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Optimization procedures using effect of etalon finesse and driving term on optical bistability

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Abstract

In this work, analytical study for simulating a Fabry-Perot bistable etalon (F-P cavity) filled with a dispersive optimized nonlinear optical material (Kerr type) such as semiconductors Indium Antimonide (InSb). Because of a tradeoff between the etalon finesse values and driving terms, an optimization procedures have been done on the InSb etalon/CO laser parameters, such as critical switching irradiance (I_c) via simulation systems of optimization procedures of optical cavity. In order to achieve the minimum switching power and faster switching time, the optimization parameters of the finesse values and driving terms on optical bistability and switching dynamics have been studied.

For different values of a cavity finesse (F=25 and 2.37) the switching intensity takes low values with a high finesse etalon compared to a high switching intensity with a low finesse etalon. So, the minimum switching power for a low finesse etalon is about 0.785 mW, and is about 0.0785 mW for a high finesse etalon. The driving term peak of a high finesse etalon becomes higher and the slowing down region becomes less, leading to a fast switching about 300 ns for low finesse etalon, and about 150 ns for a high finesse etalon.

Key words
Cavity lifetime, Fabry-perot etalon, bistability.

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اجراءات التحسين بأستخدام تأثير جودة المرنان وحد الحفز على الأستقرارية الثنائية البصرية

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قسم الفيزياء، كلية العلوم، جامعة بغداد، بغداد، العراق

الخلاصة

في هذا العمل، تم اجراء دراسة تحليلية لمحاكاة مرنان فابري-بيروت (تجويف F-P)، والمملوء بمادة شبه موصلة لاخطية عالية التشتت (نوع كير) مثل انديوم-أنتيمونايد (InSb). بسبب التوفيق بين طول المسار البصري للنموذج داخل المرنان وعمر التجويف الفعال، تم اجراء تحسين على معلمات الليزر (CO laser) ولمرنان انديوم-أنتيمونايد، وذلك بأستخدام التبديل الشعاعي أو شدة التبديل الحرجة (Ic) عبر أنظمة محاكاة لأجراء تحسين التجويف البصري. من اجل تحقيق الحد الأدنى من قدرة التحويل وزمن تحويل سريع تم دراسة معلمات التحسين لقيم جودة المرنان وحد الحفز وتأثيرها على الأستقرارية الثنائية البصرية وديناميكيات التحويل. ولقيم مختلفة من جودة التجويف (F= 25, 2.37) تأخذ شدة التبديل قيمًا منخفضة مع وجود قيم عالية لجودة المرنان. لذلك فأن مقدار شدة التبديل لقيم منخفضة من دقة المرنان بحدود 0.785 mW وحوالي 0.0785 mW لمرنان عالي الجودة. لذلك ستصبح ذروة حد الحفز للمرنان عالي الجودة كبيرة وتصبح منطقة التباطؤ أقل، مما يؤدي إلى اسرع تبديل بحدود 300 ns لأقل جودة مرنان و اقل سرعة تبديل وبحدود 150 ns لاعلى جودة مرنان.

Introduction

Optical Fabry-Perot cavities are common in laser spectroscopy with interferometry and are frequently used for the stabilization of laser sources [1, 2]. A novel application for high-finesse cavities was proposed in the early 90's in the upcoming field of cavity-QED: Single atoms are strongly coupled to a cavity-stored photon field such that the mutual coherent oscillatory exchange between both sub-systems is much faster than their individual decay rates. A number of experiments, in both the optical [3], and in the microwave regime [4] can be used for quantum information processing [5], where single quantum systems such as atoms or photons carry qubits (as the quantum alternative for the well known bits in information science).

The first observation of optical bistability of the etalon cavity was in Indium Antimonide [6]. The switching dynamics study of the InSb/CO system has progressed through bandwidth measurements [7], critical slowing down [8], and noise studies [9]. These studies give a clear understanding of the role of time constants near the bistable switch points and the limitations on switching speed.

Several parameters should be considered in order to get a fully optimized device such as the beam spot size, the etalon thickness, the frequency of the input beam, and the absorption coefficient.

