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STEADY STATE OPERATION OF A NON-LINEAR FABRY-PEROT FOR OBLIQUE INCIDENCE: POLARIZATION AND BEAM ANGLE DEPENDENCE

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Résumé - Les propriétés de transmission et de réflexion d'un Pérot-Fabry non linéaire de type Kerr, dépendent fortement de l'angle d'incidence, de la largeur et de la polarisation du faisceau incident. Des expériences sur les SEED's en Si confirment les résultats théoriques. Ces propriétés permettraient de techniques de commutation alternatives.

Abstract - Transmission and reflection of a non linear Fabry-Perot show strong dependence on the angle, width and polarization of the incident laserbeam. Experiments on Si-SEEDs confirm the theory. These properties could lead to interesting alternative switching mechanisms.

1 - INTRODUCTION

The aim of the paper is to study both, theoretically and experimentally, the modification in the steady state behaviour of a bistable Fabry-Perot when the angle of incidence, the width and/or the polarization of the beam, impinging on the system is changed. It can be easily shown that, according to the ratio of angle of incidence and beam width, several regimes of operation should be distinguished.

In the two-beam regime (large beam width, small angle of incidence), Miller's approach can be generalized, leading to strikingly different transmission and reflection characteristics of the device, according to polarization and angle of incidence.

In order to compare theory and experiment qualitatively, a Fabry-Perot Si-SEED is used, showing dispersive bistability with underlying thermo-optic origin. Beam width and angle of incidence are chosen such as to be compatible with the two beam regime. Some interesting applications, resulting from the impact of polarization on the steady state characteristics of a bistable device, are highlighted.

In the so-called 'multiple beam' regime (small beam width, large angle of incidence), the lack of feedback mechanisms does not allow for a generalization of Miller's approach. However the nonlinearities present in the system lead - theoretically - to interesting features of the output signal, after convergence through a lens.

2 - THE TRANSMISSION PROPERTIES OF A KERR-TYPE FABRY-PEROT IN THE PLANE WAVE APPROXIMATION (TWO BEAM MODEL)

The stationary electric field $\tilde{E}$ inside the cavity is defined as follows, using the standard forward and backward envelope functions:

$$\tilde{E} = e^{i\omega t} \left[ E_F(\tilde{r})e^{-i\tilde{K}_F \cdot \tilde{r}} + E_B(\tilde{r})e^{i\tilde{K}_B \cdot \tilde{r}} \right]$$

A similar expression holds for the magnetic induction. To solve the corresponding non linear wave equations, for $\tilde{E}$ (in the TE case) and for $\tilde{B}$ (in the TM case), we apply the slowly varying envelope approximation (SVEA) and take a scalar non linear susceptibility $\chi^{(3)}$, modeling the thermo-optic non linear effects.
Absorption is assumed linear and small. In this case, the amplitudes of the forward and backward waves satisfy simple equations, which can easily be solved using boundary conditions and yield:

\[ \begin{align*}
\bar{E}_F(z) &= \bar{E}_F(0) e^{-\frac{\alpha_E}{2\cos \theta''} z} \\
\bar{E}_B(z) &= \bar{E}_B(0) e^{-\frac{\alpha_E}{2\cos \theta''} (D-z)}
\end{align*} \] (2)

Here \( \theta'' \) is the angle of incidence of the beam inside the cavity and \( D \) the thickness of the sample. The non linear phase shifts satisfy the following equations:

for TE polarization:

\[ \bar{K}_F \cdot \bar{\phi}_F = -\frac{\omega^2}{2c^2} \chi^{(3)} \left[ |E_F|^2 + 2|E_B|^2 \right] \] (4)

\[ \bar{K}_B \cdot \bar{\phi}_B = +\frac{\omega^2}{2c^2} \chi^{(3)} \left[ 2|E_F|^2 + |E_B|^2 \right] \] (5)

for TM polarization:

\[ \bar{K}_F \cdot \bar{\phi}_F = -\frac{\omega^2}{2c^2} \chi^{(3)} \left[ |E_F|^2 + 2 \cos \theta'' |E_B|^2 \right] \] (6)

\[ \bar{K}_B \cdot \bar{\phi}_B = +\frac{\omega^2}{2c^2} \chi^{(3)} \left[ 2 \cos \theta'' |E_F|^2 + |E_B|^2 \right] \] (7)

The angle \( \theta'' \) appears in the expressions (4) and (5) not only because \( \bar{E}_F \) and \( \bar{E}_B \) are no longer parallel in the TM case, but also because \( \text{div} \ E \) is no longer zero.

