Optics Communications 358 (2016) 20–23

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Electromagnetically induced holographic imaging

Tianhui Qiu [a,*], Lixin Xia [b,*], Hongyang Ma [a], Chunhong Zheng [a], Libo Chen [a]

[a] School of Science, Qingdao Technological University, Qingdao 266033, People's Republic of China
[b] College of Physics and Electrical Engineering, Kashgar University, Kashgar 844008, People's Republic of China

ARTICLE INFO

Article history:
Received 29 June 2015
Received in revised form
3 September 2015
Accepted 5 September 2015
Available online 16 September 2015

Keywords:
Electromagnetically induced transparency
Holographic interferometry
Electromagnetically induced grating

ABSTRACT

The electromagnetically induced Talbot effect offers a nondestructive and lensless way to image ultracold atoms or molecules (Wen et al., 2011 [12]). In this paper, we propose another atomic imaging scheme based on the holographic imaging principle, in which three types of light source are employed as the imaging light to perform spatial interference. Compared to the previous self-imaging scheme, in the present one both the amplitude and phase information of the object can be imaged with the characteristic of arbitrarily controllable image variation in size, and the object to be imaged is no longer subject to the periodic structure.

1. Introduction

Holography is a lensless imaging method and is capable of recording both the amplitude and phase information of an arbitrary shaped object by spatial interference of an object beam and a reference beam. Since it is firstly reported by Gabor in 1948 [1], much interest has been attracted from theoretical and experimental aspects. This is due to its significant advantages and important applications in optical storage, reconstruction and information processing [2–4]. The principle of holographic imaging is always in development, and digital holography [5], rainbow holography [6], optical scanning holography [7], quantum holography [8], etc. have been proposed. In most of the existing works about holographic imaging the object to be imaged is usually material. Recently, the Talbot effect of a nonmaterial grating was reported. Such a grating is the so-called electromagnetically induced grating (EIG) [9,10], which is generated by utilizing a strong standing wave to periodically modulate the optical response of a medium composed of ultracold atoms or molecules to a weak probe field based on electromagnetically induced transparency (EIT) effect [11]. This technique, i.e., electromagnetically induced Talbot effect (EITE), provides us a new choice to image ultracold atoms or molecules [12]. To our knowledge, the electromagnetically induced first-order and second-order Talbot effects have been proposed for this purpose [12,13]. While based on the both principles only the amplitude information of the nonmaterial grating can be imaged, and the objects to be imaged must have periodic structure enslaved to the basic principle of Talbot effect. In this paper, we propose another type of lensless imaging scheme, electromagnetically induced holographic imaging (EIHI), for ultracold atoms or molecules. Three types of light sources are employed for the atomic imaging by spatial interference. We demonstrate that the obtained imaging in the coherent light case is completely the same as the generated EIG itself, while in the case of thermal light shielded by a pinhole it can be magnified on demand simply by adjusting the system parameters.

2. Description of the model

The scheme of the EIHI under consideration is sketched in Fig. 1(a). A light field is split by a beam splitter (BS) into object beam traveling along the object path and reference beam freely along the reference path. These two beams are then interfered and the intensity is recorded by the detector D. A cloud of length L consisting of an ensemble of three-level ultracold atoms in the Λ configuration (see Fig. 1(b)) is placed on the object path. The atomic transitions $|g\rangle \leftrightarrow |e\rangle$ is excited by the weak object beam with Rabi frequency Ω_o. A strong standing wave formed by two strong control fields which are symmetrically displaced with respect to the object path (see Fig. 1(c)) is employed for driving the transition $|s\rangle \leftrightarrow |e\rangle$. Without loss of generality, in the paper we consider the simplest one-dimensional standing wave case. Then the Rabi frequency of the standing wave can be written as $\Omega_c \cos(\pi x/a)$, where a is the spatial period of the applied standing wave, and can in principle be made arbitrarily larger than the wavelength of the object beam by varying the angle between the two wave vectors of two control beams, and x is the position in the standing wave field. The periodical manipulation about the response of the atoms to the weak object beam realizes when it goes

* Corresponding authors.
E-mail addresses: qth@mail.bnu.edu.cn (T. Qiu), xialx0227@126.com (L. Xia).

http://dx.doi.org/10.1016/j.optcom.2015.09.018
0030-4018/

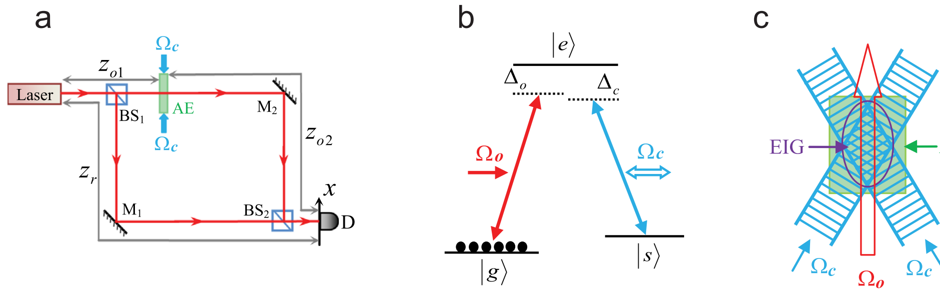

Fig. 1. (a) Setup to realize the EIHI. AE: atomic ensemble, BS: beam splitter, and M: mirror. (b) Schematic diagram of atom-field interaction. (c) Configuration of EIG generation.

through the atomic ensemble.

