Optical Bistability and Mirror Confinement Induced by Radiation Pressure

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This paper reports the observation of optical bistability due to a radiation-pressure-induced change of the length of a Fabry-Perot resonator. In addition, for higher laser powers, a purely optical mechanism leading to the stabilization of the resonator has been observed.

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Bistable optical devices have been the subject of much research over the past several years. A typical such device is an interferometer filled with a medium having a refractive index dependent on the light intensity incident upon it. Because the refractive index determines the *effective* optical cavity length, the interferometer's transmission is thereby nonlinearly related to the incident intensity, and hysteresis effects characteristic of bistable response are possible.[1] Since the only role of the medium is to change the cavity length, one can imagine eliminating it by introducing nonlinearities in the *physical* cavity length. Radiation pressure is capable of doing this. This Letter reports observation of hysteresis in such a system.

The system is a plane Fabry-Perot interferometer in which one mirror is very light, and is suspended to swing as a pendulum. If we regard the other mirror as fixed, the position of the movable mirror determines the interferometer spacing. The light in the cavity will exert a pressure on that mirror, driving it towards equilibrium, with the gravitational and inertial forces balancing the pressure. Because the resonator transmission is a highly nonlinear function of its position, bistability is to be expected in this device, although one may question whether it will be observable, because the radiation pressure effect may be small compared to noise. The observations to be reported below, however, incontrovertibly show bistable response. That the response is due to radiation pressure is strongly indicated by a general agreement of a computer simulation with the experimental observations. In addition, an effect expected from extensive computer studies has been confirmed by the experiment: When the incident light intensity exceeds values appropriate to bistable response, the system becomes extremely stable, and mechanically resonant mirror motion is suppressed.

The interferometer constructed for these studies consisted of a plane massive mirror of standard design, and a small quartz plate, mass 60 mg. Both mirrors were dielectrically coated to a reflectance of 0.92 for the light mirror and 0.99 for the fixed one. The plate was suspended by two tungsten wires to hang about 0.8 mm from the fixed mirror. The resulting interferometer had a finesse of about 15. The laser could be used single-mode or multimode, and provided power levels ranging from a few milliwatts to 5 W.

The interferometer was acoustically isolated in an evacuable chamber which is mechanically tied to bedrock. The experiments were done both in air and in reduced pressure. Gas viscosity provides mechanical damping of the pendulum oscillations. The presence of air raises the possibility that radiometric forces will contribute. The observed response times, on the order of 0.1 to 0.3 sec, indicate, however, that they are not a major contributor to the effects seen, since characteristic radiometric response times are on the order of minutes.[2] They might eventually change the offset of the interferometer, thus altering the required switching power. Mechanical motion and drift of the system somewhat limit the ability to observe the bistability. Observations of this effect could only be made at night when civilization-caused ground noise was minimal. A separate seismometer monitored the ground noise in order to help identify peaks in the spectral response not due to radiation-driven mirror motion.

Two types of experiments were performed. In the first, the incident light intensity was held fixed, and the audio-frequency spectrum of the transmitted intensity was measured with use of a fast-Fourier-transform spectrum analyzer: The character of this audio-frequency spectrum depended on the intensity of the incident light. After interpretation of the results by computer simulation, in a manner to be described below, the intensity region appropriate to bistable behavior could be determined, and the second type of experiment could be done. After further improvement in the stability of the system, the laser intensity was slowly scanned across the bistable region, from feeble intensity to high intensity, and back. Scanning cycle times ranged from 2 to 5 min, times long compared to the damping time of the mirror. The result of one such scan is shown in Fig. 1. The hysteresis cycle typical of bistable behavior is clearly evident.