Using the same notations as in /1, 2/, the solution of equations (2)-(7) using the proper boundary conditions, yield

\[ \bar{\phi}_F(D) - \bar{\phi}_B(D) = \frac{A \omega \chi^{(3)}}{2cn^2 \alpha_E T(\theta,\text{Pol})} \int_0^{\mu_0} \frac{\alpha_{E_D}}{c_0} \ln \tau_{NL} (1-e^{-\alpha_{E_D} \cos \theta''}) (1+R(0,\text{Pol}) e^{-\alpha_{E_D} \cos \theta''}) \] (8)

where \( R \) is the reflection coefficient at one interface of the Fabry-Perot and

\[ A = 3 \quad \text{for TE - polarization} \]

\[ = 1 + 2 \cos \theta'' \quad \text{for TM - polarization} \]

The overall transmission coefficient of the device can be cast in the traditional Airy formula:

\[ \tau_{NL} = \frac{T^2(\theta,\text{Pol}) e^{-\frac{\alpha_{E_D}}{\cos \theta''}}}{(1-R(0,\text{Pol}) e^{-\frac{\alpha_{E_D}}{\cos \theta''}})^2 + 4 R(0,\text{Pol}) e^{-\frac{\alpha_{E_D}}{\cos \theta''}} \sin^2 \Delta} \] (9)

Similarly, the non linear reflection coefficient can be obtained /5/.

The impact of a variable angle of incidence on the behaviour of a bistable device is thus threefold. First, an increase of the angle of incidence implies a longer optical pathlength through the resonator, enhancing the non linear effects. Second, a variation of the angle of incidence brings about a change in the value of the reflection coefficients of both interfaces of the non linear Fabry-Perot for a constant polarization. Third, a rotation of the polarization plane from TE to TM can alter the value of the reflection coefficients of both interfaces in a dramatic way.

Using the dummy variable technique /6/ numerical solutions of (6) can be obtained. (Fig. 1a, 2a) The following values (S.I. units) are used for the Si-etalon in order to allow qualitative comparison with Si-SEEDS:

\[ D = 500 \times 10^{-6} \quad \alpha_E = 1100 \quad \text{n} = 3,56 \]

\[ \lambda = 1,06 \times 10^{-6} \quad \chi^{(3)} = 10^{-12} \]
Fig. 1a and 2a show the response of the Fabry-Perot as predicted by the theoretical calculations for different incidence angles and different states of polarization respectively. Fig. 1b and 2b display the experimental results.

3 - EXPERIMENTAL RESULTS ON Si-SEEDS

In order to check this theory, experiments were performed on a Si-SEED. This nonlinear device is, indeed, very suitable to match with all the previous assumptions: it has a Fabry-Perot configuration and uses a thermo-optic effect to produce giant dispersive non-linearities /4/.

Using a 180μm thick sample and working at the resonant 1.06μm YAG-wavelength, we measured the \( P_{\text{refl}}-P_{\text{in}} \) characteristics for different angles of incidence \( \theta \) at a constant linear state of polarization. Fig. 3 displays the experimental set-up. Results are shown in Fig. 1b.

Fig. 3: Experimental set-up for measuring the polarization and angle dependence of the \( P_{\text{refl}}-P_{\text{in}} \) characteristics.
A second experiment was performed by measuring the device characteristics for different states of polarization, i.e. TE and TM, for a constant angle of incidence $\theta$. Results are shown in Fig. 2b.

4 - COMPARISON THEORY - EXPERIMENTS

Figures 1a, b clearly show, theoretically (a) and experimentally (b) the impact of the increased pathlength inside the resonator, with increasing angle of incidence $\theta$: as the non linear effects are enhanced, the hysteresis loop is broadened; but as absorption is more important, higher switching irradiances are observed. It is important to notice that the changes of reflectivities and transmittivities at both interfaces are negligible for the range of variations considered here. For larger angles, this allegation no longer holds. Figures 2a, b display theoretically (a) and experimentally (b) the difference between TE and TM operation of a non linear etalon for oblique incidence: changing the polarization state (in the range of rather large angles of incidence) seriously affects the feedback mechanism. This leads to a decrease of the hysteresis width and possibly to other functions of the device. Qualitative agreement between theory and experiments is striking.

5 - CONCLUSION

Varying the angle of incidence in a given polarization state permits to adjust the hysteresis width and the switching irradiance of a non linear Fabry-Perot. Furthermore, changing the polarization state seems to be an excellent tool to modify the function of the device by controlling the reflectivities at the resonator's interfaces: the system can go from an optical memory to an optical transistor regime. It should also be stressed that, subsequent to the modulation of the reflectivities, the modifications in the finesse can lead to a commutation of the device. As a result, it is possible to develop an alternative, intensity independent switching, mechanism /6/.

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REFERENCES


* In ref./1/ formula (6), the factor $kD_1$ should be read $kD \cos \theta$.