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Switching dynamics in terms of effective time constant to determine switching points using a Debye relaxation equation

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Abstract
In this work, the switching dynamics of a Fabry-Perot etalon were analyzed in term of effective time constant, which changes dramatically near the switching points. The switch-ON and switch-OFF have been analyzed numerically using a modified Debye dynamic equation. The method used to determine the solution of the Debye relaxation equations solved numerically to predict the behavior of the etalon for modulated input power.

Keywords: Debye relaxation equations and switching dynamics.

ديناميكيات التحويل بدلالة الثابت لزمني المؤثر لتحديد نقاط التحويل باستخدام معادلة الاسترخاء لديباي

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الخلاصة
في هذا العمل، يتم تحليل ديناميكية التحويل الخاصة بمرنان فابري-بيروت من خلال ثابت زمني فعال والذي يتغير بشكل مثير بالقرب من نقاط التبديل للفتح والغلق. كذلك تم تحليل عملية التحويل عدديا باستخدام معادلة الاسترخاء لديباي المعدلة, فالطريقة المستخدمة هي لدراسة حل المعادلات التفاضلية للوسط الغير خطي لمرنان فابري-بيروت. حل معادلات الاسترخاء لديباي عدديا هو للتنبؤ بسلوك المرنان لطاقة الادخال المضمنة.

Introduction

A Fabry-Perot interferometer has been used extensively in spectroscopy, maser and laser resonators[1]. However, In the optical regime,it has been limited to the observation of the cavity's static response. Advances in the lasers and optical coatings now offer the opportunity to explore the time response of the Fabry-Perot interferometer. However, this dynamic behavior has been previously observed in a high-Q superconducting cavity with a swept microwave source[2].

Optical bistability has been observed in a number of materials exhibiting the optical Kerr effect (e.g. sodium vapor, carbon disulfide, and nitrobenzene)[3]. The response time is large (in the nanosecond scale) and the power required for switching is also high. Semiconductors such as GaAs, InSb, InAs, and CdS exhibit a strong optical nonlinearity due to excitonic effects at wavelengths near the band gap[4]. A bistable device may simply be made of a layer of a semiconductor material with two parallel partially reflecting faces acting as the mirrors of a Fabry-Perot etalon [5].

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 carriers in order to change the refractive index and thereby change the optical path length of the beam[6]. However, the difference between the critical power and the holding power is small compared with the

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power change by the switching pulse. 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). The switch-ON of intrinsic optical bistable devices with external pulse was demonstrated [7]. 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 [8].

This paper presents an analytical study for simulating a Fabry-Perot bistable etalon filled with a nonlinear optical material (Kerr type) such as semiconductors (InSb) illuminated with a pulse laser. The steady state bistable is studied for different cavity parameters such as finesse (F) and initial detuning (φo) to predict the switching point (intensity) for each value of finesse and initial detuning. According to the results obtained, the switching dynamics were calculated to show the effect of the input intensity corresponding to the switching intensity calculated previously[8], and the material recombination time effect on the switching time. By overdriving the system, switch time of ~10 ns may be obtained using external pulsed sources.

Optical Bistability Dynamic Equations

An alternative method to study the dynamic or transient behavior of dispersive optical bistability (OB) systems is using the optical field equations coupled with the rate equation. The method with approximations to the optical field equation gives a phenomenon called "overshoot switching" The time dependence of the transmitted field is given by[9]:

$$\tau_c \frac{\partial E_T(t)}{\partial t} + \left\{1 - R \cdot e^{i\varphi(t)}\right\} E_T(t) = TE_o\left(t + \frac{\tau_c}{2}\right) \quad \text{....(1)}$$

where $\varphi_{(t)}$ is the round trip phase change. The second equation for the nonlinear medium obeys a Debye relaxation equation[10-11]:

$$\tau_R \frac{\partial \varphi}{\partial t} + \varphi = \beta_o + \beta |E_T|^2 \quad \text{.................... (2)}$$

where β_o contains all intensity dependent phase shifts: β is the intensity dependent phase shift. Equations (1) and (2) model the time evolution of the output field and cavity round trip phase change for time dependent inputs.

