Optics Communications 370 (2016) 172–175

Contents lists available at ScienceDirect

Optics Communications

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

# Electromagnetically induced classical and quantum Lau effect

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ARTICLE INFO

*Article history:*
Received 23 October 2015
Received in revised form
3 March 2016
Accepted 4 March 2016
Available online 11 March 2016

*Keywords:*
Electromagnetically induced transparency
Lau effect
Electromagnetically induced grating

ABSTRACT

We present two schemes of Lau effect for an object, an electromagnetically induced grating generated based on the electromagnetically induced effect. The Lau interference pattern is detected either directly in the way of the traditional Lau effect measurement with a classical thermal light being the imaging light, or indirectly and nonlocally in the way of two-photon coincidence measurement with a pair of entangled photons being the imaging light.



## 1. Introduction

The Lau effect reflects the principle of diffractive self-imaging of periodic structures [1]. Its potential applications have been found in optical metrology [2], incoherent optical spatial filtering [3], computed tomography [4], etc. In a Lau setup, a set of parallel periodic structures, gratings, for example, separated at a proper distance is illuminated with a spatially incoherent light, and a fringe pattern appears when the grating period and the axial distance between the two gratings fulfil certain relation. In physics, the Lau effect results from the Fresnel diffraction, and can be understood in detail on the basis of geometrical optics and diffraction theory [5], coherence theory [6,7], grating imaging [8], and theory of optical transfer function [9]. In the original Lau setup the image is recorded directly with one detector, which is attributed to the first-order correlation effect. Recently, the Lau effect based on the second-order and much higher-order correlation effects has been demonstrated [10,11], and the imaging light could be either classical [10] or quantum [11], and the image is recorded nonlocally with correlation measurement.

In the most existing works an imaged object is usually material. Recently, the Talbot effect of an electromagnetically induced grating (EIG) [12] was reported [13]. Such an EIG is an optical-material complex, generated from periodical manipulation of a strong coupling standing wave about the response of a medium composed of ultracold atoms or molecules to a probe light based on the electromagnetically induced transparency (EIT) effect [14]. It is believed that this electromagnetically induced Talbot effect (EITE) could provide ones a new choice to image the media of ultracold atoms or molecules [13]. So far, the first-order [13] and the second-order correlation [15] EITEs have been proposed. In this paper, we propose two schemes of Lau effect for an EIG, i.e., the electromagnetically induced classical Lau effect (EICLE), where the imaging light is a spatially incoherent thermal light, and the electromagnetically induced quantum Lau effect (EIQLE), where the imaging light is an entangled photon pair. By applying the direct measurement in the EICLE case and the two-photon coincidence measurement in the EIQLE case, the image of the EIG is obtained with the magnification factor on demand by adjusting the distance between the light source and the atomic medium, the focal length of the lens and so on. This work may enrich our the knowledge of the Lau effect and motivate novel application in optical noncontact measurements and some other fields.

## 2. Electromagnetically induced grating

The object to be imaged is a ultracold atomic medium of length $L$ in the direction $\vec{z}$. Each atom in the medium has a three-level $\Lambda$ configuration (Fig. 1(a)). One of its two atomic transitions is coupled to the weak imaging light propagating in the direction $\vec{z}$ and another to a $\vec{x}$–direction standing wave formed by two strong control beams which are symmetrically displaced with respect to the imaging path (see Fig. 1(b)). The periodical manipulation of the strong standing wave about the response of the atoms to the imaging light realizes when the imaging photon goes through the atomic medium. If all the atoms are initially prepared in the state $|g\rangle$, in the first-order approximation we derive the linear

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http://dx.doi.org/10.1016/j.optcom.2016.03.018
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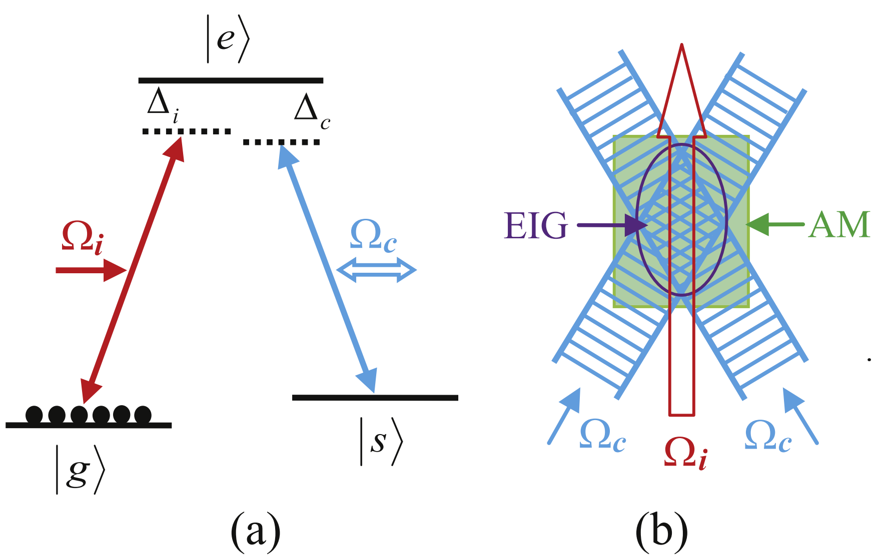


