

Standing light fields for cold atoms with intrinsically stable and variable time phases

A. Rauschenbeutel, H. Schadwinkel, V. Gomer, D. Meschede

Institut für Angewandte Physik, Universität Bonn, Wegelerstrasse 8, D-53115 Bonn, Germany

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Abstract

We present a novel method to realise a standing light field with a stable configuration in two or three dimensions. A single standing wave formed by two counterpropagating beams is folded and brought into intersection with itself. The values of the relative timephases are stable, a priori known, and can be altered arbitrarily by means of retardation plates. The polarisation configurations of three orthogonal standing waves include the standard magneto-optical trap and a novel three-dimensional pure polarisation lattice which we have investigated in a first spectroscopic measurement, providing strong evidence for atomic localisation in both cases. © 1998 Elsevier Science B.V.

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1. Introduction

Laser manipulation of neutral atoms has over the past decade become a powerful experimental tool in many areas of physics. In order to control their motion in two or three dimensions atoms are usually exposed to a number of laser beams whose interference pattern governs the light–atom interaction and hence the atom dynamics. In general the resulting light field crucially depends on the relative phases of the interfering light beams. One method to provide a laser field with a stable intensity and polarisation configuration is to reduce the number of beams to the minimum ($d + 1$ in d dimensions) and thereby eliminate the influence of the relative phases [1]. In this case the only variable parameters are the beam geometry and polarisation. This concept is often used in the field of optical lattices [1,2] and has also been applied for 3D magneto-optical trapping with four laser beams [3] and to atom lithography [4].

However, many standard laser cooling and trapping configurations (2D atomic beam collimation, optical molasses or the magneto-optical trap) use mutually perpendicular

standing waves [5]. If in this case the phases are not under control, the microscopic properties of the light field will change in the course of a measurement.

We discuss here a new concept of producing such interference patterns with an intrinsically stable and a priori known light configuration. For illustration we have carried out spectroscopic measurements on a 3D pure polarisation lattice and a magneto-optical trap (MOT) with the total polarisation being linear everywhere.

2. Concept

The effect of the phases on the standing light field is easily seen in a two-dimensional configuration, see Fig. 1a [6], where all laser beams are linearly polarised in the xy plane and their electric fields are given by $\mathbf{E}_{1,2} = (E_0/2)\exp[i(\omega t \mp kx + \phi_{1,2})] \hat{y} + \text{c.c.}$ and $\mathbf{E}_{3,4} = (E_0/2)\exp[i(\omega t \mp ky + \phi_{3,4})] \hat{x} + \text{c.c.}$, respectively. Here k is the wavevector, \hat{x} and \hat{y} are unit vectors and ϕ_i describes the phase of the i th laser beam.

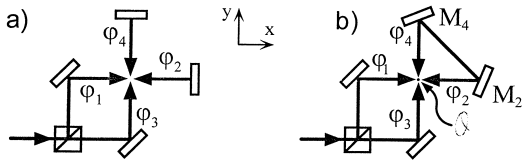


Fig. 1. 2D light fields formed by mutually orthogonal standing waves. (a) A Michelson-type set-up. The relative phases ϕ_i at the point of the beam intersection can be changed independently of each other by moving the mirrors. (b) The phases $\phi_2 = \phi_3 + kd$ and $\phi_4 = \phi_1 + kd$ now both depend on the same optical path d , eliminating the influence of the mirror positions on the total light field.

The resulting total field consists of two standing waves:

$$E = E_0 \left\{ \exp \left[i \left(\omega t + \frac{\phi_2 + \phi_1}{2} \right) \right] \cos \left(kx + \frac{\phi_2 - \phi_1}{2} \right) \hat{y} + \exp \left[i \left(\omega t + \frac{\phi_4 + \phi_3}{2} \right) \right] \cos \left(ky + \frac{\phi_4 - \phi_3}{2} \right) \hat{x} \right\} + \text{c.c.} \quad (1)$$

The values of the individual phases ϕ_i are connected to the optical path lengths in the set-up and are thus subject to the position of the mirrors exhibiting jitter in acoustic domain. Consider first the spatial terms in (1). A change in the spatial phases $\phi_2 - \phi_1$ and $\phi_4 - \phi_3$ can be expressed as a transformation of the origin in space and thus results in an overall translation of the interference pattern as a whole. Typically the internal atomic degrees of freedom evolve on much shorter time scales than the phases will jitter. Hence, the atoms can adiabatically follow this translation and the experiment will usually not be affected by it.

