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Study of optical bistability in a fully optimized laser Fabry-Perot system

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Abstract
The analytical study of optical bistability is concerned in a fully optimized laser Fabry-Perot system. The related phenomena of switching dynamics and optimization procedure are also included. From the steady state of optical bistability equation can plot the incident intensity versus the round trip phase shift (φ) for different values of dark mistuning $\left(\varphi_o = 0, \frac{\pi}{1.5}, \frac{\pi}{3}, \frac{\pi}{6}, \frac{\pi}{12}\right)$ or finesse (F= 1, 5, 20, 100). In order to obtain different optical bistable loops. The input-output characteristic for a nonlinear Fabry-Perot etalon of a different values of finesse (F) and using different initial detuning (φ_0) are used in this research. When the cavity finesse values increase, the switch-ON intensity increases for the same value of (φ_0), because the bistable loop width increases with increasing the cavity finesse values.

Key words
Optical bistability, optical switching, and Fabry-Perot cavity.

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دراسة الاستقرارية الثنائية البصرية لنظام متكون من ليزر مستمر مع مرنان فابري – بيروت

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الخلاصة
في هذا البحث، تم اجراء دراسة تحليلية لظاهرة الاستقرارية الثنائية البصرية لنظام مكون من ليزر مستمر مع مرنان فابري – بيروت ذو وسط لا خطي. ودراسة ديناميكية الفتح والغلق البصري وايجاد الحالات المثلى لتلك الظاهرة. ومن خلال معادلة الاستقرارية الثنائية البصرية للحالة المستقرة لتجويف المرنان نستطيع رسم علاقة بيانية للشدة الساقطة على وسط المرنان كدالة لازاحة الطور ولقيم مختلفة من درجة الموالفة الابتدائية لدالة الطور (φ_0) او لدرجة الدقة للنظام اللاخطي (finesse). وذلك للحصول على قيم مختلفة لحلقات ثنائية الاستقرار البصرية. وفي هذا البحث ايظا، تم استعمال خصائص الادخال والاخراج لمرنان فابري-بيروت ذو الوسط اللاخطي ولقيم مختلفة من درجة الدقة، فعند زيادة قيم درجة الدقة لتجويف المرنان فان شدة الفتح (witch-on) البصري ستزداد لنفس قيم دالة الطور الابتدائية، وهذا نتيجة زيادة عرض حلقة ثنائية الاستقرار البصرية مع زيادة قيم درجة الدقة لتجويف المرنان.

Introduction

In recent years considerable attention has been devoted to the perspectives of optical digital computers. A major factor and incentive for the rapid developments in this area has been the possibility of using light beams for parallel processing and the expectation of achieving a significant increase in computing speed as compared with conventional electronic computers. In the near future the development of simple digital optical signal processor is expected for applications in telecommunication. The rapid processing of large amounts of data is of particular importance in this field, e.g. for high resolution television and for optical information transmission. Analog optical devices are already being used for similar applications such as image processing and signal filtering. Universal digital optical computers superior in performance to electronic systems are expected at later stages of future developments. New computer architectures, such as neutral networks structured in analogy to the living brain, require a very large number of interconnections. Optical beam offers a solution to this problem.

An important prerequisite for the technical realization of digital optical processors is the development suitable switching elements, which have also been dubbed "optical transistor". In electronic transistor switches an electrical output signal is controlled by a likewise electrical input signal. In analogy to this, in a photonic switch, a light wave is controlled by another light wave whose phase, amplitude and polarization are modulated.

In conventional transistor the term "electronic" means that the input signals regulate the output by means of electrons in the switching elements. This is also the case for photonic switches, which, also in this connection, can be regarded as an extension of electronic elements to optical frequencies [1].

