Generation of Light Carrying Orbital Angular Momentum via Induced Coherence Grating in Cold Atoms

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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. 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 information encoded in a multidimensional state space.

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Since the first theoretical demonstration by Allen *et al.* [1] that a Laguerre-Gaussian (LG) laser mode possesses well-defined orbital angular momentum (OAM), the past decade has witnessed a increasing interest in the investigation of light-matter interaction associated with laser beams carrying OAM [2]. These beams possess 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 2π, in a closed circuit around the dislocation center. The OAM per photon, along the direction of propagation, of such a laser beam is given by $m\hbar$. The mechanical effect associated with LG beams was early observed through the transfer of OAM to trapped macroscopic particles [3,4]. Also, the predicted rotational Doppler shift directly related to their twisted wave fronts was observed in different situations and domains [5], as well as their reversal of phase [6]. Several nonlinear optical processes have been investigated using LG beams and, in particular, conservation of OAM was experimentally demonstrated in a number of different processes including second harmonic generation [7] and spontaneous and stimulated down-conversion [8,9]. In a previous Letter, we have also demonstrated the optical pumping of OAM of light in cold cesium atoms [10]. Recently, it was predicted theoretically [11] and experimentally observed [8] that the spontaneous parametric down-conversion produces pairs of twin photons entangled in OAM states. The possibility of encoding quantum information in a multidimensional state space, as the one spanned by the spatial modes of the electromagnetic field carrying OAM, presents indeed a considerable actual interest owing to the more efficient performance in processing quantum computation and quantum cryptography [12,13]. Within this perspective, recent works have engineered clever experimental techniques to measure the OAM of a single photon [14] and theoretically investigated schemes to prepare photons in multidimensional vector states of OAM [15]. On the other hand, the capability to perform quantum information processing is strongly conditioned to the possibility of reversibly storing a quantum state of light in a long-lived atomic coherence, and several groups have already addressed this problem through the demonstration of the storage of classical coherent optical information in an atomic medium [16,17], employing the phenomenon of electromagnetically induced transparence [18].

In this Letter, we report the first experimental observation of the generation of a coherent beam of light carrying OAM, obtained by real time Bragg diffraction into an induced coherence grating in the Zeeman sublevels of a degenerate two-level system (DTLS) of cold cesium atoms. This coherent process was recently investigated, both theoretically and experimentally, through nearly degenerate four-wave mixing (FWM) for the case where the incident beams do not carry OAM [19]. Here we will concentrate on the analysis of the spatial profile of the generated beam when the FWM beams possess phase dislocations on their wave fronts. It is worth mentioning that the use of cold atoms, as compared with thermal atoms, is particularly important within the perspective of further investigation of this process regarding to the measurement of quantum correlations associated with photons carrying OAM. We consider the standard FWM configuration where the forward (F) and the backward (B) pumping beams have the same linear polarization and are nearly counterpropagating with wave vectors $\vec{K}_F$ and $\vec{K}_B$ and with the same frequency $\omega_F = \omega_B = \omega$, which are red-detuned by Δ with respect to the atomic resonance, as indicated in the level scheme of Fig. 1(a). The incident signal beam (S), forming a small angle with the forward beam, has a wave vector $\vec{K}_S$ and a nearly degenerate frequency $\omega_S = \omega - \delta$ and is linearly polarized orthogonal to the pump beams. Choosing the quantization axis along the polarization direction of the pump beams, the pump and the signal beams will induce different dipole transitions, corresponding to the selection rules $\Delta M = 0$ and $\Delta M = \pm 1$, respectively. In such a configuration, the

