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A bistable system with an electromagnetically induced grating*

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We propose a scheme of a bistable system with an electromagnetically induced grating and analyse the optical bistabilities in the system. The stationary equations describing the system have been derived. This bistable system shows typical hysteresis behaviour.

Keywords: electromagnetically induced grating, optical bistability
PACC: 4250, 3280, 4265P

1. Introduction

Two ingredients are necessary to create optical bistability for an optical bistable system which shows a static hysteresis loop in the relation between incident and transmitted light intensities, namely a sufficiently strong nonlinearity and a suitable feedback.[1] One type of bistable system[2] is based on Bragg diffraction,[3,4] consisting of a Bragg-type acousto-optic modulation crystal and a feedback loop which manifests the hysteresis between the incident and the first-order diffraction light intensities. In this paper, we adopt an electromagnetically induced grating (EIG) to replace the role of the modulation crystal to form an electromagnetically induced optical bistable system.

The principal mechanism behind the EIG is the electromagnetically induced transparency (EIT).[5] A strong-coupling standing wave, interacting with an atomic medium, can diffract a weak probe field (propagating along a direction normal to the standing wave) into high-order diffractions. This effect is like that of a Bragg-type acousto-optic modulation crystal in a bistable system. The EIG has been theoretically discussed by Ling *et al.*[6] and experimentally demonstrated in Ref.[7]. Controlled by optical beams, a bistable system induced by EIG modulation possesses advantages over conventional systems such as, for example, low switching power with high-speed operation and low optical loss, etc.

2. Theoretical analysis

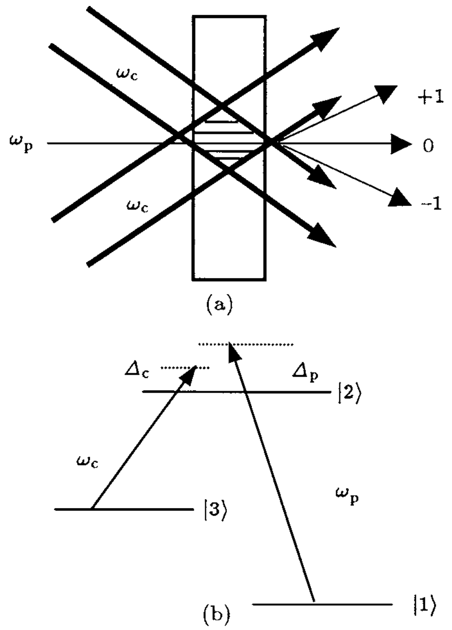

Fig.1. (a) A sketch of the EIG. (b) The energy diagram of the atomic sample used for the EIG.

We use an EIG system, as shown in Fig.1(a), which consists of two strong coupling fields of frequency ω_c (in their overlap region, a standing wave

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is formed in the medium), a weak probe field of frequency ω_p and an atomic sample. The atomic sample consists of three-level Λ-type atoms whose energy diagram is shown in Fig.1(b). The coupling fields drive the 2↔3 atomic transition, while the probe field induces the 2↔1 transition; the 3↔1 transition is a dipole forbidden transition. According to the principle of EIT, at the antinode (corresponding to the maximum intensity of the standing wave formed by the two coupling fields) is the probe light transparency, while the probe is quite opaque at the node (corresponding to the minimum intensity of the standing wave). This leads to a substantial amplitude modulation grating across the probe beam. At the same time, the dispersions to the probe field within the EIT window are opposite at nodes and antinodes. This opens the possibility of a large phase modulation across the probe beam. Therefore, such a system exerts both amplitude and phase modulations across the probe beam profile in much the same way as a hybrid grating does to the amplitude and phase of an electromagnetic wave.

