Optical Bistability in a Dissipative Thermally Expanding Etalon

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Abstract—The phenomenon of optical bistability is examined for the case of a lossy Fabry-Perot etalon. Using a multibeam interference method and thermal length expansion relationships, we derive an inverted equation which predicts the output transmission for such an etalon. Specific operating parameters are given for silicon wafer structures operating in the lattice vibration absorption regime (10 μm). Experiments using 15 ms CO_2 laser pulses and Si wafers show resonance-to-nonresonance switching.

INTRODUCTION

THE field of optical bistability has exploded with numerous theoretical and experimental efforts. Most of the theoretical work has focused on ideal two-level systems with emphasis on cooperative effects, stability, and temporal behavior. The experimental efforts have been motivated by attempts to verify theoretical predictions as well as the realization of low-power, high-speed optical logic elements for future computation and signal processing applications.

Most optical bistability (OB) devices operate on the positive feedback associated with nonlinear dispersive and absorptive effects in a variety of materials. In addition, more esoteric OB devices based on radiation pressure have recently been studied.

In this letter we examine OB produced by the positive feedback and associated longitudinal mode jumping which occurs when a dissipative etalon is allowed to expand due to an increase in the bulk material's temperature. Our analysis shows that low intensity (mW/cm^2) OB results for the infrared lattice vibration absorption region of silicon. In particular, we present an analysis of a circular silicon disk irradiated by a CO_2 laser, and experimental results for CO_2 laser pulse transmission through such a structure.

THEORY

The approach we utilize is based on the routinely used geometric series sum for the transmitted and reflected intensity through a Fabry-Perot interferometer. This calculation is slightly modified to include a *nonsaturable* loss per round trip through the structure in order to calculate the power dissipated. Calling I_0, I_T, I_R, and I_D the incident, transmitted, reflected, and dissipated intensities, we have that

$$I_0 = I_R + I_T + I_D. \tag{1}$$

The above conservation equation plus the expressions for I_R and I_T give a result for the dissipated intensity (assuming a constant beam cross-sectional area):

$$I_D = I_0 \left[1 - \frac{R(e^{-4\alpha l} - 2e^{-2\alpha l} \cos(2kl) + 1) + (1-R)^2 e^{-2\alpha l}}{R^2 e^{-4\alpha l} - 2\,\mathrm{R}e^{-2\alpha l} \cos(2kl) + 1} \right]. \tag{2}$$

α is the absorption coefficient at the wavelength of interest, k is the magnitude of the wave vector, l is the length, and R is the power reflection coefficient. Equation (2) yields a result $I_D = 0$ when $\alpha = 0$ as expected.

Since we are examining the steady-state behavior for a system where $l = l(I_D)$, we will eliminate the cos $(2kl)$ term from (2). Defining $\beta = I_T/I_0$, we may use the expression for the transmitted intensity and cast I_D in terms of β:

$$I_D = I_0 \beta \left[\frac{R^2 e^{-4\alpha l} + 1 - R(1 + e^{-4\alpha l}) - (1-R)^2 e^{-2\alpha l}}{(1-R)^2 e^{-2\alpha l}} \right]. \tag{3}$$

Setting the dissipated power equal to the heat generation rate results in $\dot{q} = I_D A$, where A is the beam cross-sectional area. Steady state is reached when the cooling rate is equal to $\dot{q}$, resulting in a uniform temperature change throughout the etalon. The case of a thin disk of area A $(l \ll \alpha^{-1})$ can be treated using Newton's law of cooling for free convection. This assumes a uniform temperature increase above the ambient temperature throughout the disk ΔT, given by

$$\Delta T = \frac{\dot{q}}{h(2A + S)}. \tag{4}$$

S is πdl where d is the disk diameter and h is a coefficient specific to the disk geometry [1]. Using the appropriate h and neglecting the area S results in

$$\Delta T = \left[\frac{d^{1/4} I_D}{2.64} \right]^{4/5} \tag{5}$$

The determination of ΔT allows us to find the thermal expansion of the etalon and results in an embedded equation for β. Using the linear length expansion expression,

$$l = l_0 + \sigma \Delta T \tag{6}$$

where l_0 is the initial ($I_0 = 0$) length and σ is the coefficient of linear expansion, results in

$$\beta = \frac{C_1}{C_2 - C_3 \cos\left[2kl_0 + 2kG(I_0\beta)^{4/5}\right]}. \tag{7}$$