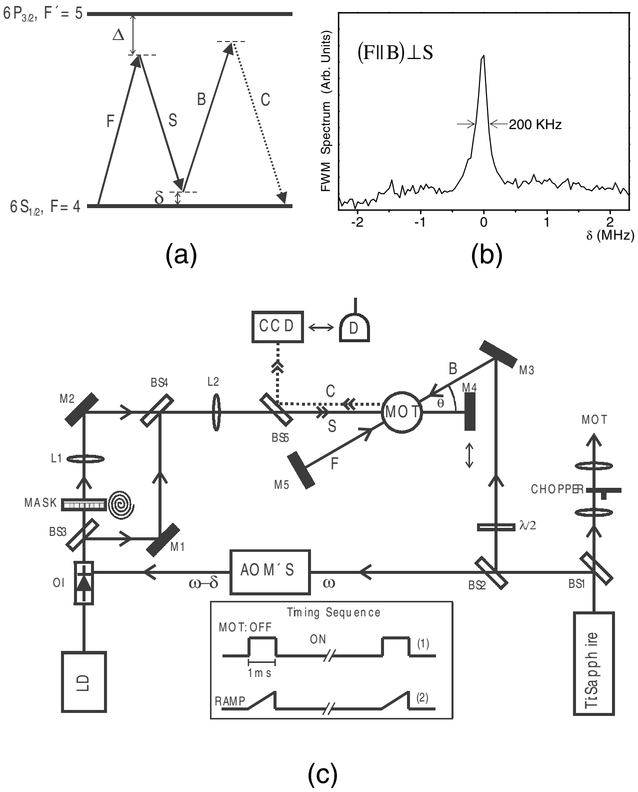

FIG. 1. (a) DTLS of the cesium D_2 line used to investigate the nearly degenerate FWM process. The arrows represent the photons absorbed and emitted in this parametric process. (b) FWM spectrum observed for orthogonal polarization between the pumps and the signal beam. (c) Experimental setup: OI: optical isolator; BS: beam splitters; M: mirrors, L: lenses; AOMs: acousto-optic modulators. Inset: (1) voltage signal used to switch off the MOT beams and quadrupole magnetic field and to trigger the scanning voltage ramp (2). The injection beam with frequency $\omega - \delta$ is also intensity modulated according to this timing sequence.

nonlinear medium generates a nearly phase conjugate beam (C), which originates exclusively from the induced coherence gratings between pairs of Zeeman sublevels in the ground and excited states. We assume that the pump field amplitudes $\mathcal{A}_F$ and $\mathcal{A}_B$ are spatially constant, while the signal beam S is described by a LG mode propagating along the z direction with a complex field amplitude, at the plane $z = 0$, given, in cylindrical coordinates (r, φ, z), by $\mathcal{A}_S \propto [(r\sqrt{2})/\omega_0]^{|m|} \exp[-r^2/\omega_0^2] \times \exp(-\mathrm{i}m\varphi) L_p^m[(2r^2)/\omega_0^2]$, where ω_0 is the minimum half-beam waist and L_p^m is the associated Laguerre polynomial. For the considered nonlinear process, the complex amplitude of the generated field is given by $\mathcal{A}_C \propto \chi^{(3)} \mathcal{A}_F \mathcal{A}_B \mathcal{A}_S^*$, where $\chi^{(3)}$ is the effective third order nonlinear susceptibility of the atomic medium associated with the corresponding polarization configuration. Under phase matched conditions, the generated wave has a frequency and a wave vector given, respectively, by $\omega_C = \omega_F + \omega_B - \omega_S = \omega + \delta$ and $\vec{K}_C = \vec{K}_F + \vec{K}_B - \vec{K}_S \approx -\vec{K}_S$, which express the conservation of energy and linear momentum within the light modes involved in this parametric process. This simple analysis also shows that the generated beam C must include a phase dislocation in its wave front with the same topological charge as the incident signal beam S. Therefore, since these beams are nearly counterpropagating, they should carry opposite OAM, i.e., $\vec{L}_C = -\vec{L}_S = -m\hbar\hat{z}$. Although the above former two conservation laws have been verified in the vast literature on FWM, its counterpart for the case where the incident beams possess OAM still needs to be demonstrated. In what follows, we describe an experiment which verifies the conservation of OAM of the light in a coherent FWM parametric process.

In the experiment, we have employed cold cesium atoms, obtained from a magneto-optical trap (MOT), as the nonlinear medium. The trapping beams are provided by a stabilized Ti:sapphire laser, red-detuned by about 12 MHz from the resonance frequency of the cesium cycling transition $6S_{1/2}$, $F = 4$–$6P_{3/2}$, $F' = 5$ at $\lambda = 852$ nm. The population lost to the noninteracting lower ground state $6S_{1/2}$, $F = 3$, was recycled by a repumping diode laser, which was kept on during all the measurements. Typically, the number of trapped atoms is of the order of 10^7 atoms, while the estimated trap temperature is in the range of mK. The experimental setup is shown schematically in Fig. 1(c). As indicated, the pumping beams F and B, with the same linear polarization, are also provided by the same Ti:sapphire laser and have the same frequency ω of the trapping beams. We use a pair of acousto-optic modulators (AOMs), one of which operates in double passage and is driven by a radio-frequency source controlled by a voltage ramp, to produce a beam with a scannable frequency $\omega - \delta$. This beam is directly injected, through the side port of an optical isolator, into a single mode diode laser, therefore locking its frequency and making it highly correlated with that of the Ti:sapphire laser. Single- and double-charge topological screw dislocation were generated by passing the diode laser output beam through two different computed-generated spiral Fresnel zone-plate masks [20], followed by the lens $L1$, which allowed us to separate the beam with the desired nested vortex from the undiffracted light and high-order Fresnel images. We first produce a single-charge signal beam, with a power of 10 μW, which is focused into the trap region with a beam waist much smaller than the trap size (≈ 2 mm). The pump beams, with approximately the same power of 2 mW, are collimated to a diameter of about 5 mm and form an angle $\theta = 3°$ with the signal beam S. The linear polarization of the signal beam is made perpendicular to that of the pump beams by the use of a half-wave plate. We first record the spectrum of the FWM generated beam C, which is reflected out of the 50/50 beam splitter ($BS5$)

