# Demonstration of orbital angular momentum conservation in coherent Four-Wave mixing in cold atoms

***S. Barreiro and J. W. R. Tabosa***

**Departamento de Física, Universidad Federal de Pernambuco, 50670-901 Recife, PE, Brasil**

*Sergio@df.ufpe.br*

## Abstract

We report on the generation of light carrying orbital angular momentum through Bragg diffraction into an electromagnetically induced coherence grating in a degenerate two-level system of cold cesium atoms, demonstrating the conservation the conservation of orbital angular momentum of light in a coherent four-wave mixing process. The induced Zeeman coherence grating is shown to contain the spatial phase structure of the incident beams. The exchange of phase information between a light beam with orbital angular momentum and a long-lived atomic coherence opens up the way to process quantum process information encoded in a multidimensional state space.

## Introduction

Laguerre-Gaussian (LG) laser mode possesses well defined orbital angular momentum (OAM) [1]. These beams posses wave-front screw dislocations or vortices to which are associated a topological charge, specified by an integer number m, determining the accumulated phase change, in units of $2\pi$, in a closed circuit around the dislocation center. The OAM per photon, along the direction of propagation , of such laser beam is given by $m\hbar$. Several nonlinear optical processes have been investigated using LG modes and, in particular, conservation of OAM was experimentally demonstrated in a number of different processes including second harmonic generation [2] and spontaneous and stimulated down-conversion [3,4].

Recently it was predicted theoretically [3] and experimentally observed [5] that the spontaneous parametric down-conversion produces pairs of twin photons entangled in OAM states. The possibility of encoding quantum information in a multi-dimensional state space [6] presents actually a considerable interest. On the other hand, the capability to perform quantum information processing is strongly conditioned to the possibility of reversibly store a quantum state of light in a long-lived coherence.

In this work, we report the first experimental observation of the generation of a coherent beam of light carrying OAM [7], obtained by real time Bragg diffraction into a induced Zeeman coherence grating in cold cesium atoms, and direct evidence of the conservation of the orbital angular momentum of light is demonstrated.

## Experimental Setup

We employ the standard four-wave mixing (FWM) configuration where the forward (F) and the backward (B) pump beams have the same linear polarization and the same fixed frequency $\omega$, while the signal beam (S) has a linear polarization orthogonal to that of the pump beams and a variable frequency $\omega-\delta$. The pump frequency is red-detuned by about $\Delta$=12 MHz with respect to resonance frequency of the closed transition $6S_{1/2}$, $F=4 - 6P_{3/2}$, $F'=5$ *of* the cesium $D_2$ line, as indicated in Fig.1-(a). The simplified experimental scheme is shown in Fig.1-(c). Light from a stabilized Ti:Sapphire laser is used for magneto-optically trap (MOT) the atoms, to produce the pump beams and, after having its frequency shifted by $\delta$ by a pair of acousto-optic modulators, to inject a diode laser. Simgle and double topological charge beam were generated by passing the diode laser output beam through two different computed-generated spiral Fresnel zone-plate mask. The signal beam carrying the topological charge is focused onto the MOT forming a small angle with the pump beams. In Fig.1-(b) we show the subnatural FWM spectrum (200KHz) of the generated signal, recorded within a time interval of 1ms during which the MOT beams and the quadrupole magnetic field are switched off according to the time sequence shown in the inset of Fig.1-(c).