Figure 2 shows a schematic diagram of the electromagnetically induced bistable system. The input beam (with intensity I_1) diffracts into the first-order diffraction via the EIG formed by the interaction of the two coupling fields and the input field (that is, the probe field in Fig.1) with the atomic sample, as shown in Fig.1. This system can be described by the following coupled equation[4]

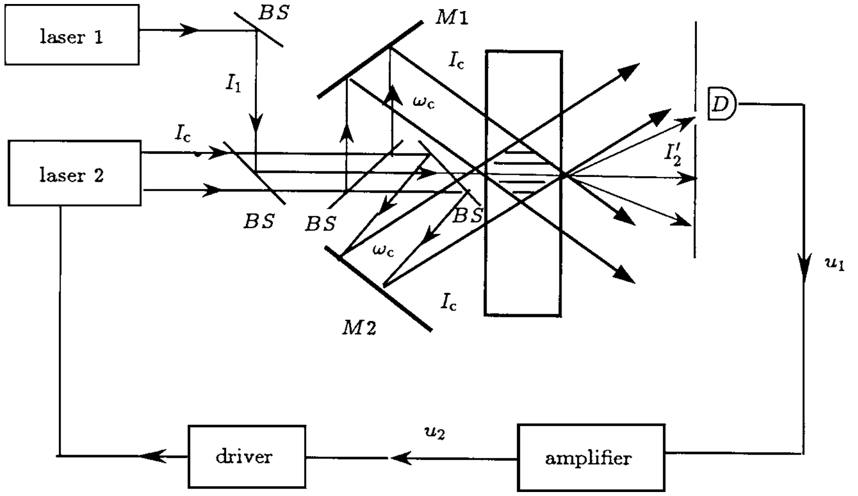

Fig.2. Schematic diagram for the bistable system based on EIG: BS, beam splitter; $M1$ and $M2$, reflecting mirrors; D, photoelectric detector.

$$\begin{cases} u_1(t) = \alpha I_1 k' T(I_\mathrm{c}+I_\mathrm{c0}), \\ \tau \mathrm{d}I_\mathrm{c}/\mathrm{d}t + I_\mathrm{c} = \beta' u_1(t), \end{cases} \tag{1}$$

where I_1 is the intensity of the input beam (probe), $u_1(t)$ is the output voltage after detection, α is the conversion coefficient of the photoelectric converter, k' is the diffraction efficiency, I_c is the intensity of the coupling field and its initial value is I_c0, τ is the response time of the system, and β' is the amplifier coefficient. $T(I_\mathrm{c}+I_\mathrm{c0})$ is defined as the transmission function of the EIG in the first-order direction[6]

$$T(I_\mathrm{c}+I_\mathrm{c0}) = \left| \int_0^1 T(x, I_\mathrm{c}+I_\mathrm{c0}) \exp(-\mathrm{i}2\pi x)\mathrm{d}x \right|^2, \tag{2}$$

where the transmission function $T(x, I_\mathrm{c}+I_\mathrm{c0})$ for medium thickness L (along the z-direction) is

$$T(x, I_\mathrm{c}+I_\mathrm{c0}) = \exp(\alpha_r(x)L)\exp(\mathrm{i}\alpha_i(x)L). \tag{3}$$

In the EIG system shown in Fig.1, the absorption coefficient $\alpha_r(x)$ and dispersion coefficient $\alpha_i(x)$ of the input light are expressed as follows[6]

$$\alpha_r(x) = -\frac{[\gamma_{31}^2 + (\varDelta_\mathrm{p}-\varDelta_\mathrm{c})^2] + \gamma_{31}(I_\mathrm{c}+I_\mathrm{c0})\sin^2(\pi x)}{(1+\varDelta_\mathrm{p}^2)[\gamma_{31}^2 + (\varDelta_\mathrm{p}-\varDelta_\mathrm{c})^2] + 2[\gamma_{31} - \varDelta_\mathrm{p}(\varDelta_\mathrm{p}-\varDelta_\mathrm{c})](I_\mathrm{c}+I_\mathrm{c0})\sin^2(\pi x) + (I_\mathrm{c}+I_\mathrm{c0})^2\sin^4(\pi x)}, \tag{4a}$$

