note that the orientation of the forks of the idler in Fig. 3a (m_i=+1) is inverted (mirror image) when compared to the idler in Fig. 3b (m_i= -1).

The interference patterns in Fig. 3 have a rather low visibility. Even though the spontaneous emission is negligible in our experiment, we still have some sources of noise, as the residual light background in the room and the dark counting rate of the APD detector, because the final intensities detected are very low. The data acquisition takes a rather long time(about one hour) and small drifts of the phase difference may take place in the interferometer. The most important point is, however, the fact that the stimulated emission only gives rise to coherent light. In this case, if the OAM transfer was not complete, other coherent modes would be present and interference between them would be detected in the intensity patterns of Fig. 2a and Fig. 2b. Therefore, the OAM transfer and conservation is guaranteed by both the intensity profiles of Fig. 2 and interference fringes of Fig. 3.

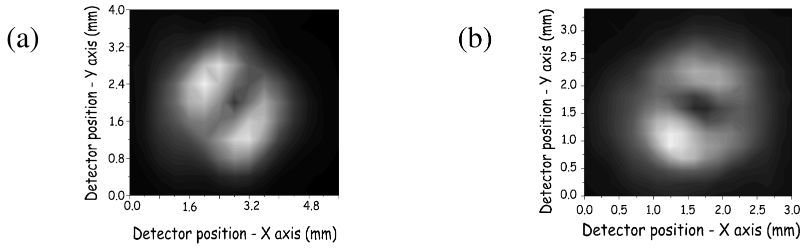

Figure 2: Gray scale bitmap plotted from a 20x20 matrix with the transverse intensity of the idler beam. a)Pump $LG_{0,1}$ mode m_p=+1 and b)Auxiliary $LG_{0,1}$ mode m_s=+1

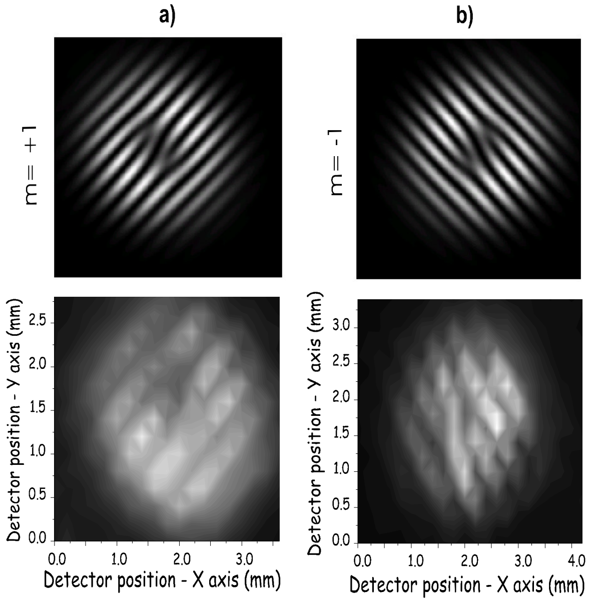

Figure3: Gray scale bitmap plotted from a 20x20 matrix with the transverse interference pattern of the idler beam. a)Pump $LG_{0,1}$ mode m_p=+1. Theoretical simulation (top), experimental result(bottom). b)Auxiliary $LG_{0,1}$ mode m_s=+1. Theoretical simulation (top), experimental result(bottom).

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 laser 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 $m_p = m_s + m_i$. 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[5], as a LG beam with m=+1 looks like a LG beam with m= -1 propagating backwards.

Conclusions

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.

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