Dawes et al. [2] report an all optical switch that operates at low light level, and consists of laser beams counter propagating through a warm rubidium vapor that induces an off axis optical pattern. A switching laser beam causes this pattern to rotate even when the power in the switching beam is much lower than the power in the pattern. The observed switching energy density is very low, suggesting that the switch might operate at the single photon level. This approach opens the possibility of realizing a single photon switch for quantum information network.

In narrow bandgap semiconductors, the discovery of giant third order optical susceptibility [3] and optical bistability in InSb [4] and GaAs [5] opened up many possibilities for all optical data manipulation such as signal processing and optical computing [6, 7]. In all these processes the bistable switching mode can be considered as the most important optical function.

Switching experiments in GaAs were first demonstrated by Gibbs et al. (1979) [8]. In this investigation, the GaAs etalon was cooled to a temperature of ~10 K (liquid helium temperature) and obtained switch-ON time was ~1ns using an external pulse (200 Ps pulse duration, 590nm wavelength and Energy = 0.6nJ). Other interesting results were achieved by Tang et al. (1982) [9] on a GaAs sample held at 80 K (liquid Nitrogen temperature) using pulse (10Ps pulse duration, 600 nm wavelength and Energy = 1nJ) for which the observed switch –ON time was ~200Ps limited by the detector time resolution. For an InSb etalon, bistable switching was achieved [10] using a pulse from a Nd:YAG mode locked laser. The work of this field has been extended to cover different kinds of semiconductors such as CuCl. For this etalon the switch-ON of ~250Ps and switch-OFF of ~450Ps were measured [11] and it was shown that the switch time depends on the absorption.

The optical bistability (O.B) in photonic multilayers doped by grapheme sheets are studied by Dong Zhao et al in 2017, stacking two Bragg reflectors with a defect layer between the reflectors. O.B stems from the nonlinear effect of grapheme, so the local field of defect mode (D.M) could enhance the nonlinearity and reduce the thresholds of bistability achieves the tenability of bistability due to that the D.M frequency and transmittance could be modulated by the chemical potential. Bistability thresholds and interval of the two stable states could be remarkable reduced by decreasing the chemical potential. The study suggests that the tunable bistability of the structure could be used for all-optical switches in optical communication systems [12].

The dynamical hysteresis of a semiconductors microcavity as a function of the sweep time illustrated by Rodriguezet et al. in 2017. The hysteresis area exhibits a double power law decay due to the influence of fluctuations, which trigger switching between metastable states. Upon increasing the average photon number and approaching the thermodynamics limit, the double power law evolves into a single power law. This algebraic behavior characterizes a dissipative phase transition [13].

Jeremy Butet and Olivier J.F.Martin introduced the influence of Fano resonances on the nonlinear response of hybrid plasmonic nanostructures, i.e., nanoantennas loaded with a nonlinear optical material, is theoretically investigated using the combination of a surface integral equation method and an analytical model [14].

It has been established that the switch-ON and OFF in optically bistable devices will occur by superimposing an external pulse on a continuous wave holding the system close to one of the critical points of the bistability curve. The role of the external pulse in this process is to generate more carrier in order to change the refractive index and thereby change the optical path length of the beam. However, if the difference between the critical power and the holding power is small compared with the power change involved by the switching pulse, the switching is ruled by a pulse energy scaling law [15]. This characteristic is pointed out in a numerical study of absorptive bistability in a good cavity limit (where the cavity lifetime is more than the material life time, $\tau_c >> T_1$) and has been analytically proved by Mandel [10] by a asymptotic analysis. The switch-ON of intrinsic optical bistable devices with external pulse was demonstrated [16, 17] and to get the switch-OFF time, the input intensity must be reduced below the switch-OFF intensity. Obviously, the switching of the devices in either direction ON and OFF with external pulses and keeping the input intensity constant is very desirable in many applications.

