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POSSIBLE HYSTERESIS LOOPS OF RESONATORLESS OPTICAL BISTABILITY *

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ABSTRACT

We qualitatively show that hysteresis loops of intrinsic optical bistability phenomena without any additional feedback may be of various shapes including those of a butterfly and a three-winged bow.

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As the key principle of an all–optical digital logics towards optical computing, optical bistability (OB) is currently among the most significant research directions in the physics of highly excited materials. To obtain OB one traditionally combines an optical nonlinear medium possessing saturable absorption or/and Kerr–type refractive index with a resonator providing the feedback. The hysteresis loop (HL) of the output/input characteristics (OIC) of the OB, that looks mostly like S–shaped, develops counter–clockwise [1]. However, under certain circumstances HLs may be of different more or less complicated forms. A new kind of HL with one common intersection point between two stable states was reported in [2]. In [3] a nonlinear optical medium with induced absorber in a ring resonator was shown to manifest four topologically distinct OIC of the HL which cover those mentioned in [1,2]. The authors of [4] studied HL and multistability in a double resonator with an additional feedback and found various kinds of HLs with possible existence of five stable output states for a given input. The behaviour of an induced absorber in a hydrid ring resonator was investigated in [5] where instantaneous counting for both dispersive and absorptive nonlinearity could lead to very confused HLs.

Novel ways of achieving OB based on the intrinsic (resonatorless) feedback due to self–focusing by nonlinear refraction [6] or due to the kinetics between the photo–induced excitation real population and its relaxation by recombination processes [7,8] or due to other mechanisms have now been already well–recognized. The HL of such a resonatorless OB has been known as gone clockwise contrary to that in a resonator [7,8].

In this letter, we qualitatively show that the HL of the resonatorless OB might, in principle, be more complicated as compared with those reported in [7,8] and under some conditions it might display itself bow–shaped (or butterfly–shaped as called in [3]) or three–winged–bow–shaped with two intersection points of stable states.

Taking into account the intramedium photons which are driven by the input intensity I_i and whose density is assumed proportional to the output intensity I_t, the OIC of the resonatorless OB in the medium is determined by the two following equations [9,10] (see also [11]):

$$I_i = \frac{[(\rho+\alpha)^2+\beta^2]\rho}{1-\rho} \qquad (1)$$

$$I_t = \frac{[(\rho+\gamma)^2+\lambda^2]\rho}{1-\rho} \qquad (2)$$

where ρ labels the relative density of some quasi–particles (electrons, holes, excitons, biexcitons, ...) or the relative temperature in the case of thermally induced OB; α, β and λ specify the medium and the experiment parameters such as quasi–particle energy, dephase and depopulation times, medium–light coupling constant, constants of interaction between quasi–particles, detuning, etc. Their concrete expressions for the cases of Frenkel– and Wannier–excitons can be found in [9,10] and [11], respectively. From (1) and (2) it follows that I_t as a function of I_i depends parametrically on ρ. The necessary [12] and sufficient [10] conditions for the curves $\rho = \rho(I_i)$ and $\rho = \rho(I_t)$ to be S–shaped are respectively of the forms:

$$27\beta^2 < \alpha^2(8\alpha+9) \quad \text{and} \quad \alpha < 0 \qquad (3)$$

and

$$27\lambda^2 < \gamma^2(8\gamma + 9) \quad \text{and} \quad \gamma < 0 \,. \tag{4}$$

Otherwise, I_i and I_t increase monotonically for growing ρ in its physical region: $0 \leq \rho \leq 1$ (see [10]). If (3) hold, the OIC will be bistable disregarding (4) are met or not. However, the shape of the curve $I_t = I_t(I_i)$ is sensitively affected by the fulfillment of (4). If (4) are not fulfilled (but (3) are), the OIC will have a well–known shape [7,8] of resonatorless increasing absorption bistability with the HL being passed clockwise. When both (3) and (4) hold I_t will vary versus I_i in a very complicated manner. Depending on the sequence of the turning points $\rho_1, \rho_2, \tilde{\rho}_1, \tilde{\rho}_2$ (see [3,9,10] of the curves $\rho = \rho(I_t)$ and $\rho = \rho(I_i)$, and by a graphical method described in detail in [10] six topologically possible shapes of OIC have been schematically sketched in [9] whose HLs develop as seen from Fig.1. Note that the butterfly–shaped HL with both switchings down (Fig.1a) is also observed in [2] and in [3] (see Fig.6b of [3]), whereas that with both switchings up (Fig.1b) is not discussed yet in [2] and [3] but it is numerically plotted in [11] (see Fig.2 therein). Further, our HLs in Figs.1c,1e and 1f correspond to those in Figs.6c,6d and 6a of [3], but the HL in our Fig.1d is by no reason omitted in [3]. Our results here thus seem most general in comparison with [2,3] and [11].

