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## Operation of an All-Optical Bistable Device Dependent upon Incident and Transmitted Optical Power

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**Abstract**—In this letter we describe and demonstrate the optically bistable operation of an all-optical nonlinear Fabry-Perot etalon (NLFP) in which the power-dependent cavity phase shift has a contribution dependent upon the internal cavity power and a contribution directly dependent upon the power incident on the cavity. When the contributions have the same parity, the optically-bistable behavior is essentially the same as that seen in the now standard bistable NLFP (counterclockwise hysteresis in transmission). For opposite parity there is a range of relative strengths for which bistable operation cannot be obtained, but outside of that range bistable behavior having clockwise hysteresis in transmission is possible. We present a demonstration of this latter bistable behavior in which the NLFP was a GaAlAs laser diode amplifier driven by a similar diode laser. Low-frequency modulation of the laser power by direct variation of the laser drive current produced a small shift in laser wavelength proportional to the laser power, providing the cavity phase shift term proportional to the incident power, while the nonlinear refractive index of the NLFP provided the phase shift proportional to the transmitted power.

### I. INTRODUCTION

IN THE conventional operation of a nonlinear Fabry-Perot etalon (NLFP) nonlinearity and hysteresis may be observed in the transmitted power due to a cavity phase shift dependent upon the optical power within the etalon. Since the transmitted power is proportional to the internal power, and since it can be measured directly, a conventional NLFP can be considered to operate with a cavity phase shift dependent upon transmitted power. By contrast, a hybrid electrooptical bistable device may use a combination of incident, reflected, or transmitted optical power to control the cavity phase shift electronically. With this dependence, the behavior can be substantially different from a conventional all-optical NLFP. Smith, Turner, and Mumford [1] demonstrated a hybrid Fabry-Perot with an internal electrooptic crystal inducing a phase shift pro-

portional to the light reflected from the cavity, and observed bistability in the transmitted power having a clockwise hysteresis loop, opposite in sense from conventional hysteresis. Cavityless devices based on electrooptic polarization rotation [2]–[4] proportional to both incident and transmitted power have shown similar clockwise transmission bistability. Gibbs [5] noted that an all-optical analog of these hybrid devices could be built by injecting part of the input signal through the edge of the etalon to make a nonresonant contribution to the cavity phase [6]. A device employing such edge-injection has been built, but was operated in a slightly different manner [7].

In this letter we generalize the description of an NLFP dependent upon incident power  $P_{in}$  and transmitted power  $P_{out}$ , writing the etalon single pass cavity phase shift as

$$\varphi = \varphi_0 + \beta P_{in} + \Gamma P_{out} \quad (1)$$

where  $\varphi_0$  is the initial cavity detuning, and  $\beta$  and  $\Gamma$  are appropriate nonlinear phase shift coefficients. (Behavior dependent upon reflected power may be written in terms of  $P_{in}$  and  $P_{out}$ .) Section II presents the basic analytic treatment and discusses the differences in performance between conventional and two-term devices, and differences between two-term devices having terms with the same and opposite parity. In Section III we report on the all-optical operation of an NLFP having cavity phase shift dependent upon both transmitted and incident power. At low speed (several Hz) this device is well described by the basic two-term theory, and at higher speeds illustrates the effect of varying  $\beta$  and  $\Gamma$  during operation.

### II. THEORETICAL ANALYSIS

Previous work with mirrorless [2] and Fabry-Perot [1] electrooptic devices has presented analyses relevant to the two-term NLFP operation we describe. The present analysis is more general and extended. We can write the NLFP transmission both as an Airy function of  $\varphi$

$$T_A = \frac{P_{out}}{P_{in}} = \frac{A}{1 + F \sin^2 \varphi} \quad (2)$$

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and [with (1)] as a linear function

$$T_L = \frac{\varphi - \varphi_0}{\Gamma P_{in}} - \frac{\beta}{\Gamma} \quad (3)$$