and detected by a fast photodiode (D), as a function of the pump-signal detuning δ. The FWM spectrum is recorded within the ≈ 1 ms time interval during which the trapping beams were blocked by a mechanical chopper (transmission duty cycle of 95%), which also triggers the turn-off of the quadrupole magnetic field and the frequency scan of the signal beam S. This time sequence and a typical FWM spectrum are shown in the inset of Fig. 1(c) and in Fig. 1(b), respectively. The measured linewidth of the generated FWM signal is of the order of 200 KHz, which is much smaller than the natural linewidth of the excited state ($\Gamma/2\pi = 5.3$ MHz), indicating that it originates from a long-lived Zeeman ground state coherence. The FWM reflectivity, measured in relation to the signal beam power, is of the order of 10%.

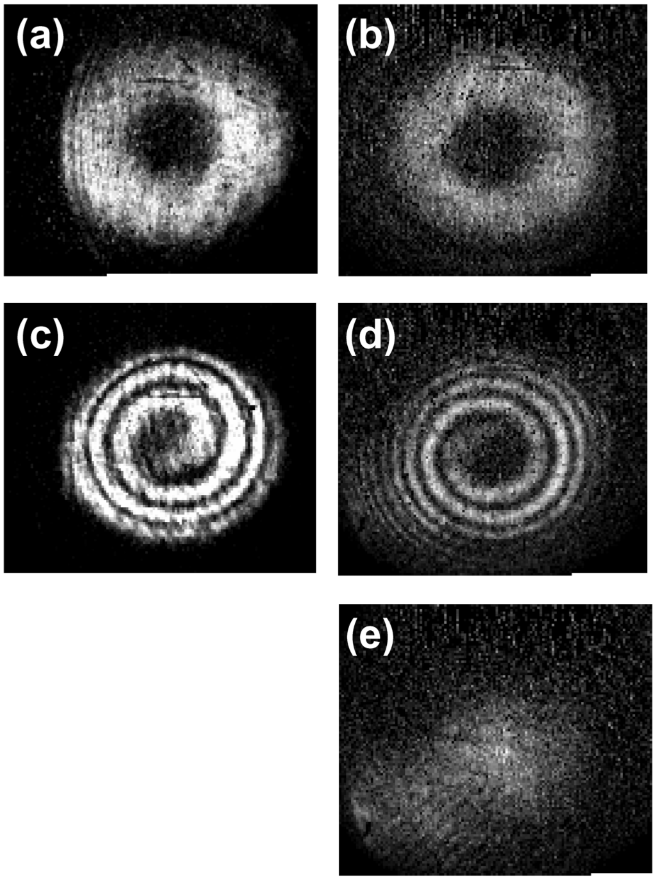

FIG. 2. Observed light spatial distribution and interference pattern for the single charge ($m = 1$, $p = 0$) signal beam S: (a) and (c); and for the generated phase conjugate beam C: (b) and (d). The interferograms are obtained using, respectively, the reflected incident reference wave by mirror $M4$, and the corresponding generated reference wave [whose profile is shown in (e)] via the same FWM process. The presented images are obtained by subtracting from the corresponding image the dark image, recorded when the injection of the diode laser is blocked, where no coherent signal is observed.