The above coefficients only depend on material parameters and are given by

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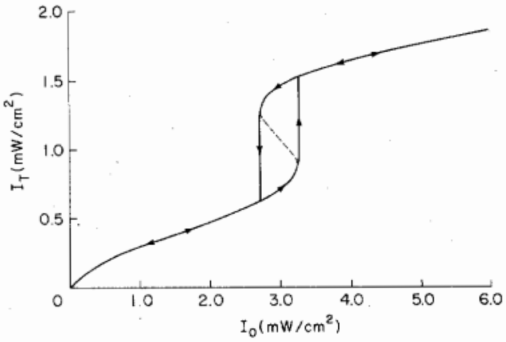


Fig. 1. Input intensity versus transmitted intensity for a 2.5 cm diameter, 0.5 mm thick silicon etalon irradiated at 10 μm.

$$C_1 = (1 - R)^2 e^{-2\alpha l_0} \tag{8a}$$

$$C_2 = R^2 e^{-4\alpha l_0} + 1 \tag{8b}$$

$$C_2 = 2 \mathrm{Re}^{-2\alpha l_0} \tag{8c}$$

$$G = \left[\frac{\sigma d^{1/4}}{2.64} \frac{R^2 e^{-4\alpha l_0} + 1 - R(1 + e^{-4\alpha l_0}) - (1 - R)^2 e^{-2\alpha l_0}}{(1 - R)^2 e^{-2\alpha l_0}} \right] \tag{8d}$$

Recalling that $\beta = I_T/I_0$, we see that multivalued solutions for β in (7) imply bistability.

Uniformly Irradiated Si Wafer

In this section we will examine the specific case of a silicon wafer uniformly irradiated by a 10 μm wavelength CO_2 laser beam. The wafer is taken to be 0.5 mm thick and has a diameter of 2.5 cm. The value of α is 200 m^{-1} and the thermal length expansion coefficient is $\sigma = 3 \times 10^{-8}$ m/°C [2], [3]. Using the uncoated reflectivity and the above relationships yields values of 0.32, 1.04, 0.39, and 0.76 for C_1, C_2, C_3, and G, respectively. Equation (7) was solved for β using a root finder program and regions of multiple valued solutions were found. The transmitted intensity versus input intensity for the structure described is shown in Fig. 1.

Since the effect we describe is due to thermal length expansion, it is imperative to determine the temperature changes which are taking place in the structure. This result places an upper limit on the thermal stability of the environment surrounding the etalon. Calculations indicate that input intensities up to 20 mW/cm^2 result in ΔT values on the order of 10°C. In the three-root region of input intensities below 5 mW/cm^2, the changes are smaller, on the order of 1-2°C. At this point it is worth mentioning that these temperature differences, centered about 25°C, result in negligible index of refraction variations at wavelength of 10 μm. The available data on silicon indicate that a $\Delta T \sim 70$°C is required for a 0.5 mm thick structure to exhibit index of refraction related switching phenomena.

Finally, we should like to make mention of the expected switching time of such a structure. In the case of a thermally expanding dissipative etalon, the rate determining step is thermal equilibration. A rough estimate using the thermal diffusion constant of Si yields a value of 1.6 ms for the structure we describe.

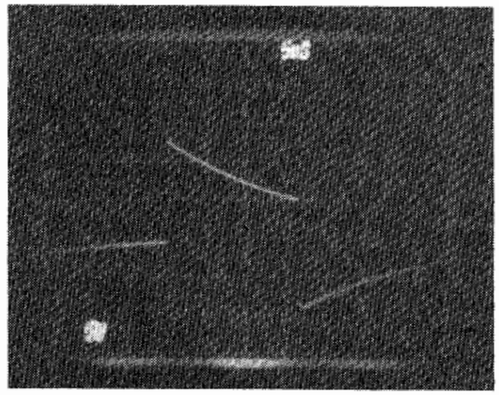
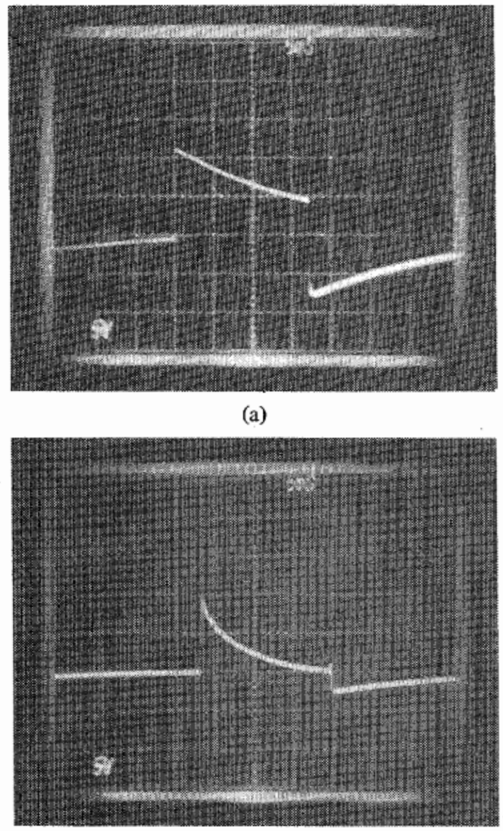


Fig. 2. CO_2 laser pulse incident on the silicon etalon. The time scale is 5 ms/div and the amplitude is 5 V/div.