using etalon front and rear reflectivities  $R_f$  and  $R_b$ , thickness  $D$ , linear refractive index  $n$ , operating wavelength  $\lambda$ , single pass absorption (or gain) coefficient  $\alpha D$ , effective mean reflectivity  $R_\alpha = \exp(-\alpha D) * \sqrt{(R_f R_b)}$ , peak transmission  $A = (1 - R_f)(1 - R_b)/(1 - R_\alpha)^2$ , and coefficient of finesse  $F = 4R_\alpha/(1 - R_\alpha)^2$ . The method of graphical solution of (2) and (3) to find  $P_{out}$  versus  $P_{in}$  is well known for the case of  $\beta = 0$  [8]:  $T_L(\varphi)$  produces a family of lines with different  $P_{in}$  that intersect at the point ( $\varphi = \varphi_0$ ,  $T = 0$ ), which we denote as the pivot point. For  $\beta/\Gamma > 0$  this pivot point moves onto the negative  $T$  axis, as shown in Fig. 1(a). Fig. 1(b) illustrates the type of nonlinear transmission and hysteresis produced in this case, which is qualitatively similar to conventional NLFP behavior, although the hysteresis loop is generally narrower than that for conventional operation of the same cavity. With (1)-(3) strictly valid and with sufficient input power, counterclockwise transmission bistability can be obtained whenever  $-\beta/\Gamma < A/(1 + F)$ , which is the minimum transmission level. For  $-\beta/\Gamma > A$  the pivot point lies above the Airy curve in Fig. 1(c), with the intersections of  $T_L$  and  $T_A$  lying in the second quadrant, producing the nonlinear transmission shown in Fig. 1(d). With increasing incident power the transmission first tunes through a maximum, and then switches to a low state. The result is a clockwise hysteresis in the transmitted power. In the range  $A/(1 + F) \leq -\beta/\Gamma \leq A$  the specific values of  $F$ ,  $\varphi - \varphi_0$ , and  $\beta/\Gamma$  must be examined to determine whether  $T_L$  can have multiple intersections with  $T_A$ , and, if there are multiple intersections, whether hysteresis is clockwise, counterclockwise, or is not attainable by intensity variation. For the balance of the letter we will deal with the case of clockwise transmission hysteresis.

We can conceive of two general schemes in which an all-optical NLFP has phase dependence upon both transmitted and incident power. In the first the  $\beta P_{in}$  contribution is due to a slight variation in operating wavelength proportional to  $P_{in}$ , such as that seen when the drive current of a diode laser is varied. In typical diode laser operation the laser output power  $P_L$  varies as  $P_L = C(i_L - i_{th})$  for laser pump current  $i_L$ , threshold current  $i_{th}$ , proportionality coefficient  $C$ , and  $i_L > i_{th}$ . For slow variations, the laser wavelength  $\lambda$  changes linearly with  $i_L$  [9]-[11] due to thermal variation of the bandgap. For slow  $i_L$  variation we may obtain a  $\beta P_{in}$  contribution from a conventional NLFP by writing the etalon phase as

$$\varphi = \frac{n\pi D}{\lambda_0 + \left(\frac{d\lambda}{dP_L}\right)P_L} + \Gamma P_{out} \quad (4)$$

For small variations in  $\lambda$  the first term on the right can be expanded to yield

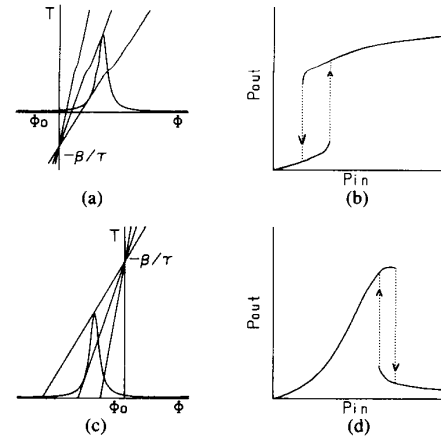


Fig. 1. Illustration of bistable operation in transmission for  $\beta/\Gamma > 0$  and  $\beta/\Gamma < -A$ . Diagrams on the left-hand side show intersections in the ( $\varphi$ ,  $T$ ) plane of  $T_L$  and  $T_A$  for various values of  $P_{in}$ . The slope of the line  $T_L$  decreases as  $1/P_{in}$ . Those on the right-hand side show the behavior of  $P_{out}$  as a function of  $P_{in}$ .  $\Gamma > 0$  is assumed. (a) For  $\beta/\Gamma > 0$  the pivot point lies below the Airy curve. (b) The bistable loop for  $\beta/\Gamma > 0$  has a similar shape to a conventional loop. (c)  $\beta/\Gamma < -A$  sets the pivot point above the Airy curve. (d) The bistable loop for  $\beta/\Gamma < -A$  has hysteresis opposite to the conventional direction. As  $P_{in}$  rises, switching occurs from high to low transmission.