An alternative representation of the source term $(\beta_o + \beta E_T^2)$ for the nonlinear material is formed by an etalon with $\tau_R >> \tau_c$, if the transverse effectswere neglected, diffusion and nonlinear decay is given by equation(3) in which the internal intensity (I_{int}) is related to the input intensity (I_{in}) by[12-13]:

$$I_{\text{int}} \propto \frac{I_{in}}{1 + F\sin^2(\varphi + \varphi_o)} \quad \text{.......................... (3)}$$

where φ is the nonlinear phase due to the change in cavity tuning induced by the optical nonlinearity, φ_o represents the initial detuning, and *F* is the coefficient of finesse .

$$F = \frac{4R}{(1 - R)^2} \quad \text{..................................(4)}$$

When equation (3) is used, the dynamical equation (2) becomes:

$$\tau \frac{\partial \varphi}{\partial t} + \varphi = \frac{I_{in}}{1 + F\sin^2(\varphi + \varphi_o)} \quad \text{................. (5)}$$

Where I_{in} is scaled to be in unit of phase. Eq. (5) is used to represent the dynamic behavior of InSb etalon device, where the equation represents efficiently the dynamic behavior of the system. To study the switching dynamics of a Fabry-Perot etalon, equations (1) and (2) are analytically studied to predict the behavior of the cavity for modulated input power.

From equation (5), it can be seen that the approach to the steady state is exponential[14-15].

$$\frac{1}{\tau_e} = \frac{1}{\tau}\left[\frac{1+F\sin^2(\varphi_s+\varphi_o)+\varphi_s\cdot F\sin 2(\varphi_s+\varphi_o)}{1+F\sin^2(\phi_s+\phi_o)}\right] \qquad \text{....(6)}$$

and

$$\frac{1}{\tau_e} = \frac{1}{\tau}\cdot\frac{1}{1+F\sin^2(\varphi_s+\varphi_o)}\frac{\partial I_{in}}{\partial \varphi_s} \qquad \text{............... (7)}$$

Results and Discussion

From equation (7), a plot of (τ_e) versus (I_{in}) for various values of initial detuning (φ_o) and Finesse values (F) as in the bistable loops are shown in Figure-1. From this figure, the variation of effective time constant (τ_e) as a function of input intensity for finesse value is equal to one (**F** = 1) with differential gain. Each plot reveals that as the switch points for bistability are approached, the effective time constant (τ_e) increases dramatically. This characteristic indicates that as (a and c in this figure approaches), their response will be severely suppressed or, in contrast,. In addition, beyond the point of contact in region (b) in each figures where $\frac{\partial I_{in}}{\partial \varphi_s}$ is negative, there is no stable solution and small disturbances will begin significantly over time, taking the system from one bistable state to the other. In the upper state region (c), the system will again have an effective time constant which is appropriate to the detuning from the switch-down point and this will characterize the switch-OFF dynamics. A matlap programs were used to study the variation of the effective time constant as a function of input intensity for different finesse value and initial detuning.