Optical bistability is a phenomenon which arises in the transmission of light by an optical cavity filled with a resonant medium. Precisely, we consider a c-w laser beam which is injected into a resonant cavity tuned or nearly tuned to the incident light. The incident beam is partially transmitted partially reflected and partially scattered by the cavity. When the cavity is empty the transmitted intensity is proportional to the incident intensity, where the proportionality constant depends on the cavity detuning and the finesse of the cavity. On the other hand, when the cavity is filled with material resonant or nearly resonant with the incident field the transmitted intensity is a nonlinear function of the incident intensity. Therefore, the transmitted power and the system behavior can be determined by the factor $\frac{\alpha L}{T}$, where α is the absorption coefficient, L is the sample thickness, and T is the mirror transmissivity. In particular, under suitable conditions, the transmitted intensity varies discontinuously and exhibits a hysteresis cycle. This is so-called optical bistability (OB). This phenomenon was predicted by Szoke and Coworkers in 1969 [18]. Some years later performed a numerical treatment of OB in a Fabry – Perot cavity, which suggested experiment works as illustrated in Fig.1. The main requirements to get such phenomenon are the nonlinearity of the medium and the optical feedback action. Optical bistability can be classified as absorptive or dispersive depending on whether the feedback occurs by way of an intensity dependent absorption or by way of an intensity-dependent refractive index. These experiments have shown that this system is the basis for quite a number of device application as optical memory, optical transistor, clipper, …etc. These crucial results stimulated a very active, theoretical research which bifurcated into two direction. The first channel was mainly interested in the device aspects of the phenomenon and in particular investigated the feasibility of electro-optical system to produce bistability and related phenomena. The second channel studies optical bistability as a fundamental field of the interaction between multiatomic system and radiation. Precisely, it considers the optical bistable system as the passive counterpart of the laser.

Theory of optical bistability

Two requirements are needed to observe O.B.: the nonlinearity of the medium and cavity feedback. The medium may be material with an intensity dependent refractive index,

$n = n_0 + n_2 I$ (1)

where n_0 is the linear refractive index and n_2 the nonlinear refractive index.

The feedback is produced by placing material in a F-P. etalon.

Let us now consider the case of linear F-P. (length = D) of refractive index = n_0 and mirror reflectivity R, as shown in Fig.1. When this cavity is illuminated with input intensity I_{int}, the transmission (T) of this cavity is described by as [19]:

$$\mathrm{T} = \frac{1}{1 + F \sin^2 \varphi_o} \qquad (2)$$

where φ_o is the linear round-trip phase shift (initial detuning) and equal to $\frac{2\pi}{\lambda} n_o D$, λ is the radiation wavelength, and F is the coefficient of finesse.

$$F = \frac{4R_\alpha}{(1 - R_\alpha)^2} \qquad (3)$$

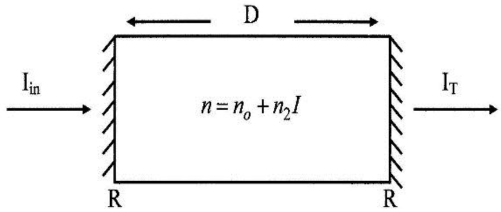

Fig.1: Fabry-Perot interferometer of length (D) and mirror reflectivity (R_α), I_{in} and I_T are the incident and transmitted intensities respectively.

As the linear refractive index (n_0) is changed to a nonlinear (n), Eq. (1) becomes:

$$n(I_{\mathrm{int}}) = n_o + n_2 I_{\mathrm{int}} \qquad (4)$$

where I_{int} is the internal intensity inside the cavity.