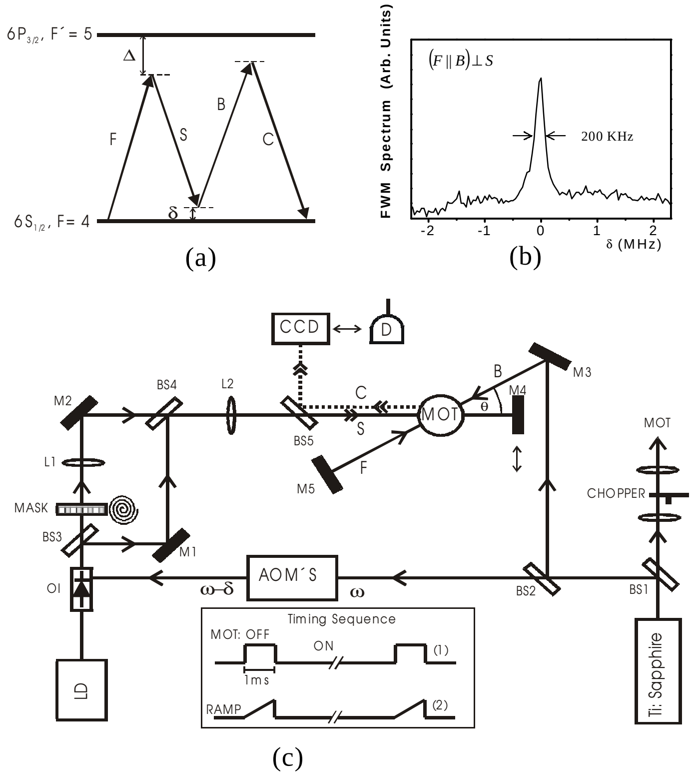


**Figure 1:** . (a) Cesium transition used to investigate the nearly degenerate FWM process. The arrows represent the photons absorbed and emitted in this parametric process. (b) FWM spectrum. (c) Experimental setup

## Results and Discussions

As mensioned observed FWM spectrum presents a subnatural linewidth, reveling that the generated phase-conjugate beam originates from a long-lived ground state coherence.

To analyze the spatial profiles of the generated and incident signal beams, we use a CCD camera and a retroreflection of the signal beam by the auxiliary mirror (M4). The corresponding profiles for simple topological charge are shown respectively in Fig.2-(a) and -(b). The topological charge of both the incident and the generated beams are analyzed with the use an auxiliary reference Gaussian beam which is also focused into the MOT region and, via the same FWM process, generates a synchronized reference wave copropagating with the generated beam C. The corresponding interferograms are shown respectively in Fig2.-(c) and -(d), from where we conclude that the beams S and C have topological charge with the same magnitude and sign. Therefore, since they propagate in opposite directions, they should carry opposite OAM, thus demonstrating the conservation of OAM within the light modes involved in this process. Similar results were obtained for a double charge signal beam, and the corresponding results are shown in the fig3.

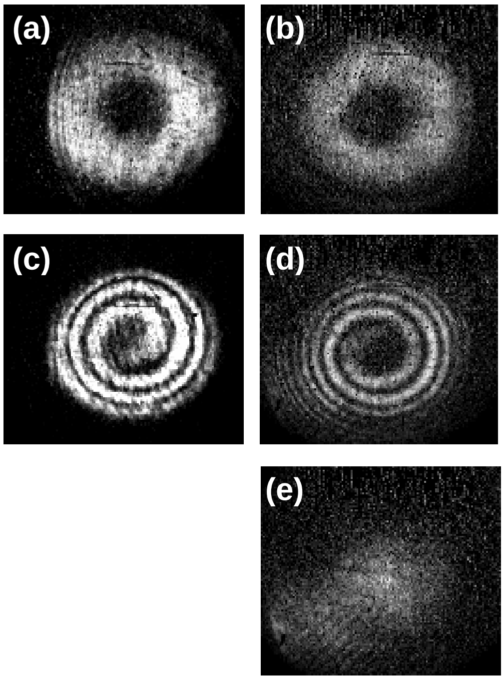


**Figure 2:** Observed light spatial distribution and interference pattern for the single charge signal beam S: (a) and (c); and for the generated phase conjugate beam C: (b) and (d). The interferograms are obtained using, respectively, the reflected incident reference wave by the auxiliary mirror M4 and the corresponding generated reference wave (whose profile is shown in (-e)).

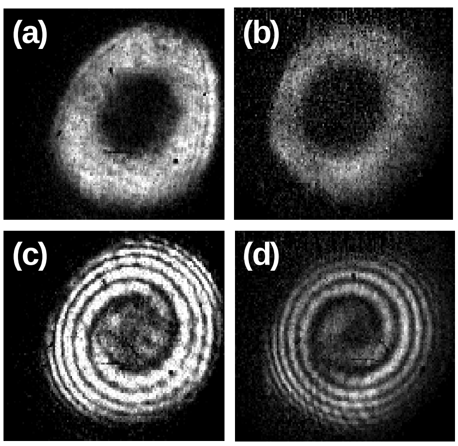

**Figure 3:** Observed light spatial distribution and interference pattern for the signal beam: (a) and (c); and for the generated phase-conjugate beam: (b) and (d).

## Conclusions

We have experimentally demonstrated the generation of a coherent beam of light carrying OAM via Bragg diffraction into an induced coherence grating, which is shown to contain the phase information of the incident beam. The observed results lead to the clear demonstration of the conservation of OAM of the light interacting coherently with an atomic system. We consider that our results present a first step towards the possibility of storage of quantum information encoded in a multi-dimensional state space and we believe it will be of considerable interest in the field of quantum information processing.

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