(a)

(b)

Fig. 3. Transmitted CO_2 pulse though the silicon etalon for the (a) nonresonant and (b) resonant positions. Scope settings are the same as in Fig. 2.

Experiments

We have observed the switching of a 2.5 cm diameter, 1 mm thick disk of intrinsic polycrystalline silicon due to a 15 ms, 200 mW/cm^2 peak intensity CO_2 laser pulse. The etalon exhibited linear behavior when the structure was placed in a destructive interference or reflecting position. Alternatively, when the wafer was angled to allow the buildup of a coherent field inside (transmission resonance), heating, expansion, and detuning occurred, resulting in a rapid decay of transmitted power. Fig. 2 shows the CO_2 pulse as measured with a Molectron pyroelectric detector incident on the etalon. Fig. 3(a)

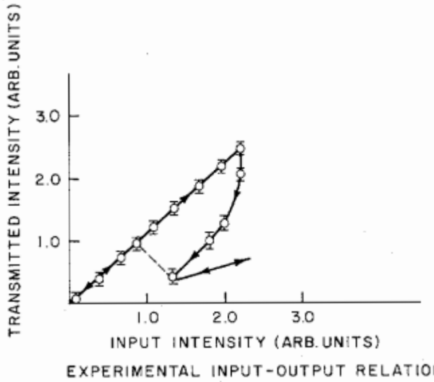


Fig. 4. Experimental input-output hysteresis curve for the silicon etalon.

and (b) shows the transmitted intensity for the initially nonresonant and resonant positions, respectively. Plotting the input versus output intensities from the data shown in Figs. 2 and 3(b) results in the experimental hysteresis curve shown in Fig. 4.

A measurement of the orientation angle spacing of the etalon between both outputs gives a value of 4°, resulting in a round trip path change corresponding to 10 μm in silicon.

Conclusions

We have described the theory of an optically bistable device which operates due to internal dissipation and thermal expansion. Equations were developed for the case of a thin disk with free convective cooling. The specific case of a silicon wafer (2.5 cm in diameter and 0.5 mm thick) uniformly irradiated in the 10 μm wavelength range was analyzed and found to give a bistable output at extremely low input intensities (1-5 mW/cm^2). Experiments using wafers 2.5 cm in diameter and 1.0 mm thick exhibited switching with input pulser in the 100 mW/cm^2 range.

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Oblique Raman and Polariton Scattering in Lithium Iodate

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Abstract—**We have predicted and measured tuning of the LO and TO oblique Raman and the oblique polariton frequencies in the 769-848 cm^{-1} spectral region in lithium iodate. Oblique scattering in $LiIO_3$ is produced by coupling of *A* and *E* symmetry crystal modes. The resulting LO and TO frequencies lie between the frequencies of the contributing modes. The intensity of the scattered light observed indicates that construction of CW or quasi-CW stimulated oblique Raman and polariton oscillators are possible.**

I. Introduction

THIS paper describes an experimental and theoretical investigation of oblique CW Raman and polariton scattering in lithium iodate. We have observed tunable Stokes shifts in the 800 cm^{-1} region from oblique phonons as well as similar frequency shifts from oblique polaritons. The intensity of the scattering observed indicates that the construction of a CW or quasi-CW oblique Raman or oblique polariton oscillator should be possible.

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Stimulated Raman scattering (SRS) has been previously used to produce radiation at a fixed frequency offset from lasers operating in the UV, visible, and IR regions of the spectrum [1]. Raman scattering is scattering from a mechanical vibration which results in the production of phonons at the frequency of the mechanical resonance and a photon whose frequency is shifted from the pump's frequency by the frequency of the mechanical resonance.

Polariton scattering, scattering from a mode which is partially electromagnetic and partially mechanical, can produce electromagnetic radiation at the vibrational frequency [2].

For light propagation and mechanical vibrations along crystal axes, the existence and the polarization of Raman or polariton scattering can be reliably predicted by group theory. Oblique scattering occurs for propagation angles not parallel to a crystal axis and leads to mixing of the modes predicted by group theory. For example, oblique phonons or polaritons in $LiIO_3$ are produced by the coupling of *A* and *E* symmetry crystal modes to produce a single mode whose longitudinal-optical

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