We assume that all the atoms are initially prepared in the state $|g\rangle$. Then, by first-order approximation, we can obtain the linear susceptibility of the system at the object beam frequency:

$$\chi = \frac{N|\vec{\mu}|^2}{2\hbar\epsilon_0}\frac{\Delta_{oc} + i\gamma_{gs}}{|\Omega_c|^2\cos^2(\pi x/a) - (\Delta_o + i\gamma)(\Delta_{oc} + i\gamma_{gs})}, \tag{1}$$

where N, $\vec{\mu}$ and ε_0 are atomic density, dipole moment vector and the vacuum permittivity, respectively. The two-photon detuning Δ_{oc} is equal to $\Delta_o - \Delta_c$, where Δ_o and Δ_c are the detunings of the object beam and standing wave with respect to the corresponding atomic transitions. γ is the decay rate of the atom in its excited state and γ_{gs} is the dephasing rate of the atomic spin excitation.

The transmission profile of the object beam at the output surface of the atomic medium can be obtained by solving Maxwell's equation of the object beam and reads

$$E_o(x, L) = E_o(x, 0)\exp\left[\frac{-k\chi'' L}{2}\right]\exp\left[\frac{ik\chi' L}{2}\right], \tag{2}$$

where $\chi = \chi' + i\chi''$, k ($\lambda = 2\pi/k$) is the wave number (wavelength) of the object beam, $E_o(x, 0)$ is the object beam profile before it enters the atomic medium, and $E_o(x, L)$ functions the reflected or transmitted optical amplitude of the object to be imaged in the traditional holographic imaging schemes, Eq. (2) of Ref. [6], for example. At the transverse locations around the nodes of the standing wave, the object beam is absorbed according to the well-known Beer law because the intensity of control field there is very weak. In contrast, at the locations around the antinodes, the object beam is absorbed much less due to the EIT effect. Then the absorption and refraction of the object beam will experience a periodic variation and an EIG can be obtained in the standing wave direction. If the system is at resonance $\Delta_o = \Delta_c = 0$, i.e.,

$$\chi = \frac{N|\vec{\mu}|^2}{2\hbar\epsilon_0}\frac{i\gamma_{gs}}{|\Omega_c|^2\cos^2(\pi x/a) + \gamma\gamma_{gs}},$$

only the periodic amplitude modulation across the object beam profile, a phenomenon reminiscent of the amplitude grating, is realized. In nonresonant circumstance, the phase modulation will be introduced so that the hybrid modulation (both amplitude and phase modulation) grating is available. Because of the EIG periodicity, Eq. (2) can be recast into Fourier series:

$$E_o(x, L) = \sum_{n=-\infty}^{+\infty} c_n \exp\left[-i\frac{2n\pi x}{a}\right], \tag{3}$$

where $c_n = (1/a)\int_0^a E_o(x, L)e^{i2\pi nx/a}\,dx$ is the coefficient of the nth harmonic.

Now, we look at the holographic imaging of the one-dimensional EIG generated in the above. It should be noted that, as a proof-of-principle experiment, the one-dimensional object to be holographically imaged is an amplitude grating. We assume the object beam is much weaker than the reference beam, and the temporal coherence condition is satisfied, then the holographic pattern of the EIG is dominated by the interference term:

$$\left\langle E_r^*(x)E_o(x)\right\rangle = \int dx_0'\,dx_0\,h_r^*(x, x_0')h_o(x, x_0)\left\langle E_0^*(x_0')E_0(x_0)\right\rangle, \tag{4}$$

where $E_0(x_0)$ is the light field distribution in the source plane. $E_o(x)$ and $E_r(x)$ are the fields in the recording plane for the object beam and reference beam, respectively. x_0, x_0' and x are the transverse positions across the beams. Under the paraxial approximation, the impulse response functions of the object beam and reference beam are written as

$$h_o(x, x_0) \propto \int dx'\,E_o(x', L)\exp\left[\frac{ik(x_0 - x')^2}{2z_{o1}} + \frac{ik(x' - x)^2}{2z_{o2}}\right],$$
$$h_r(x, x_0) \propto \exp\left[\frac{ik(x - x_0)^2}{2z_r}\right], \tag{5}$$

respectively, where we define $z_o = z_{o1} + z_{o2}$, $z_{o1}(z_r)$ is the distance from the light source to the atomic medium (the detector D), and z_{o2} is the distance between the medium and the detector D.

For obtaining the holographic imaging, we consider three types of light sources here. The first source is a plane-wave coherent light, i.e., $\left\langle E_0^*(x_0')E_0(x_0)\right\rangle = \alpha^*\alpha$. Substituting Eqs. (3) and (5) into Eq. (4) and completing the integration, the interference term (4) can be factorized to be

$$\left\langle E_r^*(x)E_o(x)\right\rangle_c \propto \sqrt{\frac{k}{i2\pi z_{o2}}}\exp[ik(z_o - z_r)]\int dx'\,E_o(x', L)\exp\left[\frac{ik}{2Z_c}(x' - x)^2\right]$$
$$\propto \sum_{n=-\infty}^{+\infty} c_n \exp\left[-i\frac{n^2\pi\lambda Z_c}{a^2}\right]\exp\left[-i\frac{2n\pi x}{a}\right], \tag{6}$$

here $Z_c = z_{o2}$ defines the effective diffraction length. Eq. (6), which originates from the interference of the object beam and reference beam, gives the complex optical amplitude on the recording plane, and functions as Eq. (5) of Ref. [6]. According to Eq. (6), we can easily see that the equal-path condition in the interferometry does not meet because the object beam and reference beam are split from a coherent light source, a laser for example, with both better temporal and spatial coherence to perform spatial interference. Recalling the Talbot effect [14], Eq. (6) has the same form with the result of traditional Talbot effect, which is a near-field diffraction phenomenon and can obtain self-imaging of a periodic object that replicates at certain planes without the need of any lens. Then some conclusions are immediately in order from Eqs. (2) and (6). The first exponential term of Eq. (6) describes the phase changes of the diffraction orders and tells us whether self-imaging occurs or