$$\varphi_0 + \beta P_{in} = \frac{n\pi D}{\lambda_0} - \left[ \frac{n\pi D \left(\frac{d\lambda}{dP_L}\right) \left(\frac{P_L}{P_{in}}\right)}{\lambda_0^2} \right] \cdot P_{in} \quad (5)$$

which defines  $\beta$ . For the GaAs family of lasers [9], [10]  $d\lambda/dP_L > 0$ , hence  $\Gamma > 0$  is required in the NLFP for clockwise transmission hysteresis. This can be supplied by using the electronic nonlinearity of GaAs or GaAlAs that is electrically pumped to invert the electron-hole population, or by using the thermal refractive index variation. Because of the thermal nature of the wavelength variations, this scheme is limited to low-speed operation. In our experiments with this scheme 20 Hz was a practical upper limit.

A second scheme would make use of a material, such as InSb [12], where thermal and electronic index variations have opposite parity and can be employed essentially independently [13]. Operation would be similar to a conventional NLFP, but with a portion of the incident beam diverted to an opaque absorbing layer so as to heat the active region of the etalon. For small, slow variations the temperature and thermal index changes are proportional to the incident beam power, providing the  $\beta P_{in}$  term. Being thermal, this scheme is also limited to low-speed operation. If a material with significant absorption (hence heating proportional to internal etalon power) such as GaAs were used, a dynamic analysis may be required to describe the behavior.

### III. EXPERIMENTAL OBSERVATION OF BISTABILITY

Our experimental apparatus is a simplified version of that used in [14]. Hitachi HLP-1400 laser diodes were

used as the master laser and as a Fabry-Perot amplifier (NLFP). Both diodes had a nominal  $\lambda$  of 844 nm. The NLFP diode was dc biased at 0.99 of the threshold current.  $10\times$  and  $20\times$  microscope objectives focused the output from the rear of the master laser onto a monitor  $D1$ , and relayed the beam from the front face through a magneto-optic isolator with about 28 dB isolation to the input face of the amplifier diode. A photodetector  $D2$  observed the output of the amplifier through a relay objective. The diodes were mounted on Marlow Industries thermoelectric coolers to control the temperature and nominal operating wavelength. Rated temperature stability was  $\pm 0.1^\circ\text{C}$ , but short term (30 min) stability was much better than  $0.05^\circ$ . During our experiments the amplifier was held at a constant temperature of  $15^\circ$ . Initial detuning was accomplished by varying the temperature of the master laser.

Measurements were made of the amplifier single-pass gain, finesse, amplification, and gain saturation [14] to characterize its performance. Small signal gain was 22 dB with saturation output power (to  $-3$  dB) of  $80\ \mu\text{W}$ . The small signal coefficient of finesse was about  $F = 300$ , which was saturated down to roughly 100 at the minimum power level needed for bistable switching and down to  $F = 50$  at higher powers. We estimate the power coupling from the laser into the amplifier to be 0.4 percent, with most of the loss due to the low efficiency of coupling the light from the final microscope objective into the laser diode amplifier. The value of  $\beta$  was determined by measuring the change in the dc  $i_L$  (at constant cooler temperature) needed to vary  $\lambda$  between two adjacent amplifier transmission peaks, and then scaling this to the variation of  $P_{in}$  with  $i_L$  that was observed during the bistability study. In this  $\beta$  measurement  $P_{in}$  was held constant by attenuating the laser beam with a pair of polarizers so that the shift from  $\varphi = 0$  to  $\varphi = \pi$  had no contribution from  $\Gamma P_{out}$ . The values of  $\varphi_0$  were determined by first noting the temperature (at constant  $i_L$ ) at which  $\varphi = \pi, 0, -\pi$ , thus establishing  $d\lambda/d$  temperature.  $\varphi_0$  at one operating temperature was found for low  $P_L$  by temperature tuning to  $\varphi = 0$ , then subtracting the  $\beta P_{in}$  and  $\Gamma P_{out}$  contributions. Values of  $\varphi_0$  for other temperatures were linearly extrapolated from this point.  $P_{out}$  was determined directly with the calibrated detector  $D2$ . By determining  $P_{out}$  at resonance and knowing the amplifier gain we deduced  $P_{in}$  and calibrated the  $P_{in}$  signal from detector  $D1$ .  $\Gamma$  was determined by using it as a fitting parameter when comparing the experimental bistability curve with the results of (1)–(3). The electronic and thermal refractive index variations (both positive, but with different speeds and magnitude) contributed to  $\Gamma$  as evidenced by our observation that variation in amplifier current changed the magnitude of  $\Gamma$  and the speed of the bistable switching. Switching times were about  $1\ \mu\text{s}$ , indicating that the thermal refractive index variation dominated.