$$\alpha_i(x) = -\frac{-\varDelta_\mathrm{p}[\gamma_{31}^2 + (\varDelta_\mathrm{p}-\varDelta_\mathrm{c})^2] + (\varDelta_\mathrm{p}-\varDelta_\mathrm{c})(I_\mathrm{c}+I_\mathrm{c0})\sin^2(\pi x)}{(1+\varDelta_\mathrm{p}^2)[\gamma_{31}^2 + (\varDelta_\mathrm{p}-\varDelta_\mathrm{c})^2] + 2[\gamma_{31} - \varDelta_\mathrm{p}(\varDelta_\mathrm{p}-\varDelta_\mathrm{c})](I_\mathrm{c}+I_\mathrm{c0})\sin^2(\pi x) + (I_\mathrm{c}+I_\mathrm{c0})^2\sin^4(\pi x)}, \tag{4b}$$

where γ_{31} is the dephasing rate between levels 1 and 3. $\Delta_p (= \omega_p - \omega_{21})$ and $\Delta_c (= \omega_c - \omega_{31})$ are the frequency detuning of the probe and coupling fields from their corresponding atomic transition frequency, respectively. Equation (4) indicates two types of grating with different parameters, as follows.

(1) Pure amplitude grating. When both Δ_p and Δ_c are zero, Eq.(4b) reveals that α_i vanishes, implying that no phase modulation takes place. This leads to a situation where the EIG has the characteristics of an amplitude grating.

(2) Hybrid (amplitude and phase) grating. When one or both of Δ_p and Δ_c are nonzero according to Eq.(4a), we discuss one of the phase modulation gratings where the coupling fields have a high intensity and are on resonance with the $2 \leftrightarrow 3$ transition (Δ_c=0), and the input field is tuned away from the $2 \leftrightarrow 1$ transition but still operates within the EIT window ($\Delta_p \neq 0$). The high coupling intensity reduces the loss of light, while a nonzero Δ_p induces a nonzero α_i, and thus a phase modulation across the input field. This scheme takes advantage of the two features of EIT, i.e. transparency and high dispersion, and therefore results in an atomic hybrid grating that can effectively diffract light into the first-order diffraction.[6]

Equation (1) can be transformed into a more simple form

$$\mathrm{d}I_c(t)/\mathrm{d}t + I_c(t) = kI_1T(I_c(t) + I_{c0}), \qquad (5)$$

which is the dynamic equation for this optical bistable system and $k = \alpha k' \beta'$.

Letting $\mathrm{d}I_c/\mathrm{d}t = 0$ and $I_c(\infty) = I_2$, then we have the steady-state equation from Eq.(5),

$$I_2 = kI_1T(I_2 + I_{c0}). \qquad (6)$$

3. Results and discussion

In this section, the steady-state equation (6) is used to investigate the bistable characters for the system shown in Fig.2. Let us begin our study with a case in which the pure amplitude EIG is used. Figure 3 displays the typical bistable hysteresis for the system. It is required that the value of parameter k (which is proportional to the amplifier coefficient β) is not as low as 100 due to the fact that the first-order diffraction light attained by this pure amplitude grating is very limited.

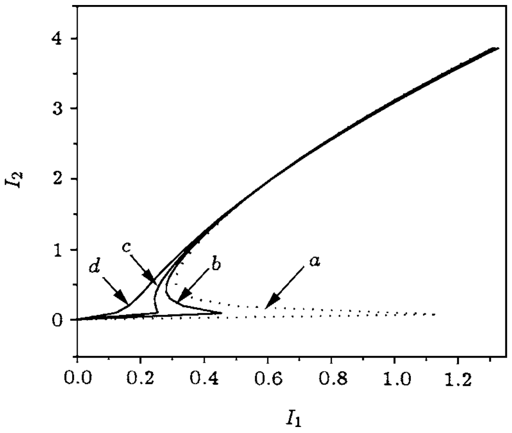

Fig.3. The optical bistability demonstrated with an amplitude type of EIG: γ_{31}=0.1, L=4, k=100. Curves a, b, c and d correspond to I_{c0}=0.0, 0.05, 0.1 and 0.2, respectively.