Many attempts have been made to get the optimum conditions of low switching power and fast switching speed of the bistable devices using different specifications such as high finesse case [10] and low finesse case [11]. For an active F-P cavity under plane wave illumination conditions, the critical switching irradiance below which bistability can not be obtained.

Design considerations for the simplest bistable element include choice of material, the frequency of the holding laser radiation, and hence the linear absorption and nonlinear refraction of the active medium, the sample length, and the reflectivity of the front and back sample faces, can be obtain to optimize a number of possible criteria: minimum holding power or intensity, maximum contrast between switch-OFF and switch-ON, minimum switching speed, …. etc.

In this paper, we present to conduct analytical study for simulating a Fabry-Perot bistable etalon filled with a nonlinear optical material such as InSb illuminated with a pulse laser (a CW CO laser leads to a switching energy about 11.77 pJ). To fully optimized InSb etalon (high finesse etalon). In order to achieve the minimum switching power and faster switching time, the optimization parameters of the effect finesse values and driving terms on optical bistability and switching dynamics must be studied.

Theoretical work

(i)- The effect of finesse values

The critical switching irradiance (I_c) can be estimated from the studies of Frank [12]:

$$I_c = \left[\frac{\lambda\alpha}{3\pi n_2}\right] f\left(R_f , R_b , \alpha D\right) \qquad (1)$$

where λ is the beam wavelength, α is the absorption coefficient, n_2 is the nonlinear refractive index and R_f, R_b, αD which appear in the cavity characteristics factor represent the front face, back face reflectivity of the etalon and the absorption length, respectively.

When $R_f R_b = e^{-4\alpha D}$, the cavity factor takes a minimum value and for a high finesse can be written as [13]:

$$f\left(R_f, R_b, \alpha D\right)=\frac{8}{3\sqrt{3}}\frac{\left(1-\sqrt{R_f R_b}\,e^{-\alpha D}\right)^2}{\left(1-R_f\right)\left(1+R_b e^{-\alpha D}\right)\left(1-e^{-\alpha D}\right)}\frac{1}{\sqrt{F}} \quad (2)$$

where F represents the coefficient of the cavity finesse (F= $4R_\alpha$ / (1- R_α), also R_α = $(R_f\ R_b)^{1/2}$ exp(-αD)), and D is the cavity length. When R_f = R_b the minimum cavity factor is:

$$f_{\min}=\frac{3\sqrt{3}}{2}\left(1-R_f\right) \quad (3)$$

which is about 0.39 for R_f = R_b = 0.85.

The best way to show the importance of a high finesse etalon in reducing the switching power may be understood through Fig.1. There are two cases have been considered a high and low finesse etalon for the same detuning. The intersection of the input power (straight line 1) with a high finesse curve produces a small bistable loop, but with a low finesse case the large bistable loop can be achieved. However, the intersection of line 2 with a high finesse and low finesse curves will produce critical switching characteristic and a bistable loop respectively. To conclude this argument, it is easy to get low switching power with a high finesse etalon compared to a high switching power with a low finesse etalon for the same detuning.

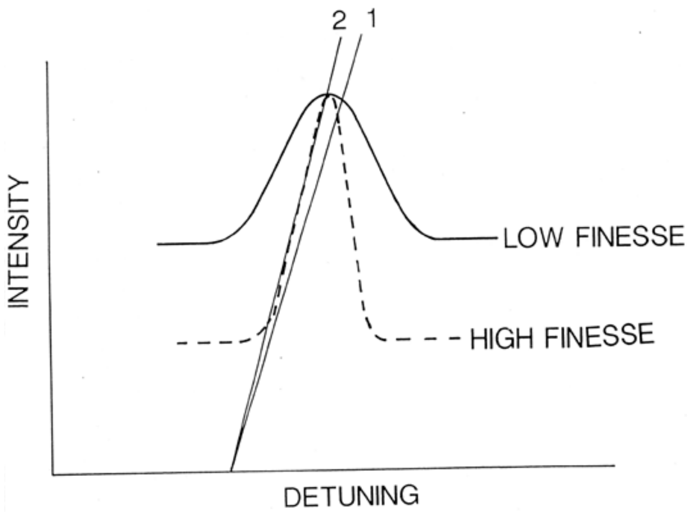

Fig.1: The intersection of the input power (straight line) with a high and low finesse curves [12].