The nonlinear phase shift is described by

$$\varphi = \frac{2\pi}{\lambda} n_2 I_{int} D \qquad (5)$$

The general form of the transmission (Airy function) which includes the linear and nonlinear phase shift is:

$$\mathrm{T} = \frac{1}{1 + F \sin^2(\varphi + \varphi_o)} \qquad (6)$$

I_{int} related to the internal phase thickness is:

$$R_B I_{\text{int}} = I_T \tag{7}$$

where R_B is the reflectance of the output mirror of the F-P, and

$$I_T = T \cdot I_{in} \tag{8}$$

By using Eqs. (7) and (8), Eq.(6) becomes:

$$R_B I_{\text{int}} = \frac{I_{in}}{1 + F\sin^2(\varphi + \varphi_o)} \tag{9}$$

so that scaling:

$$R_B = \frac{2\pi \cdot n_2 D}{\lambda} \tag{10}$$

and appropriately scaling I_{in} to be dimensionless, eq.(9) becomes

$$\varphi = \frac{I_{in}}{1 + F\sin^2(\varphi + \varphi_o)} \tag{11}$$

Different bistable loops obtained when the loops plotted between φ_0.

The transmission of a F-P cavity is also given as

$$T = \frac{I_{int}(1-R)}{I_{in}(1+R)} \tag{12}$$

Results of optical bistability

From the steady state optical bistability Eq. (11) one can plot the incident intensity versus the round trip phase shift (φ) for different values of dark mistuning $\left(\varphi_o = 0, \frac{\pi}{1.5}, \frac{\pi}{3}, \frac{\pi}{6}, \frac{\pi}{12}\right)$ or finesse (F= 1, 5, 20, 100). Figs.2-6 represent the input-output characteristic for a nonlinear Fabry-Perot etalon of a different values of finesse (F) and using different initial detuning (φ_0), in order to obtain different optical bistable loops.