A particularity to be stressed is that the resonatorless curve $I_t = I_t(I_i)$ is characterized not only by the successive order of the above–said turning points as stated in [3,8,10] but also by three other factors: (i) The values of these turning points, (ii) the values of extrema of the functions $I_i = I_i(\rho)$ and $I_t = I_t(\rho)$, and (iii) the concrete forms of the curves $\rho = \rho(I_i)$ and $\rho = \rho(I_t)$. Since α, β, γ and λ in (1) and (2) are cumbersome functions of the medium and the experiment parameters, the numerical plotting of the OIC based on such parameters cannot, in general, show up all the possible shapes of $I_t = I_t(I_i)$ from the topological point of view. By the reason, the authors of [11] drew the OIC for a given set of parameters and obtained their Fig.2 (see [11]) unknowing whether other topological different shapes of OIC exist or not, and, if they exist, what they are. Other choices of parameters may give the same kind of the OIC, and hence by doing so one hardly finds all the possibilities that may happen. At this moment, the graphical method suggested in [10] helps us to handle such a difficulty. Using the method, we plot in Fig.2, for example, the OIC from the known curves of $\rho = \rho(I_i)$ and $\rho = \rho(I_t)$ for the situation of $\rho_1 < \tilde{\rho}_1 < \tilde{\rho}_2 < \rho_2$. We see that different shapes of $\rho = \rho(I_i)$ with one and the same shape of $\rho = \rho(I_t)$ may degenerate qualitatively different OIC. Namely, as can be checked from Fig.2, the broken–line case yields the HL resembling that in Fig.1f, while the solid–line case produces that like Fig.1b (!) though their full OIC (see Fig.1b in [9] and the solid–line curve in the 4th quarter of Fig.2 of this letter) are distinct at all. Since the HLs of Fig.1b and of the solid–line case in Fig.2 correspond to different sequences of the turning points, i.e. the former is of the situation of $\rho_1 < \tilde{\rho}_1 < \rho_2 < \tilde{\rho}_2$ and the situation for the latter is $\rho_1 < \tilde{\rho}_1 < \tilde{\rho}_2 < \rho_2$, and they both display themselves butterfly–shaped with two switchings up, we can conclude that the successive order of $\rho_1, \rho_2, \tilde{\rho}_1, \tilde{\rho}_2$ does not characterize single–valuedly the development of the HL.

Applying our graphical method with more care to the shape of the curves $\rho = \rho(I_i)$

and $\rho = \rho(I_t)$ we, in addition to the six possibilities discussed in [9,10], schematically draw in Fig.3 the new six topological variants of the OIC whose corresponding HLs are also represented in Fig.4. The nature of HLs in Figs.4c to 4f is similar to that in Fig.1. The HLs in Figs.4a and 4b are, however, of new kind which have two intersection points of the two stable states with a switch–up for increasing I_i and another switch–down at lower input intensity for descreasing I_i. They look imitatively like a three–winged bow. It is worth noticing that direct switching between the stable states at the intersection points cannot occur because their phases differ from each other.

Finally, we wish to add that making use of the HL with no intersection points between stable states one can transform the cw laser radiation into a sequence of square pulses [13], whereas with the aid of the butterfly–shaped HL a sequence of triangular pulses may be produced [2]. The HL with the shape of a three-winged bow then opens a possibility of obtaining a pulse sequence in the form of a saw with inequable tooths which could be man–controlled for oriented practical purposes by choosing appropriate input parameters. Furthermore, the above–said variety of the HL shape must influence optical properties of a medium under intense irradiation. Say, the anomaly of nonlinear polariton dispersions should be "more anomalous" than that predicted e.g. in [14, 15].

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FIGURE CAPTIONS

Fig.1 Hysteresis loop development of the six OB possibilities outlined in [9].

Fig.2 Graphical reproduction of two kinds (broken– and solid–line) of OIC with different $\rho = \rho(I_i)$ and with one and the same $\rho = \rho(I_t)$ in the siutation of $\rho_1 < \bar{\rho}_1 < \bar{\rho}_2 < \rho_2$.