(ii)- The effect of the driving terms

The Rang-Kutta method [14] of the numerical integration has been used to calculate and to show how the driving term $\partial\varphi_{(t)}/\partial t$ behaves as one changes the holding phase in a bistable loop region. This term represents the dynamical equation of nonlinear phase due to the change in cavity detuning induced by the optical nonlinearity.The driving term is given by [14]:

$$f\left(\varphi_{(t)}\right)=\frac{\partial\varphi_{(t)}}{\partial t}=\frac{1}{\tau_R}\left(\frac{I}{1+F\sin^2\left(\varphi_{(t)}+\varphi_o\right)}-\varphi_{(t)}\right) \quad (4)$$

where τ_R represents the recombination time, φ_o is the initial detuning of the cavity, R is the reflectivity, I is the input intensity, t represents the carrier lifetime at the surface, φ is the nonlinear phase due to the change in cavity detuning induced by the optical nonlinearity for a Fabry-Perot etalon filled with a nonlinear medium, and φ_t represents the round trip phase change.

The first step in solving Eq. (4) is by putting the initial values of (t) as (t_o) and $\varphi_{(t_o)} = \varphi_h$. Scaling time (t) to a recombination time (τ_R), i.e. t=1 to τ_R and when the step size is confined (for example, the different in scaling of carrier lifetime is $\Delta t=0.1$), the solution becomes:

$$\left.\begin{aligned} k_1 &= \Delta t\big(f(\varphi_{(t)})\big) \\ k_2 &= \Delta t\left(\varphi_h + \frac{1}{2}k_1\right) \\ k_3 &= \Delta t\left(\varphi_h + \frac{1}{2}k_2\right) \\ k_4 &= \Delta t(\varphi_h + k_3) \end{aligned}\right\} \quad (5)$$

And

$$\Delta\varphi = \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4) \quad (6)$$

The driving term is at its maximum when the intensity (I_o) lies on top of the Airy function (position 1) and when (I_o) becomes on the bottom of the Airy function curve (position 2) the driving term takes a minimum value, as shown in Fig.2.

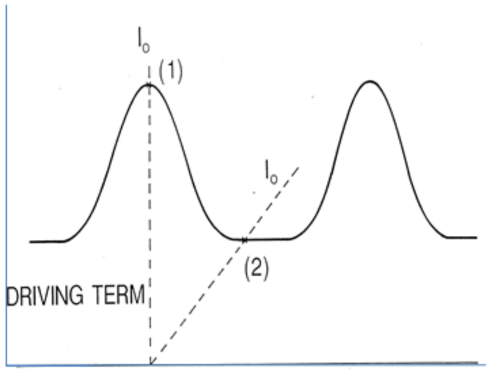

Fig.2: The dependence of the driving term on the incident intensity I_{in} [14].

To show how the driving term varies, we must consider the following cases. In case one, when the holding phase is zero or any minimum value, the output characteristic, as shown in Fig.3(a) will start with nonlinear characteristic and long slowing down region as shown in Fig.3(b). In case two, the holding phase becomes very close to the switch point leading to fast switching output characteristics, as shown in Fig.3(c).