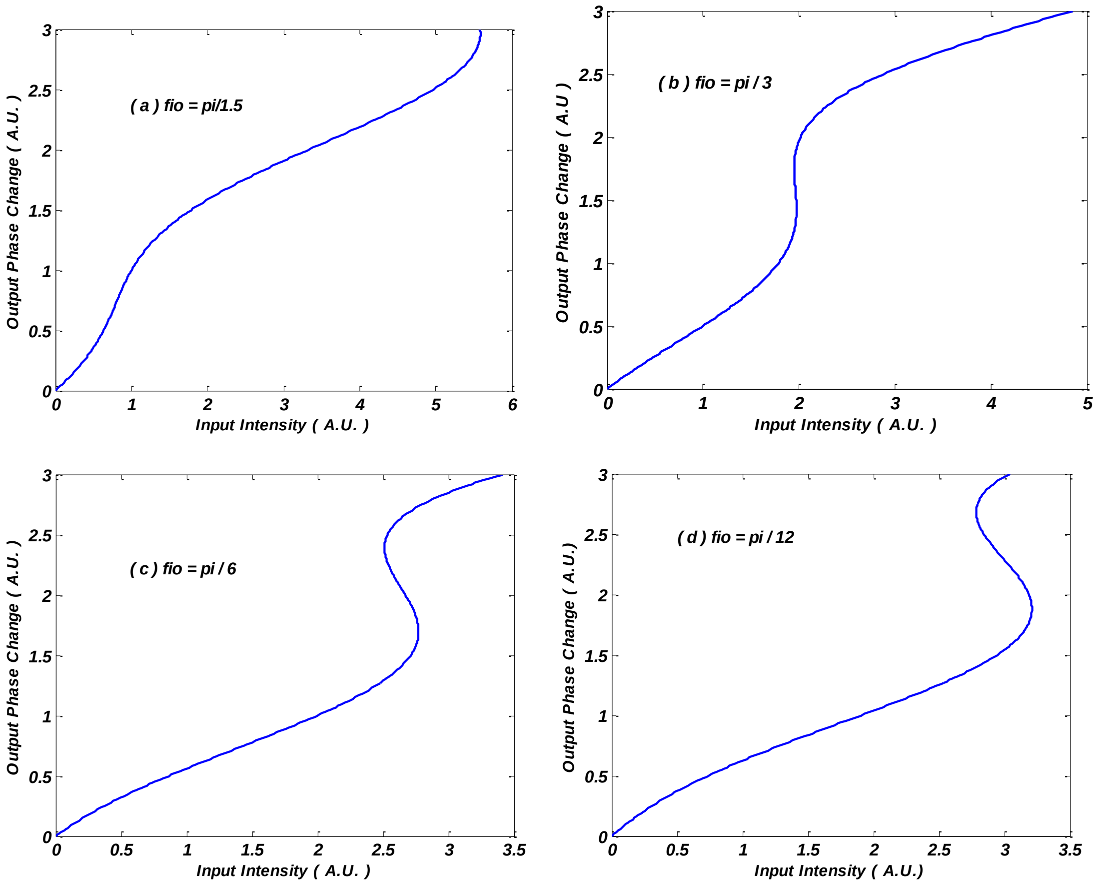

Fig.2: Input-Output characteristic for a nonlinear Fabry-Perot etalon of finesse value (F=1) and using different initial detuning.

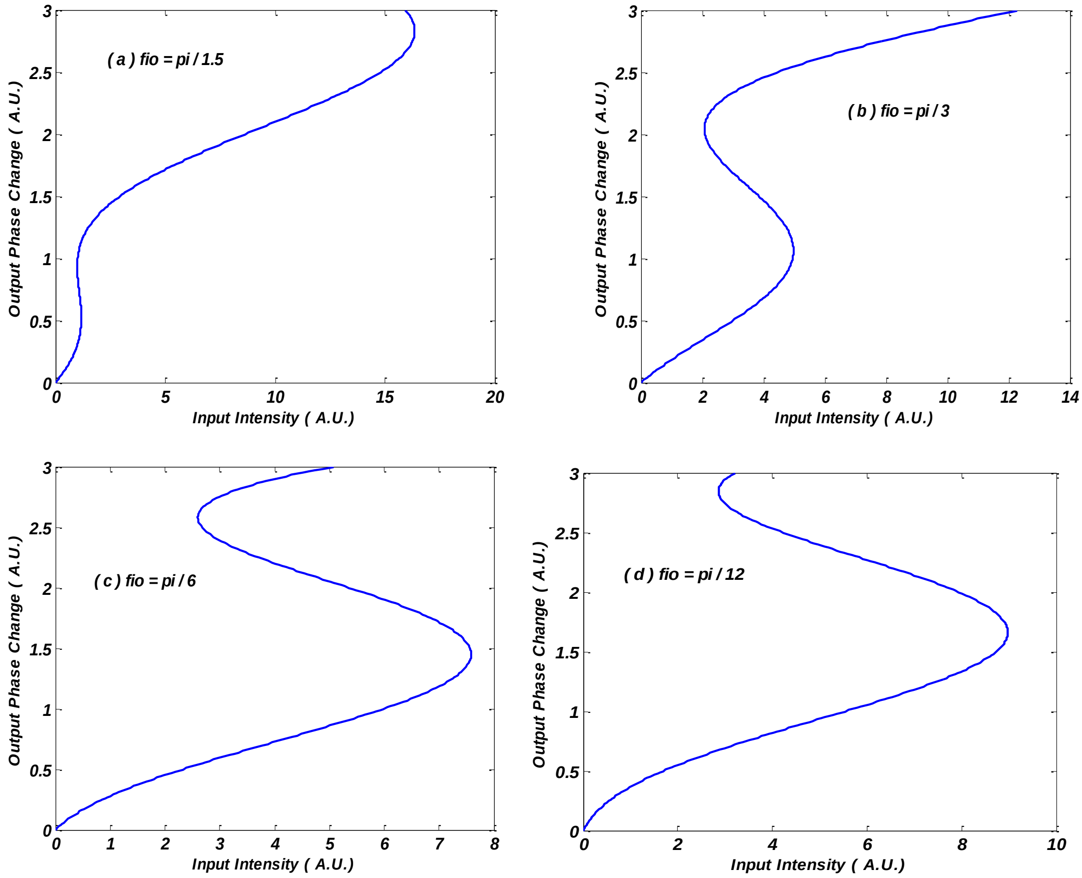

Fig.3: Input-Output characteristic for a nonlinear Fabry-Perot etalon of finesse value (F=5) and using different initial detuning.