**Fig. 1.** (a) Schematic diagram of atom–field interaction. (b) Configuration of EIG generation.

susceptibility of the system at the imaging light frequency

$$\chi - i = \frac{N|\vec{\mu}|^2}{2\hbar\varepsilon_0}\frac{\Delta - ic + i\gamma - gs}{|\Omega_c|^2\cos^2(\pi x/a) - (\Delta_i + i\gamma)(\Delta_{ic} + i\gamma_{gs})}. \tag{1}$$

Here $\Omega_c$ is the Rabi frequency of the control beam; $\Delta_{ic}$ ( $= \Delta_i - \Delta_c$ ) is the two-photon detuning, and $\Delta_c$ ($\Delta_i$) is the detuning of the control (imaging) light with respect to the corresponding atomic transition; $\gamma$ is the decay rate of the atom in its excited state, $\gamma_{gs}$ is the dephasing rate of the atomic spin excitation, $N$, $\vec{\mu}$ and $\varepsilon_0$ are the atomic density, dipole moment vector and the vacuum permittivity, respectively. $a$ is the spatial period of the standing wave, which, in principle, can be made arbitrarily larger than the wavelength of the imaging light by adjusting the angle between the two wave vectors of the control beams, and $x$ is the position in the standing wave field. The transmission profile of the imaging light at the output surface of the atomic medium can be obtained by solving Maxwell's equation of the light and reads [16]

$$E_i(x, L) = E_i(x, 0)\exp\left[\frac{-k_i\chi - i''L}{2}\right]\exp\left[\frac{ik_i\chi_i' L}{2}\right]. \tag{2}$$

Here $\chi_i = \chi_i' + i\chi_i''$, $k_i$ is the wave number of the imaging light, and $E_i(x, 0)$ is the corresponding light profile before it enters the atomic medium. At the transverse locations around the nodes of the standing wave, the light is absorbed according to the usual Beer law. In contrast, at the locations around the antinodes, the absorption is much less due to the EIT effect. If the system is resonance $\Delta_i = \Delta_c = 0$, only the periodic amplitude modulation across the imaging profile is realized. This action is similar to that of an amplitude grating. In the nonresonant circumstance, the phase modulation is introduced into the grating so that the hybrid modulation (both amplitude and phase modulations) grating is available.

## 3. Electromagnetically induced Lau effect

*EICLE*: We first study the EICLE. The scheme under consideration is shown by Fig. 2, where the imaging light is a spatially incoherent thermal light, which sequentially passes through two same atomic media, and then is recorded by the scanning detector $D$ located at the focus of a lens. If the distance from the light source to the first atomic medium is $z_0$, the distance between the first medium (lens) and the second one is $z_1$ ($z_2$), under the paraxial approximation, the impulse response function for the imaging light can be written as

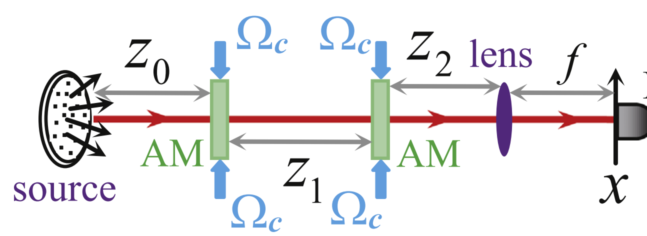


**Fig. 2.** EICLE setup. AM: atomic medium.

$$h(x, x_0) \propto \iint dx'\, dx'' E_i^1(x', L)E_i^2(x'', L)\cdot$$
$$\exp\left\{ik_i\left[\frac{(x' - x_0)^2}{2z_0} + \frac{(x'' - x')^2}{2z_1} + \frac{(f - z_2)x^2}{2f^2} - \frac{xx''}{f}\right]\right\}, \tag{3}$$

where $f$ is the focal length of the lens, $x_0$ is the transverse coordinate on the plane of light source, and $E_i^1(x', L)$ ($E_i^2(x'', L)$) is the transmission profile of the imaging light at the output surface of the first (second) atomic medium with $x'$ ( $x''$) being the corresponding transverse coordinate. Then, the intensity distribution at the detector is

$$I = \iint dx_0\, dx_0' h(x, x_0)h^*(x, x_0')\left\langle E_0^*(x_0')E_0(x_0)\right\rangle. \tag{4}$$

The imaging light is spatially incoherent and satisfies $\left\langle E_0^*(x_0')E_0(x_0)\right\rangle = I_0\delta(x_0' - x_0)$, where $E_0(x_0)$ is the distribution of the light field on the plane of its source and $I_0$ is the constant light intensity. Using Eqs. (3) and (4), and completing the integration, we obtain

$$I \propto \int dx'\left|E_i^1(x', L)E_i^2\left(x' + \frac{L_c}{f}x, L\right)\right|^2, \tag{5}$$

where $L_c = \frac{m}{2}z_T$ has been defined in terms of $z_T = 2a^2/\lambda_i$, the quantity so-called is the Talbot length. The Lau effect arises as the condition $L_c = z_1$ is fulfilled. Apparently, the Lau effect has an inherent relation with the Talbot self-imaging effect [17]. Eq. (5) shows that the Lau interference pattern has the period of $\frac{f}{L_c}a$, or in other words, the period of the self-imaging changes with a magnification of $\frac{f}{L_c}$, and the image obtained for $m$ being an odd integer