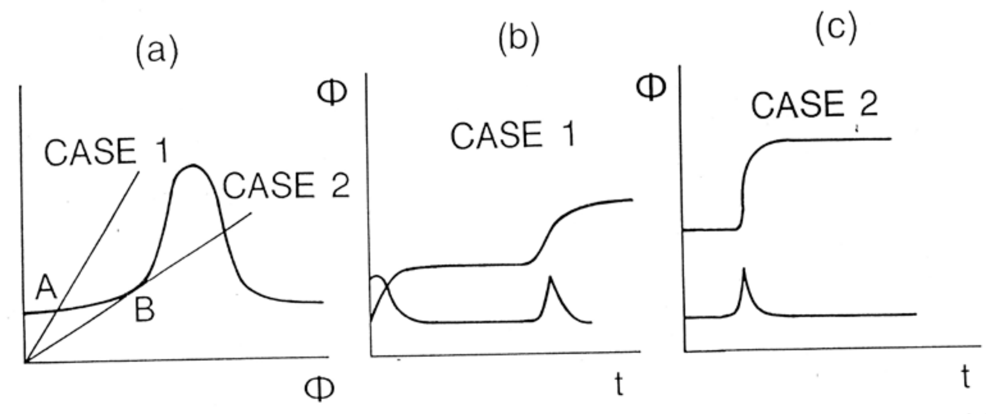

Fig.3: (a) The intersection of the phase with the Airy function. When the holding phase is far away from the switch point, the output characteristic will start with nonlinear characteristic and long slowing down, (b) when the holding phase becomes very close to the switch point, the fast switching characteristics will occur (c) [14].

when the focusing beam radius on the bistable element is less than the diffusion length, the carriers will diffuse out and fill the same volume.The relation between the switching power and spot diameter is given by [12, 14]:

$$P_c = \frac{\pi L_D^2}{2} g\left(\frac{\omega_o}{L_D}\right)\frac{\hbar c}{\sigma_n \tau} f\left(R_f, R_b, e^{-\alpha D}\right) \quad (7)$$

where

$$g(x) = \frac{8 e^{\frac{-x^2}{8}}}{Ei\left(\frac{x^2}{8}\right)} \quad , \quad x = \frac{\omega_o}{L_D}$$

where ω_o Is the spot diameter, and:

$$Ei(x) = \int_x^{\infty} \frac{e^{-u}}{u}\, du$$

For high finesse case the cavity factor (at R_F=R_b) getting from Eq. (2).
The switching power becomes:

$$P_c = \frac{\pi L_D^2}{2} \frac{8e^{-\omega^2 / 8L_D^2}}{\ln\left(\frac{\omega_o{}^2}{8L_D^2}\right) - \left(\frac{\omega_o{}^2}{8L_D^2}\right) + \left(\frac{\omega_o{}^4}{256L_D^4}\right) - \left(\frac{\omega_o{}^8}{4608L_D^8}\right)} \cdot \frac{\hbar c}{\sigma_n \tau} f\left(R_{F,} R_b, e^{-\alpha D}\right) \quad (8)$$

Result and discussion

The plot of etalon thickness versus switching intensity for different values of cavity finesse (F=25 and 2.37) is shown in Fig.4. It is obvious that the low switching intensity with a high finesse etalon compared to a high switching intensity with a low finesse etalon for the same detuning. A MATLAP program version seven was used to study the optical bistability, switching dynamics and optimization of a nonlinear Fabry-Perot etalon.
It can be seen from Eqs.(7, 8) that the minimum switching power for a low finesse etalon is about 0.785mW, and about 0.0785 mW for a high finesse etalon.

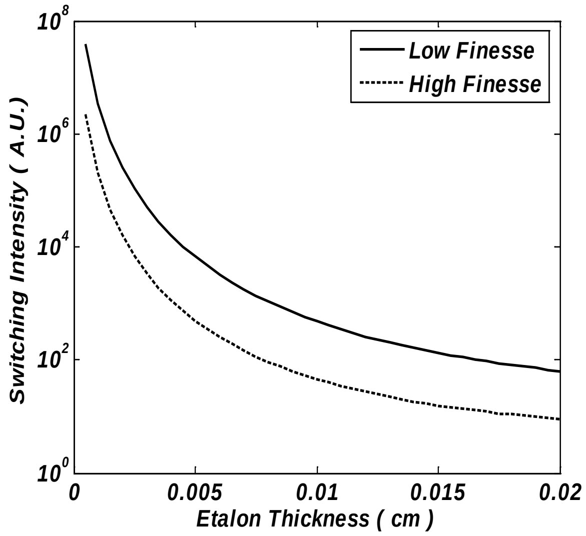

Fig.4: The effect of the etalon thickness on the switching intensity for different values of cavity finesse.