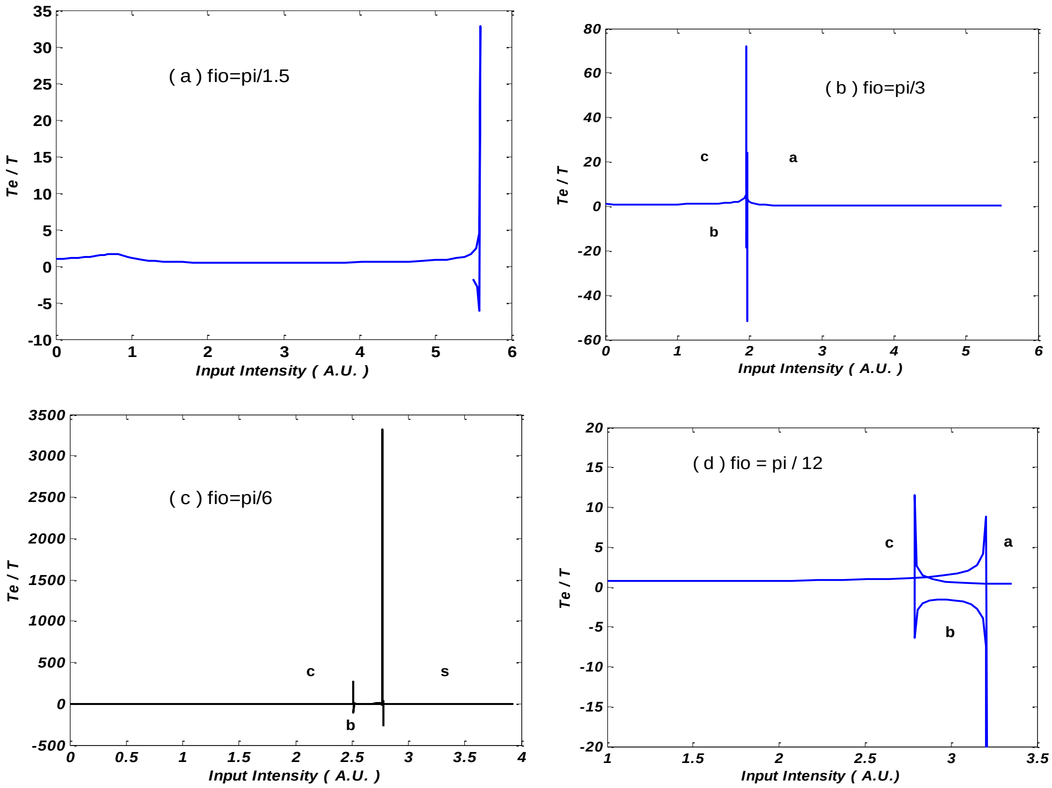

Figure 1-Variation of effective time constant τ_e as a function of input intensity for finesse value F=1; (a) differential gain, (b) critical switching, (c) & (d) bistability loops.

Figure-2 represents the variation of effective time constant (τ_e) as a function of input intensity for a finesse value of five (F = 5) with differential gain. This figure reveals that as the switch points for bistability, the effective time constant (τ_e) increases dramatically. This characteristic implies that as a switch point is around (regions (a) and (c) in this figure) the response of the system will be exponentially damped or, conversely, the system will be unable to respond to noise frequencies above a critical frequency determined by the effective time constant.

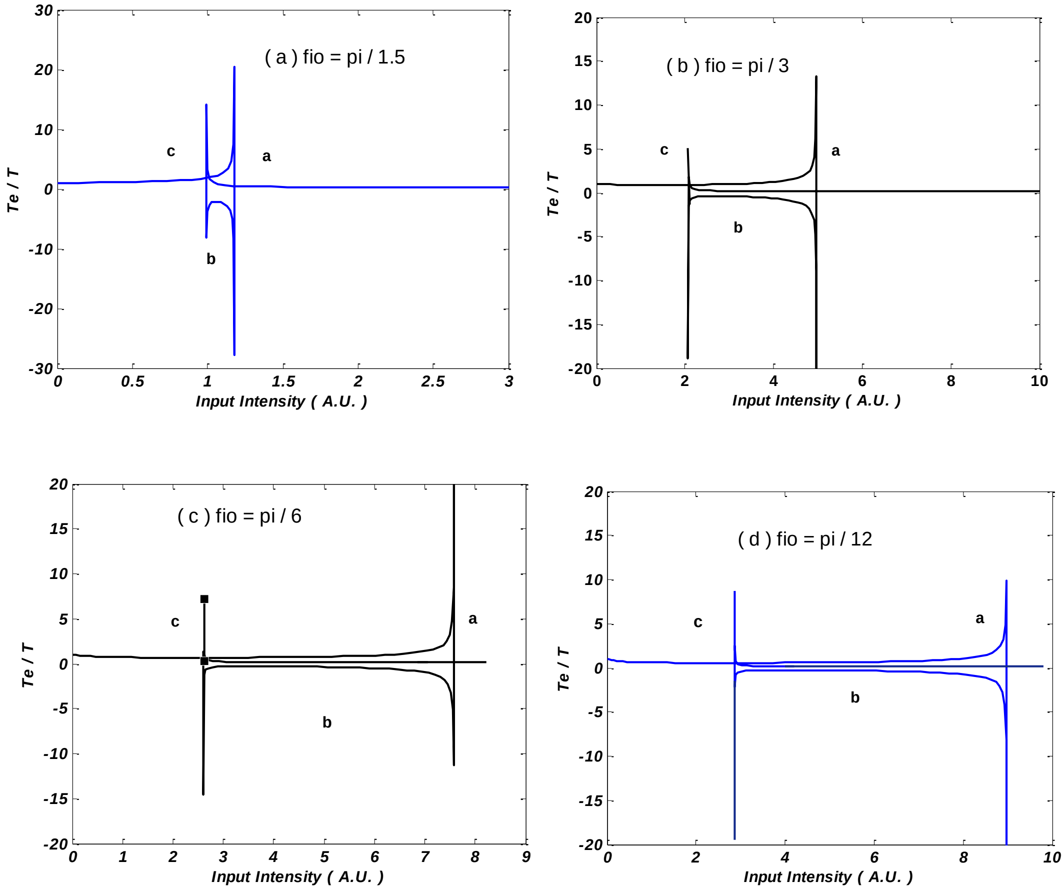

Figure 2-Variation of effective time constant τ_e as a function of input intensity for finesse value F=5. (a) differential gain, (b) critical switching, (c) & (d) bistability loops.

Figure-3 shows the variation of effective time constant (τ_e) as a function of input intensity for finesse value equal to 20 (F = 20) with differential gain. The effective time constant (τ_e) increases dramatically.