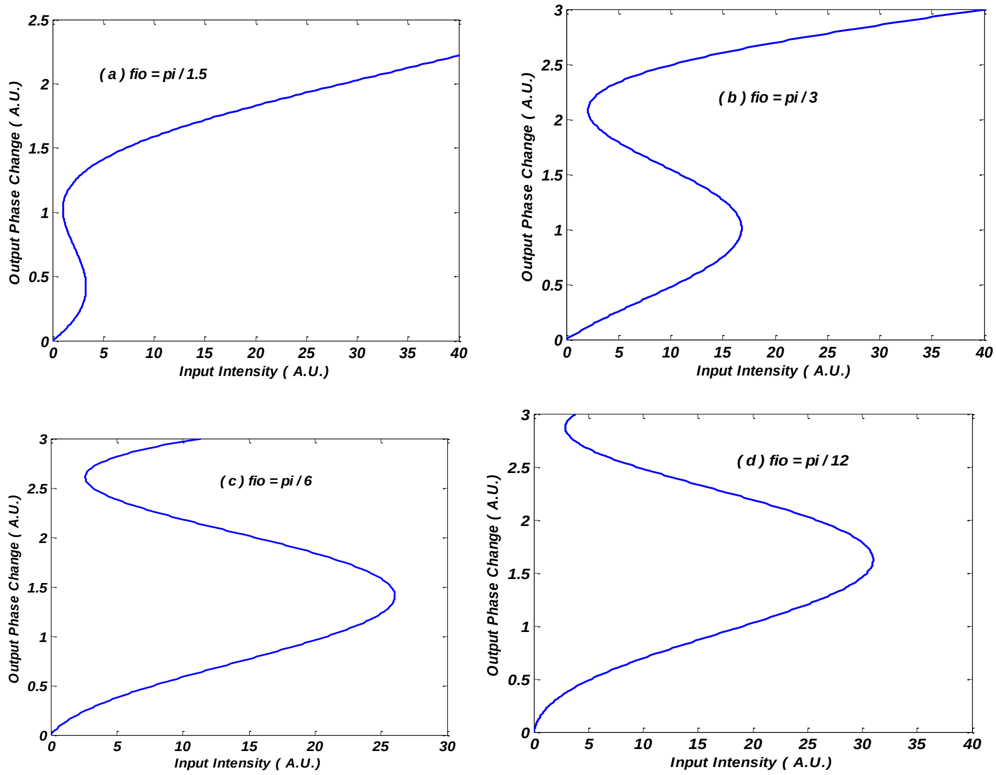

Fig.4: Input-Output characteristic for a nonlinear Fabry-Perot etalon of finesse value (F=20) and using different initial detuning.