The way the driving term varies near the critical switch point for various finesse values (2.37, 15 and 100) are shown in Figs.5-7 respectively. The upper trace in each figure represents the change in the driving term. For the same percentage of stand-off from the switch point, the driving term peak of a high finesse etalon becomes higher and the slowing down region becomes less, leading to a fast switching as compared with a slow switching in a low finesse etalon. It was found from Figs.5-7 that the minimum switching time was about 300 ns for a low finesse etalon, and about 150ns for a high finesse etalon.

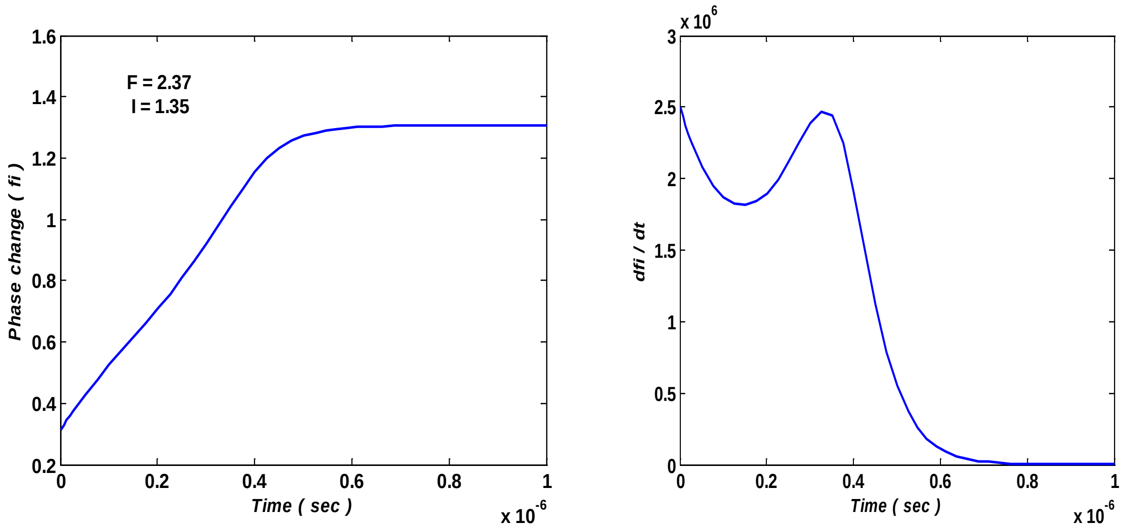

Fig.5: The change in the driving term in a low finesse etalon (F=2.37) using switching intensity (I=1.35) and the initial detuning $(\varphi_o = 0.6221\,\pi)$.