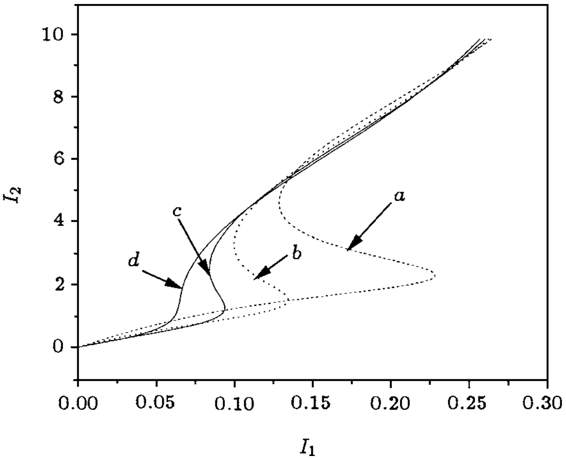

Fig.4. The optical bistability demonstrated with a hybrid type of EIG (Δ_c=0.0, Δ_p=2.2): γ_{31}=0.1, L=4, k=100. Curves a, b, c and d correspond to I_{c0}=5.0, 6.0, 6.5 and 7.0, respectively.

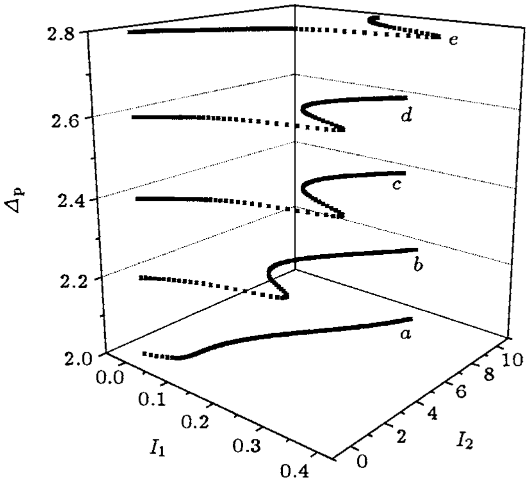

Fig.5. Comparison between different optical bistable systems using parameter of EIGs: γ_{31}=0.1, L=4, k=100, I_{c0}=5.0. Curves a, b, c, d and e correspond to the grating parameters Δ_c=0.0; Δ_p=2.0, 2.2, 2.4, 2.6 and 2.8, respectively.

In the second case, in Fig.2, we investigate the bistabilities of the system where a hybrid type EIG is utilized. The discussion is divided into two parts. Firstly, we discuss the optical bistabilities where a specific EIG ($\Delta_c = 0.0$, $\Delta_p = 2.2$) is chosen. The parameters are the same except for I_{c0} for the curves and the results obtained are those shown in Fig.4. The other part of the discussion involves the comparison of the optical bistabilities for several EIGs. The parameters of the EIGs are chosen to be Δ_c=0.0, Δ_p=2.0, 2.2, 2.4, 2.6 and 2.8 respectively. The optical bistable curve for every EIG is shown in the x–y plane in Fig.5, while the corresponding parameters of the EIG are marked in the z-axis. Figure 5 shows that the width of the bistable intensity (at which the hysteresis transits from a low branch to a high branch) enlarges with the increase of the detuning Δ_p.

4. Conclusion

In this paper, the EIG has been applied to the optical bistable system. It is shown that both the amplitude and hybrid EIG can be utilized if appropriate parameters are used. Under the same conditions, a hybrid grating has a width of the bistable field intensity (at which the hysteresis transits from the low branch to the high branch), which enlarges with the increase of the detuning Δ_p.

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