The effect of the temporal terms in (1) is more dramatic. Omitting the spatial phases for simplicity, the total field is now proportional to

$$\cos(kx) e^{i\Phi} \hat{y} + \cos(ky) \hat{x}, \quad (2)$$

with the *relative timephase* $\Phi = (\phi_1 + \phi_2 - \phi_3 - \phi_4)/2$. Any change in Φ will modify the interference pattern. For example if Φ is equal to zero the total light polarisation is linear everywhere while for $\Phi = \pi/2$ we get spatially alternating right and left circular polarisations.

In experiments on optical lattices by the Munich group [6] the relative timephase was kept constant by actively stabilising the optical path length difference on the interferometric signal detected at the open port of the beamsplitter in Fig. 1a. The absolute value of the relative timephase in this approach depends on the phase jumps introduced through the beamsplitter on the transmitted and reflected beams [7]. In general these phase jumps are asymmetric and unknown and have to be deduced from calibration measurements that require spectroscopy on optical lattices.

Our concept allows to circumvent active stabilisation, to know the relative phases in advance, and yet to retain the standard configuration of mutually orthogonal standing waves. If one chooses the optical set-up shown in Fig. 1b it can easily be seen that $\phi_2 = \phi_3 + kd$, where kd is the phase accumulated on the path $d = \mathcal{O}M_2M_4\mathcal{O}$. The phase ϕ_4 now depends on the same optical path $\phi_4 = \phi_1 + kd$. Hence the relative timephase Φ between the two standing waves is always equal to zero. It depends neither on the individual phases ϕ_i (these include in particular the phase jumps at the beamsplitter) nor on the path length d .

A more fundamental way to understand this idea is to regard the light field as one single standing wave formed by two beams counterpropagating through the apparatus. This standing wave is folded and brought into intersection with itself. Thus, as it is valid for a standing wave, both intersecting parts have identical timephases.

This point of view also makes clear that there is another way to obtain standing light fields with intrinsically stable timephases: a standing wave produced by back-reflection from a mirror can also be folded to intersect itself. In this case the laser power will not be divided at a beamsplitter. However, the fact that the single laser beam has to cross twice the number of optical elements (vacuum windows, etc.) could cause problems. The choice will depend on details of the experimental design.

In the plain set-up presented in Fig. 1b the relative timephase is intrinsically stable and its value is a priori known to be zero. Furthermore it can be altered as illustrated in Fig. 2. Here the optical path length is different for the two beams counterpropagating through the waveplate due to their orthogonal linear polarisations. One finds that the relative timephase in this case is given by $\Phi = r/2$, where r is the retardation of the waveplate. Correspondingly for orthogonal circular polarisations the timephase can be changed by means of a Faraday-rotator.

Thus the timephases can be set to an arbitrary value without changing the polarisation states of the beams, as

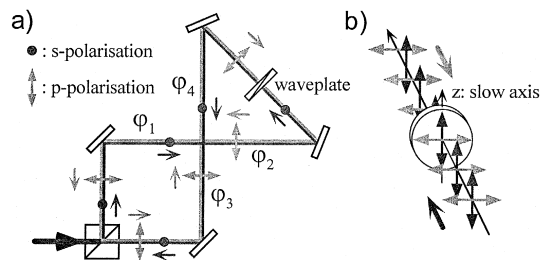


Fig. 2. Altering the timephase: (a) the beamsplitter divides the emerging laser beam into two orthogonal polarisations indicated by different grey scales, (b) the waveplate of retardation r introduces different optical path lengths yielding $\phi_2 = \phi_3 + kd$ and $\phi_4 = \phi_1 + kd + r$. Without changing the polarisation states of the counterpropagating beams we have introduced a relative timephase $\Phi = r/2$.

long as one chooses the normal modes of propagation (i.e. $lin \perp lin$ for the waveplate or $\sigma^+ - \sigma^-$ for the rotator). Of course, this normal mode condition has to be fulfilled only at the location of the waveplate (rotator), making other polarisation configurations accessible at the intersection of the laser beams by using additional polarisation optics.