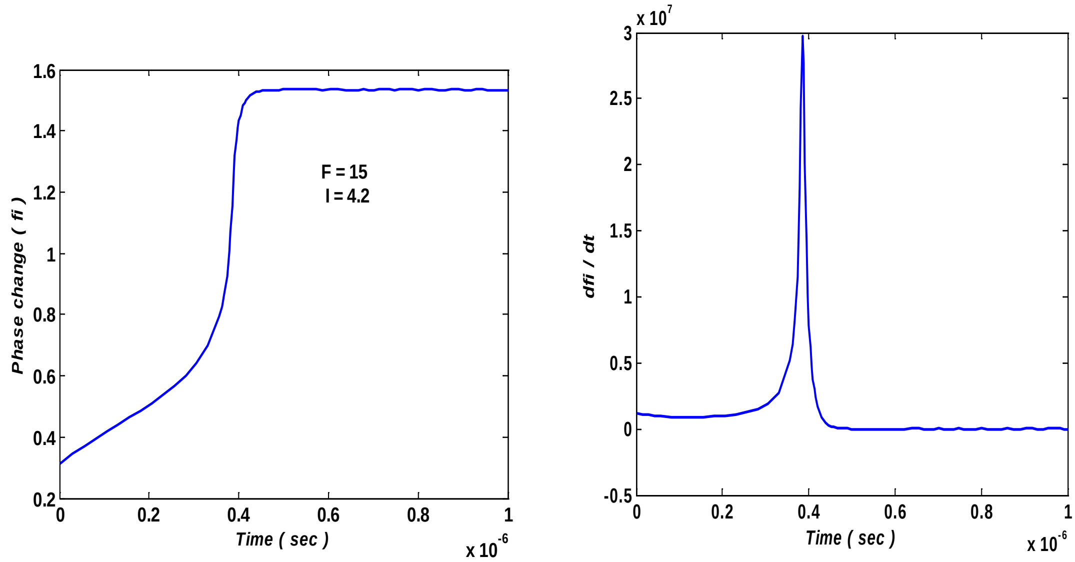

Fig.6: The change in the driving term for a finesse value (F=15) using switching intensity (I=4.2) and the initial detuning $(\varphi_o = 0.6221\,\pi)$

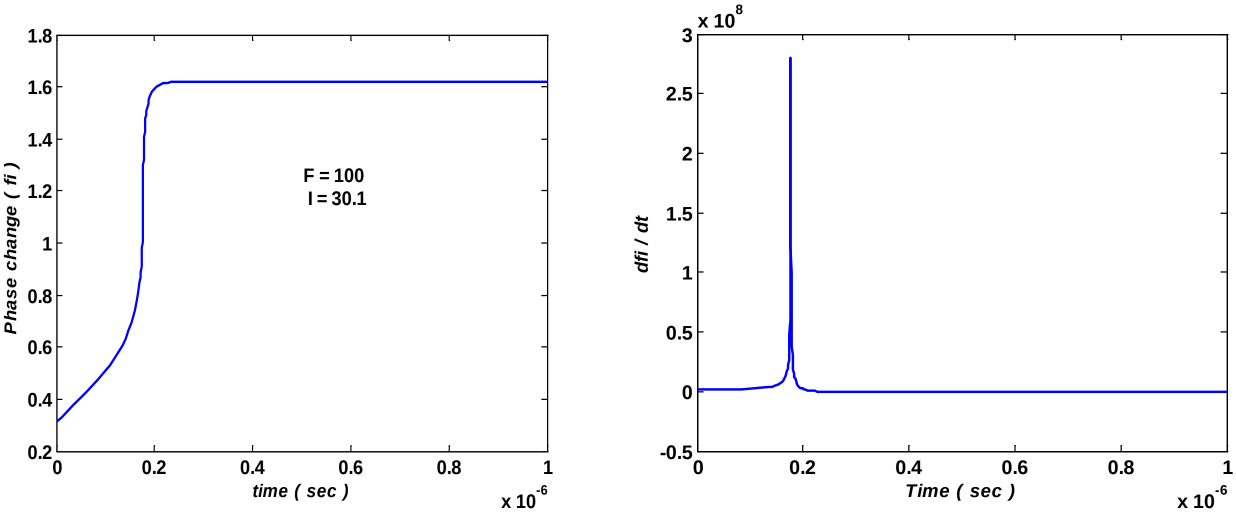

Fig.7: The change in the driving term in a high finesse etalon (F=100) using a switching intensity (I=30.1) and the initial detuning $(\varphi_o = 0.6221\,\pi)$.

Conclusions

In narrow bandgap semiconductors, the discovery of giant third order optical susceptibility and optical bistability in InSb opened up many possibilities for all optical data manipulation such as signal processing and optical computing.

The two values of an etalon finesse (F = 25 and F= 2.37) are both experiment the switching intensity reach low values put the value a high finesse etalon compared to a high switching reach with a low finesse etalon. The minimum switching power for a low finesse etalon about 0.785 mW, and is about 0.0785 mW for a high finesse etalon.

While, the driving term varies near the critical switch point for various finesse values (2.37, 15 and 100). The driving term peak of a high finesse etalon becomes higher and the slowing down region becomes less, leading to a fast switching as compared with a slow switching in a low finesse etalon. The minimum switching time was about 300 ns for a low finesse etalon, and about 150 ns for a high finesse etalon.

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