To observe optical bistability the laser was tuned slightly away from resonance with the amplifier and  $P_{in}$  was varied by modulating  $i_L$  as a triangular wave from  $1.0i_{th}$  and  $1.3i_{th}$ . Fig. 2(a) presents several of the bistable

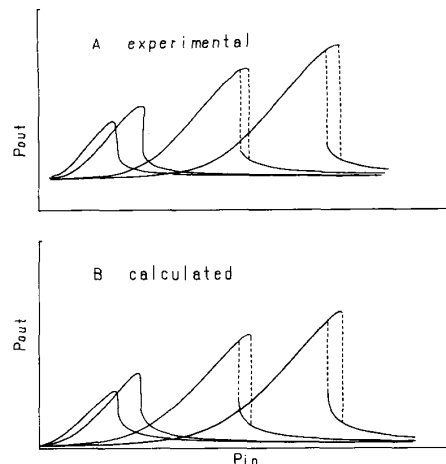


Fig. 2. Experimental and calculated bistable behavior of the transmitted power. The master laser diode temperature was varied to change the initial detuning  $\varphi_0$  for the experimental curves. The full scale for  $P_{in}$  is  $20\ \mu\text{W}$  and the full scale for  $P_{out}$  is  $600\ \mu\text{W}$  for both sets of curves. The parameters derived from the experimental data, and used for the calculated plots, in order of increasing peak power, were  $A = 52, 46.2, 32.2, 27$ ;  $F = 100, 89, 62, 52$ ;  $\varphi_0 = 0.25, 0.29, 0.60, 0.96$ ;  $-\beta/\Gamma A = 2.5, 3.3, 2.9, 3.7$ . For this experiment we derived a value of  $\beta = 0.092/\mu\text{W}$ .

loops observed for the different values of  $\varphi_0$ . These observations were made at a pulse frequency of 5 Hz. Fig. 2(b) shows plots of simulations using (1)–(3) with the values of  $\varphi_0$ ,  $\beta$ ,  $A$ , and  $F$  deduced from the experimental curves. The values of  $A$  and  $F$  were derived from the points of peak experimental transmission; thus they and the derived  $\Gamma$  values vary between curves, being in reality functions of  $P_{out}$ . The calculated curves match the experimental observations quite closely, indicating the success of the two-term NLFP model in describing this device operation. Slightly better agreement could be expected if the variation of  $A$ ,  $F$ , and  $\Gamma$  with  $P_{out}$  were included. The experimental curves have a CW offset which is due to the spontaneous emission of the amplifier.

We should note that a similar experiment was performed by Nakai, Ito, and Ogasawara [15] in which the master laser was excited by square pulses of  $2\text{--}4\ \mu\text{s}$ . They observed asymmetry in the frequency response of the amplifier as the wavelength varied at constant power. We see evidence in their published data of the same bistable effects which we describe above, but apparently they did not recognize these and did not report them.

If this device is operated at low-duty cycle with pulses rising significantly slower than the thermal excitation time, but falling substantially faster than the thermal relaxation time, an interesting optical hysteresis occurs in which there is distinct switching from the high to the low state, but no possibility for switching back to the high level. In this case the NLFP behavior during the rising edge and plateau of the input pulse is described by (1), but during the falling edge of the pulse the  $\beta P_{in}$  term is replaced by a constant term  $\beta P_{in}$  (maximum). The pivot point for  $T_L$  is  $(\varphi_0, -\beta/\Gamma)$  for the rising edge, but is  $(\varphi'_0, 0)$  for the falling edge, where the maximum value of