3. Experimental

We use a 3D-extension of the concept as is shown in Fig. 3. All laser beams are derived from a Ti-sapphire laser, frequency stabilised to the red side of the cooling $F = 4 \rightarrow F' = 5$ transition of the cesium D_2 -line. Repumping light is provided by an additional laser diode. The polarisers 1 and 2 have their axes in the yz and xz directions, respectively. Two low cost polarisation compensators of Berek-type [8] compensate the unavoidable birefringence of the upper and the lower three dielectric mirrors, respectively. They consist of uniaxial YVO_4 -crystals cut in a plane perpendicular to the optical axis. At normal incidence a laser beam will thus pass without changing its polarisation state. However, by tilting the crystal arbitrary retardation can be introduced.

The electro-optical modulators (EOMs) allow to realise different light fields and switch between them by changing the applied voltage. For example the $\lambda/4$ -voltage results in a $\sigma^+ - \sigma^-$ -polarisation configuration which, in combination with a magnetic quadrupole field forms a MOT. For the 0λ -voltage all contributing laser beams become linearly polarised. With naturally zero relative timephases in both configurations the local polarisation in the MOT is linear everywhere while the second case yields a 3D pure polarisation lattice (PPL) without intensity gradients in which we observed trapping by optical forces in an earlier experiment [9].

Cesium atoms are captured from the background vapour by the MOT. In order to further cool the atoms we increase the laser detuning and switch the light field into the desired configuration without losses of trapped atoms. After allowing the atoms to thermalise, we record the transmission of an additional laser beam which propagates at a small angle with the z axis through the cloud of cold atoms. This beam has an intensity well below saturation

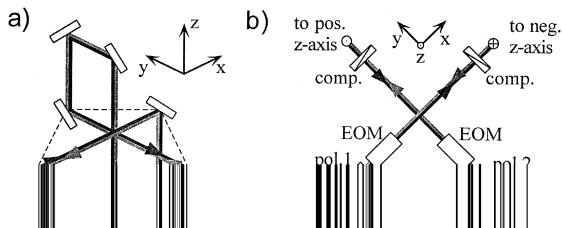


Fig. 3. (a) Sketch of the 3D set-up. The polarisation optics used is shown separately in (b). For details see text.

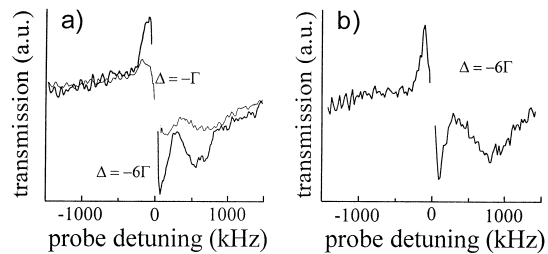


Fig. 4. Single shot transmission spectra at equal laser intensities: (a) of the MOT at different cooling laser detuning Δ in terms of the natural linewidth $\Gamma = 5.2$ MHz and (b) of the PPL. All signal amplitudes are shown with the same scale. The central parts of the original spectra were distorted by radio interference from the phase-lock (even in the absence of trapped atoms) and have been removed for clarity.

intensity and is derived from an additional diode laser that is phase-locked to the cooling laser and scanned around its frequency.

Fig. 4 shows transmission spectra of the MOT and of the PPL. All three exhibit characteristic narrow resonances which are symmetric with respect to zero detuning. These are usually interpreted in terms of Raman transitions between vibrational levels of atoms localised in optical micro-potentials [10,6]. The additional structure on the positive side of the detuning originates from transitions between differently light shifted Zeeman sublevels [11].

The zero-phase MOT has pure linear local polarisation everywhere, and the effective optical potential seen by the atoms is considerably shallower than in the case of standard optical lattices. Thus one would expect no efficient localisation. Nevertheless, Fig. 4a indicates an increase of the fraction of localised atoms as the detuning is increased. This effect can be attributed to the decrease in temperature due to sub-Doppler cooling effects which are only efficient at large laser detuning (low saturation). We also notice that due to the longer lifetime of the vibrational states in 3D confinement the resonances are much narrower than those measured in the case of a 2D MOT [12].

The observation of the narrow line in Fig. 4b, implying longer confinement, is consistent with optical potential minima at points of circular polarisation in the PPL configuration. However, quantitative analysis of the atom–light interaction in complex light fields needs further investigation.

4. Conclusions

We have presented a new concept for setting up a standing light field where the timephases are intrinsically stable and a priori known. Additionally, they can be adjusted to any desirable value by means of retardation plates or Faraday rotators. This approach allows not only a

simple experimental set-up but also gives significant flexibility in tailoring the light field. This may be of interest for experiments with optical lattices and in other laser cooling and trapping situations where stable light field topography is desired.

Acknowledgements

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