Fig.3 Six new topologically different OIC with the sequences of $\rho_1, \rho_2, \bar{\rho}_1, \bar{\rho}_2$ corresponding to those in Fig.1. The four asterisks in each OIC (two are their extrema and others are of infinite slope) reflect the four turning points (of the curve $\rho = \rho(I_t)$ and $\rho = \rho(I_i)$). The switchings between stable states take place at the asterisks of infinite slope (see Fig.4). Since Eqs.(1) and (2) are cubic ones with respect to ρ the number of the turning points is four at the most. That ensures that more topologically complex OIC with more than four asterisks will be impossible.

Fig.4 Development of the HLs corresponding to the OIC in Fig.3.

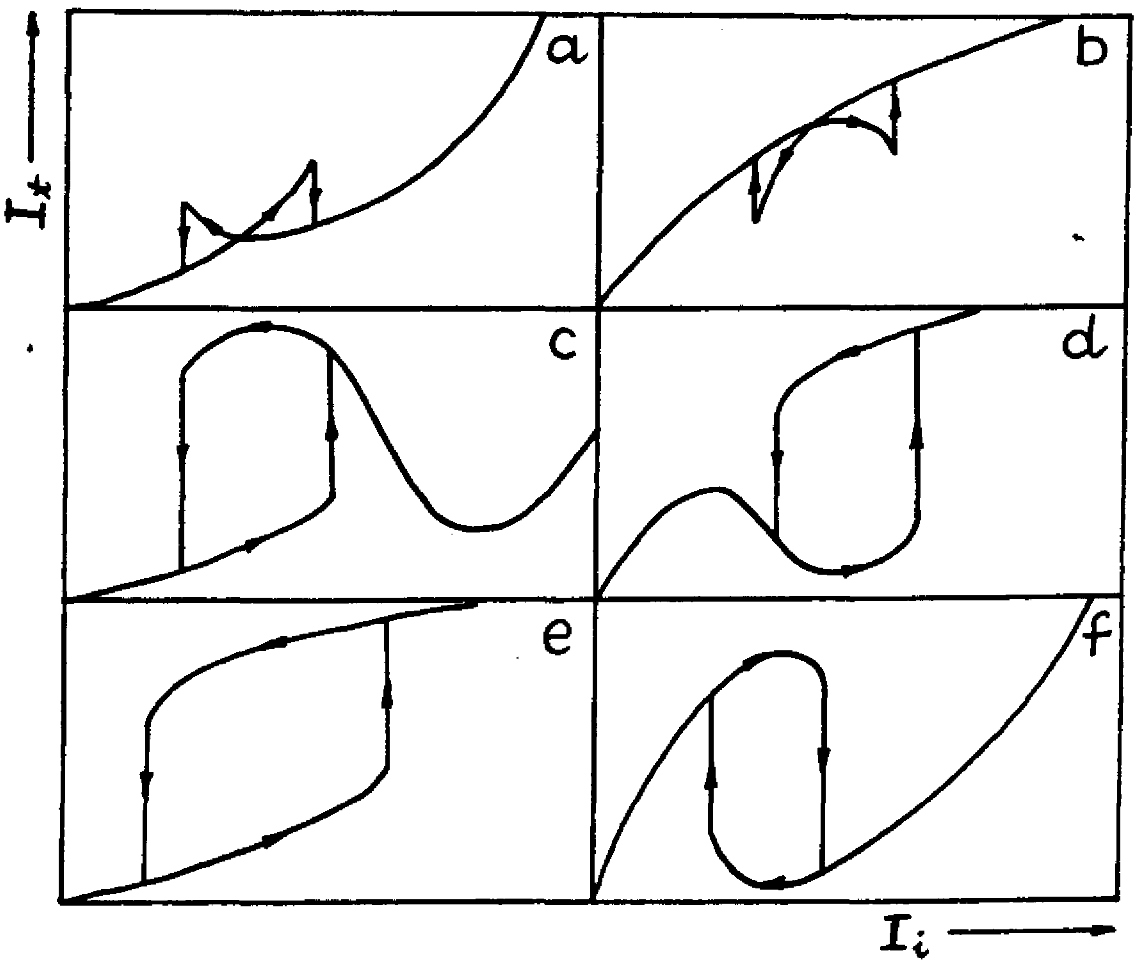

Fig.1

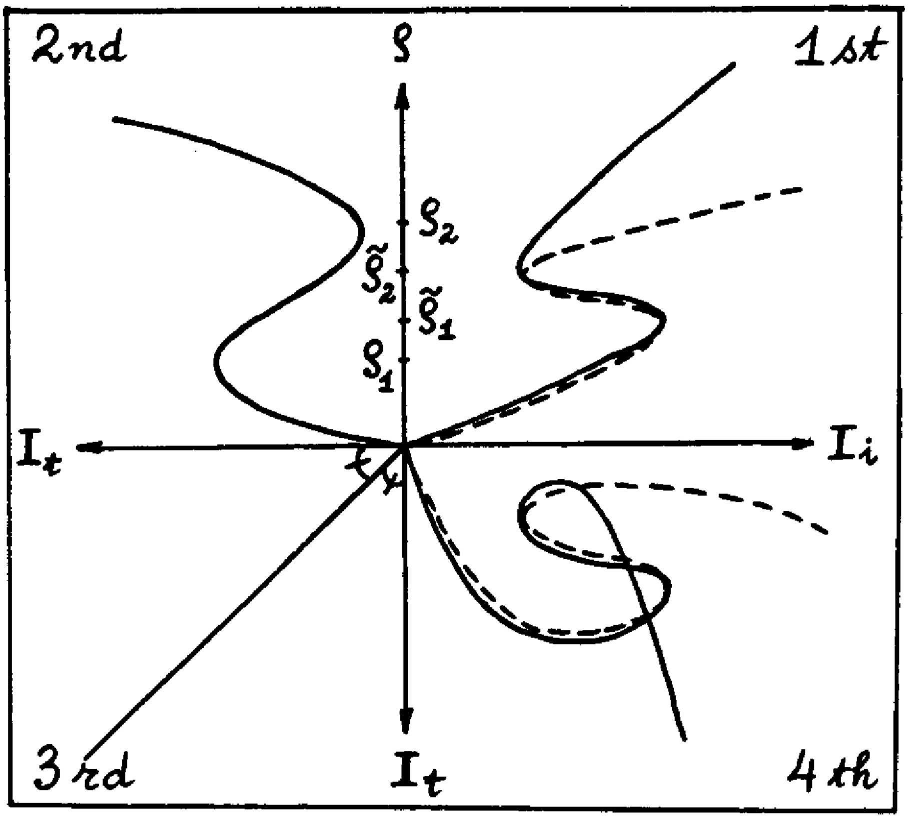

Fig.2

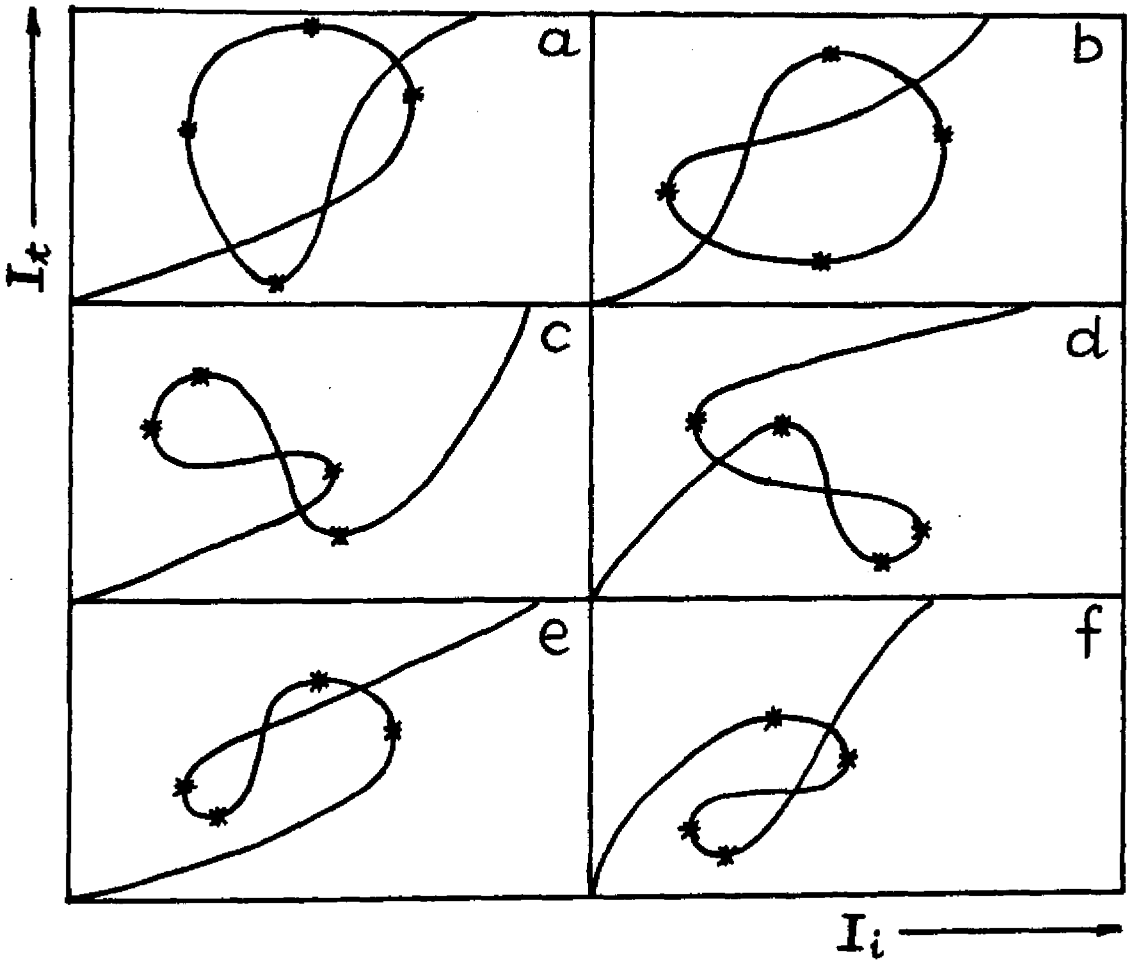

Fig.3

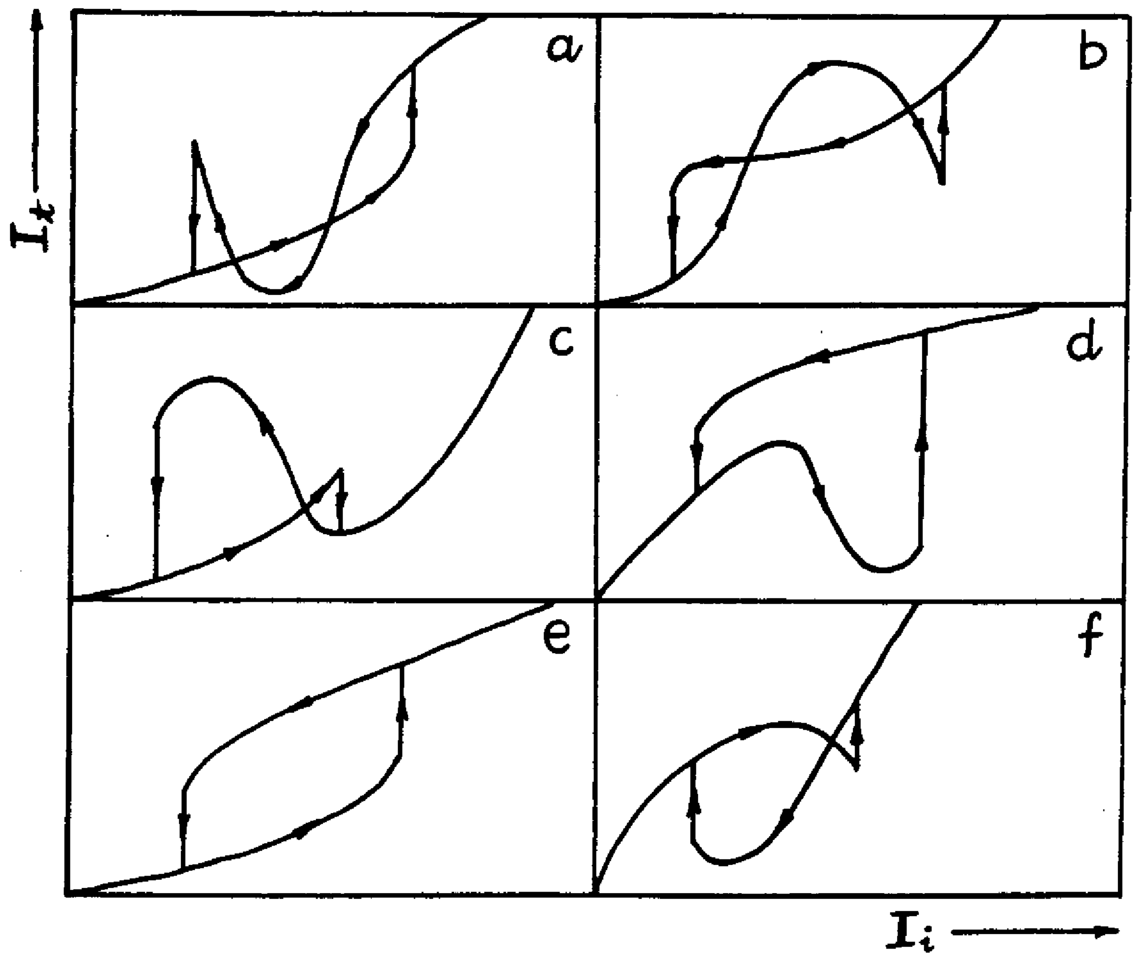

Fig.4

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