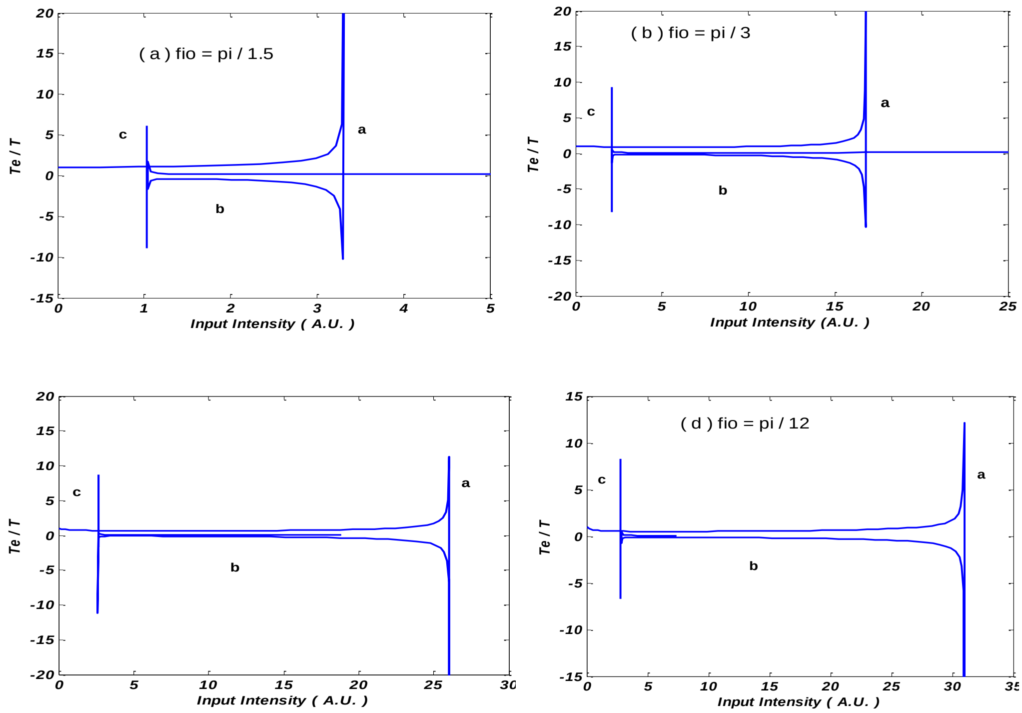

Figure 3-Variation of effective time constant τ_e as a function of input intensity for finesse value F=20. (a) differential gain, (b) critical switching, (c) & (d) bistability loops.

Figure-4 shows the variation of effective time constant (τ_e) as a function of input intensity for finesse value equal to 100 (F = 100) with differential gain. The switch points for bistability are approached and the effective time constant (τ_e) increases dramatically also.