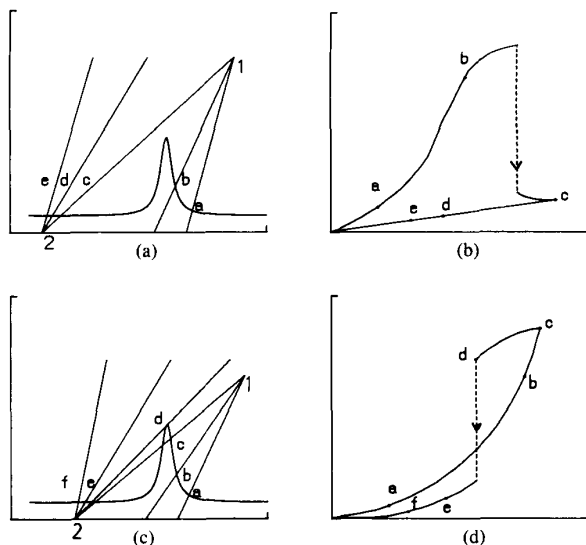


Fig. 3. Optical hysteresis resulting from very slow relaxation of  $P_{in}$  phase contribution. Left diagrams show  $T_A$  and  $T_L$  intersections in  $(\varphi, T)$  space as in Fig. 1(c); those on the right show  $P_{out}$  versus  $P_{in}$  as in Fig. 1(d). For increasing  $P_{in}$  the pivot point is  $(\varphi_0, -\beta/\Gamma)$ , labeled point 1. For falling  $P_{in}$  the  $P_{in}$  contribution retains its maximum value so that the pivot point is  $(\varphi'_0, 0)$ , labeled point 2. (a), (b) The maximum  $P_{in}$  is sufficient to switch the device to low transmission level, but relaxation takes place only at low transmission. No switch-off occurs. (c), (d) The maximum  $P_{in}$  reaches the bistable region of operation but is insufficient to reach the switching point. Switching to low transmission occurs as the intensity falls. If  $P_{in}$  has not reached the bistable region then  $\varphi'_0$  lies under the peak of the transmission curve and hysteresis occurs without switching.

the input determines  $\varphi'_0$ :

$$\varphi'_0 = \varphi_0 + \beta P_{in}(\text{maximum}). \quad (6)$$

Fig. 3 illustrates this type of behavior for two different values of peak input power. In the case of Fig. 3(a) and (b)  $P_{in}$  rises to a level sufficient to switch the transmission from a high to a low state, but the reduction of  $P_{in}$  occurs over the range of powers for which  $T_L$  has only one intersection with  $T_A$ . Thus  $P_{out}$  must fall monotonically without a second switching. Fig. 3(c) and (d) represents the behavior for a different  $\varphi_0$ . The change from rising to falling input takes place at a  $P_{in}$  value which provides three intersections between  $T_L$  and  $T_A$ , thus the switching from high to low output states take place as the input falls. By pulsing  $i_L$  with a triangle wave at 100 kHz, where the pulse rise time was 10  $\mu$ s and the fall time faster than 1  $\mu$ s, we have observed hysteresis very similar to Fig. 3(b). Some  $\beta P_{in}$  contribution remained during the falling edge of the pulse so that a small switch-up was observed, though this produced only a very small increase in the transmitted signal. By changing  $\varphi_0$  the hysteresis evolved to the form of Fig. 3(d). With further increase of  $\varphi_0$  we could eliminate the switch-down entirely, so that hysteresis without switching was observed.

#### IV. DISCUSSION AND CONCLUSIONS

An optical device with sharp threshold in the behavior of  $P_{out}$  may be used as the basis of an optical logic gate.

Although the slow speed of the device we have described renders optical gates derived from it impractical, two points deserve a brief mention. First, the shape of the device response curve allows two (and multiple) input AND, NAND, NOR, and XOR functions to be represented in the transmitted power by selecting appropriate sets of  $P_{in}$  values as input states. We have observed each of these by performing a simulated two-input experiment [16] using the apparatus described above. Second, the contrast level (ratio of high to low output power) we observed for the simulated AND gate was 4.2 : 1, which compares favorably with the 5 : 1 value recently reported for a high contrast AND gate using a laser diode amplifier in conventional NLFP operation [17]. (If the spontaneous emission power were eliminated in our experiment, we would observe a 13 : 1 contrast.)

For a nonlinear Fabry-Perot etalon that is modified from conventional operation to include a nonlinear cavity phase shift dependent upon the incident power, the nonlinear behavior of the transmission (and reflection) is substantially different from that seen in conventional operation. We have shown that if the phase shift due to incident power is opposite to that due to transmitted power (and if the ratio of the phase shift coefficient  $\beta/\Gamma$  is large enough) then the hysteresis is opposite to that seen in conventional NLFP operation. We have demonstrated this behavior in an all-optical system using laser diodes as both source laser and NLFP, although this implementation is limited to low-speed operation.

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