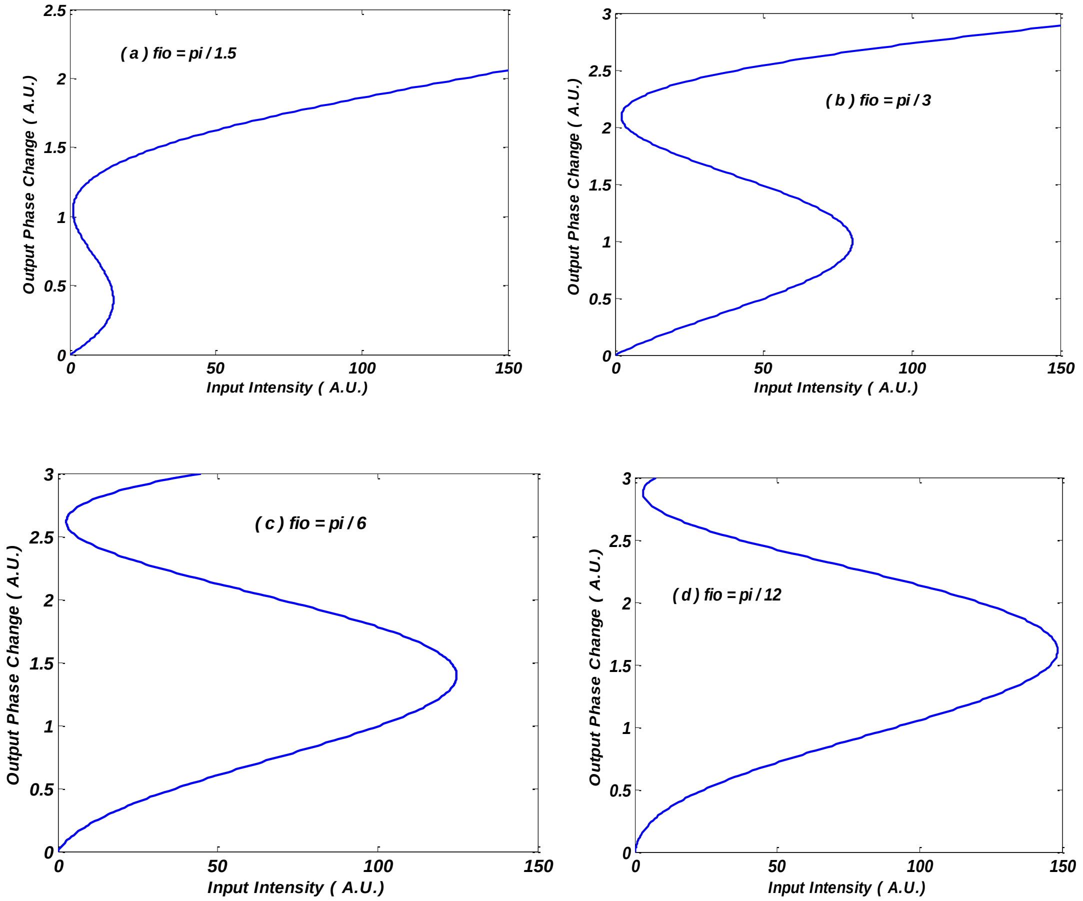

Fig.5: Input-Output characteristic for a nonlinear Fabry-Perot etalon of finesse value (F=100) and using different initial detuning.

Table 1 shows the results of each state and gives the values of the switch-ON and switch-OFF intensity for each value of initial detuning and finesse values.

Fig. 5(a) shows the relation between the dark mistuning and the switch-ON intensity for different values of cavity finesse. Fig. 5(b) shows the relation between the cavity finesse and the switch-ON intensity for different values of dark mistuning, each of which concludes that as the cavity finesse values increase, the switch-ON intensity increases for the same value of (φ_0), because the bistable loop width increases with increasing the cavity finesse values, also the switch-ON intensity decreases as the dark mistuning increases for the same value of finesse. This is also because the bistable loop width decreases as the dark mistuning value increases.

Table 1: The switch-ON and switch-OFF points for each value of initial detuning and Finesse values.