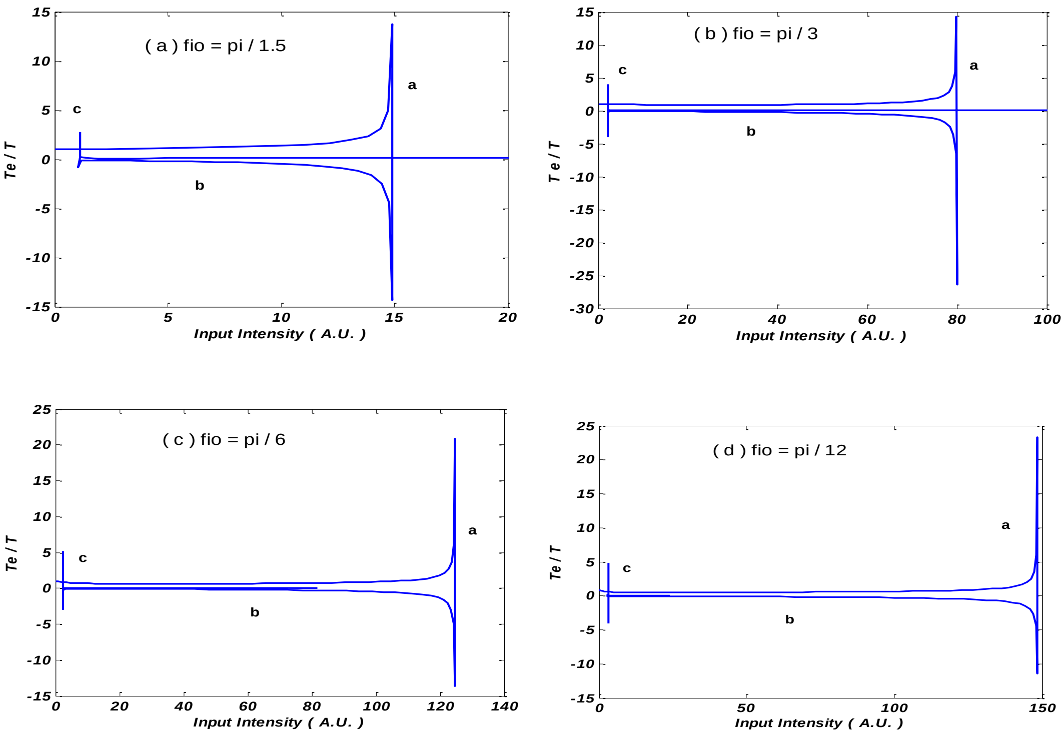

Figure 4-Variation of effective time constant as a function of input intensity for finesse value F=100. (a) differential gain, (b) critical switching, (c) & (d) bistability loops.

The rate of change of the effective time constant (τ_e) as the switch points are approached also depends on the initial detuning (φ_o) of the system. To determine the complete dynamic characterization in the bad cavity case, the following basic specifications are required: (i) the nonlinear medium time constant (τ), (ii) the initial detuning (φ_o), (iii) the etalon finesse, and (iv) the magnitude of the switching increment. These basic requirements are, however, influenced by the noise content on the system, the degree of over switch applied, and the rate at which the switching increment is applied.

Conclusion

An analytical study for the design of a bistable optical system was studied. The effective time constant increases dramatically. The response of the system will be exponentially damped or conversely. The characteristic of the system will be unable to respond to noise frequencies above a critical frequency, this behavior determined the effective time constant.

References

1. Taylor, K. Fryet et al. **2015.** Cavity enhanced nonlinear optics for few photon optical bistability. *Optical Express*, **23**(12).

2. Dawes, A.M.C., Illing, L., Susan Clark, M. and Gauthier, D.J. **2005**. All-Optical Switching in Rubidium Vapor. *Science*. **308**: 672.

3. Casteels, W. **2017.** Critical dynamical properties of a first-order dissipative phase transition. *Phys. Rev*. *A*95.

4. Miller, D.A.B., Smith, S.D. and Johnston. A. **1979.** Optical Bistability and Signal Amplification in a Semiconductor Crystal. Application of a new Low Power Nonlinear Effect in InSb. *Appl. Phys. Lett*., **35**: 658.

5. Gibbs, H.M., McCall, S.L., Venkatesan, T.C.N., Gossard, A.C., Passner, A. and Wiegmann, W. **1979.** Optical Bistability in semiconductors. *Appl. Phys. Lett*. **35**: 451.

6. Derevyanchuk O. V., Kramar N. K., Kramar V. M**. 2017**. Internal optical bistability of quasi-two-dimensional semiconductor nanoheterostructures. Scientific Proceedings International Scientific-Technical Conference (SPISTC).

7. Wilson, R.M. **2016.** Collective phases of strongly cavity photons. *Phys. Rev*. A93.

8. Gibbs, H.M., McCall, S.L., A.Passman, A., Gossard, A.C., Wiegmann, W. and Venkatesan, T.C.N. **1979.** Progress toward practical optical bistable devices. *IEEE J. Quant. Electron*. QE-15, p.108D.

9. Passner, A., Venkatesan, T. and Wiegmann, W. **1982.** External OFF and ON Switching of a Bistable Optical Devices. *Appl. Phys. Lett*. **40**(3): 205.

10. Rodriguez, S. R. K. **2017.** Probing a dissipative phase transition via dynamical optical hysteresis. *Phys. Rev. Lett*. **118**.

11. Porto, J.A., Martin-Moreno, L. and Garcia-Vidal, F.J. **2004.** Optical bistability in subwavelength slit apertures containing nonlinear media. *Physical Review*. **B70**(8).

12. Rakhmanov, M., RSavage, R.L., DReitze, D.L. and Tanner, D.B. **2001**. Dynamic resonance of light in Fabry-Perot cavities. *Appl. Phys. Lett*. **40**(3): 205.

13. Hamel, P. **2015.** Spontaneous mirror- symmetry breaking in coupled photonic-crystal Nano-lasers. *Nat. Photonics*. **9**(3): 311.

14. Alessandro Alberucci et al. **2014.** Soliton enhancement of spontaneous symmetry breaking. *Optica*. **2**(9).

15. Kravets, N. **2014.** Bistability with optical beams propagating in a reorientational medium. *Phys. Rev. Lett*. **113**.