To analyze the spatial profile of the generated C beam, we replace the photodiode by a CCD camera. Retroreflecting the signal beam S with the auxiliary removable mirror $M4$ also allowed us to record its spatial profile. The corresponding spatial profiles for the incident signal beam S and for the generated phase conjugate beam C are shown in Figs. 2(a) and 2(b), respectively. Since the beam C is generated in a transient way, i.e., it exists only for a small fraction of time, corresponding to $\delta \approx 0$, within the time window where the MOT beams and the quadrupole magnetic field are switched off, to reveal its phase structure we have used a reference wave synchronized with the generated beam C and having the same frequency of it. This reference wave was obtained by superposing with the signal beam S, at the beam splitter $BS4$, a collimated Gaussian beam provided by the same injected diode laser, as depicted in Fig. 1(c). This auxiliary Gaussian beam is also focused into the cold atomic sample and, via the same FWM process, generates a synchronized reference wave copropagating with the generated beam C. The spatial profiles of the generated reference beam and its interference pattern with the generated beam C are shown, respectively, in Figs. 2(e) and 2(d). The topological charge of the incident signal beam S is measured by retroreflecting simultaneously this beam and the incident reference wave also using the auxiliary mirror $M4$, which produce the interference pattern shown in 2(c). As can be observed, the generated beam C has the same single topological charge as the incident signal beam S. However, in order to determine the sign of its topological charge and consequently its OAM, and to compare these two physical quantities with the ones corresponding to the incident signal beam S, we have to take into account that the sense of rotation of the spiral in the interference pattern can be reversed when either of the interfering beams pass through a focus and that the topological charge changes sign upon reflection in a mirror [21]. In the experimental configuration, the incident signal beam S and the auxiliary reference beam, have approximately the same Rayleigh length (≈ 2 cm) and have their focus positions separated by about 12 cm, with the trapped atomic cloud localized approximately halfway between these two positions. In such a condition, we have experimentally verified that the spiral in the interferogram reverses its sense of rotation when we pass through each of the foci of either the signal S or the auxiliary reference beams. Therefore, by taking into account the two reversals of the spiral associated with the passage by the two foci, as well as the one associated with the reflection in the mirror, and the fact that the generated beams propagate in the opposite direction to the incident ones, the observed interferograms in Figs. 2(c) and 2(d) lead us to conclude that the generated beam C has the same topological charge sign of the incident beam S. Moreover, as these two beams propagate in opposite directions (for $\delta \approx 0$), they carry opposite OAM. This, clearly demonstrates the conservation of OAM within the light modes participating in this coherent parametric

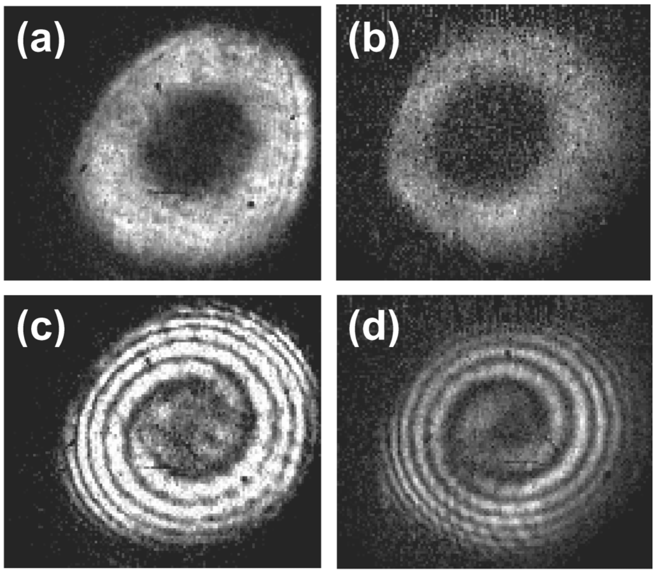

FIG. 3. Same sequence of images as in Fig. 2, but for an incident signal beam S with a double topological charge ($m = 2$, $p = 0$).

process and shows that the atomic sample does not gain any amount of OAM. We also have used a signal beam with double topological charge and the corresponding beam profiles and interferograms are shown in Figs. 3(a)–3(d). The reference wave is the same as the one used in the previous case. The double-charge signal beam also has a power of about 10 μW, and the measured reflectivity is of the same order as in the previous case. These observations are in complete agreement with the simple qualitative analysis presented before and demonstrate that, in this FWM process, originated from an induced coherence grating, in addition to the conservation of energy and linear momentum of the photons present in the involved field modes, one also needs to consider the corresponding conservation of OAM.

In conclusion, 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 beams. The observed results lead to a 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 multidimensional state space, and we believe it will be of considerable interest in the field of quantum information processing.

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