φ_o		finesse (F)										
		1	2	3	4	5	10	20	30	40	50	100
0	I_s(ON)	N.L.	N.L.	N.L.	N.L.	10.5	19	35	53	70	87	172.5
	I_s(OFF)	N.L.	N.L.	N.L.	N.L.	3.25	3.2	3.2	4	3	3	3
$\frac{\pi}{12}$	I_s(ON)	3.22	4.6	6.05	7.5	8.95	16.3	31	45.7	60.5	75	147.5
	I_s(OFF)	2.78	2.85	2.85	2.9	2.87	2.8	2.8	3	3	3	2.5
$\frac{\pi}{9}$	I_s(ON)	3.06	4.38	5.75	7.12	8.5	15.4	29.4	43.2	57	71	140
	I_s(OFF)	2.7	2.75	2.75	2.75	2.75	2.75	2.8	2.8	3	3	3
$\frac{\pi}{6}$	I_s(ON)	2.775	3.94	5.15	6.35	7.58	13.75	26	38.5	50.8	63	125
	I_s(OFF)	2.52	2.56	2.6	2.6	2.6	2.6	2.5	2.5	2.75	2.75	2.5
$\frac{\pi}{3}$	I_s(ON)	1.975	2.65	3.42	4.2	4.97	8.9	16.75	24.75	32.5	40.5	80
	I_s(OFF)	1.95	2.3	2.05	2.05	2.06	2.1	2.1	2.2	2	2	2
$\frac{\pi}{1.5}$	I_s(ON)	N.L.	N.L.	0.95	1.05	1.08	1.875	3.3	4.77	6.2	7.6	15
	I_s(OFF)	N.L.	N.L.	0.95	0.975	0.99	1.025	1.03	1.05	1.05	1.05	1

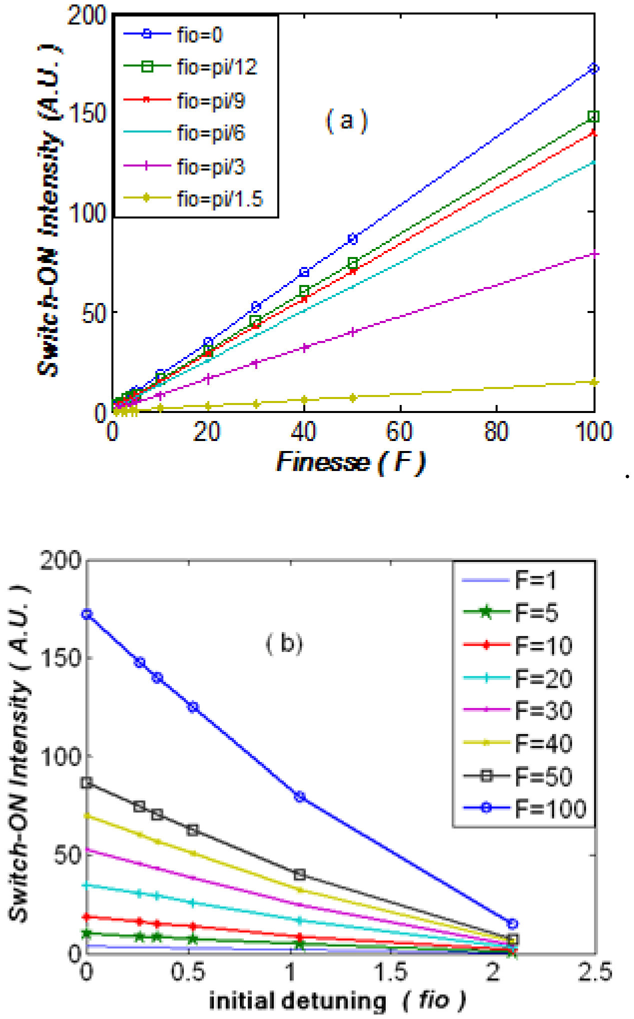

Fig.6: (a) The relation between etalon finesse value and switch-ON intensity for different values of initial detuning. (b) The relation between the etalon initial detuning and the switch-ON intensity for different etalon Finesse values.

Conclusions

An analytical study for the design of a bistable optical system was made. First, we present a theory of optical bistability for a Fabry-Perot etalon containing a nonlinear refraction material which gives various nonlinear relationship between the input and output intensity (in transmission and reflection mode of operation) starting from differential gain and critical switching to various widths of bistable loops which leads to a different switch ON & OFF points depending on the initial detuning and the cavity finesse values.

The O.B. method is supported by the graphical solution theory in calculating these switching points which shows agreement with the above results.

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