The bistable behavior of the mirror position, and hence of the transmitted light, is relatively easy to understand. The mirror dynamics, specifically the nature of the audio-frequency spectrum, is rather less so. To simulate the experimental results, a computer program was written to solve the dynamical equation for the moving mirror

$$\ddot{x}+\gamma\dot{x}+\Omega^2 x=\frac{2\kappa R T I_i}{1+R^2-2R\cos(\varphi-\varphi_0)}+\frac{F(t)}{m}. \qquad (1)$$

The first term on the right-hand side of this equation is the force/unit mass due to the radiation pressure; R and T are mirror reflection and transmission coefficients, I_i is the incident field intensity, and κ is a constant containing the mass and area of the mirror. The coordinate x measures the mirror displacement, and $\varphi=4\pi x/\lambda$, λ being the light wavelength. The constant φ_0 is necessary because the initial mirror position is offset from an interferometer resonance. The constants γ and Ω determine the pendulum motion. The second term on the right in Eq. (1) represents a mechanical driving term. In the experiment, this force is provided from noise.

The static version of Eq. (1), for $F(t)=\dot{x}=\ddot{x}=0$, identifies the intensities appropriate to bistability. With small intensities, only one static solution exists. As I_i is increased the number of solutions increases, first to three, then five, seven, etc., depending on the cavity parameters. The largest and smallest solutions are stable equilibrium points; the rest are alternately unstable and stable. The lower intensity limit for bistability is thus that for which three roots of the static equation exist. The upper limit occurs when the intensity is strong enough to switch the pendulum to a position beyond the first interferometer resonance. When the intensity is slowly varied between zero and the upper limit, the transmission will display hysteresis.

To account for the pendulum's dynamic behavior, and in particular to obtain "steady state" oscillations with an audio-frequency spectrum, it is necessary to include the driving term and solve the full equation. Here again the results depend upon the incident intensity I_i as well as $F(t)$. For the results presented here, initial conditions $x=\dot{x}=0$ were set, an offset φ_0 and a function $F(t)$ were chosen, and I_i was varied. Depending on the precise value of I_i, three regimes of operation were identified, which we call small-, medium-, and large-displacement limits. They are characterized by mirror motions small, comparable, and large, respectively, compared to the width of a Fabry-Perot resonance. We concentrate here on the first two limits.

In the small-displacement limit, and for a harmonic excitation $F(t)=F_0\sin\Omega t$, the audio spectrum consisted of a single peak about Ω. As the mirror displacement $x(t)$ increased sufficiently

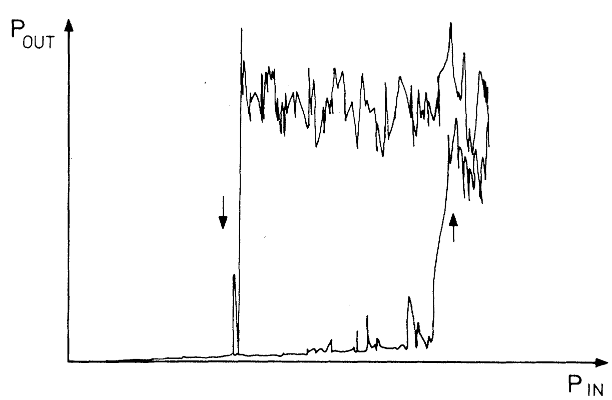

FIG. 1. Typical hysteresis cycle. In this example, the switching-up power is about 2.2 W and the switching-down power about 1.1 W. Transmitted powers are on the order of 5 mW in high-transmission branch and 0.2 mW in low-transmission branch.

to produce significant variations in transmission, we observed the appearance of higher harmonics in the spectrum. Note that depending upon I_i and φ_0, the displacement $x(t)$ could become quite complex. This point, which will be discussed in detail in a future publication, has, however, no significant impact on the audio spectrum.

Although instructive, simulations using a harmonic force $F(t)$ can only produce a spectrum at Ω and its harmonics. Introducing noise in Eq. (1) was necessary in order to understand the details of the experiment. The numerical results discussed here were obtained with a noise force $F(t)$ consisting of short impulses of random strength regularly distributed in time. A full-scale noise analysis is underway and will be presented elsewhere. In the small-displacement limit, the audio spectrum was essentially the same as with a harmonic force, except that Ω was replaced by the effective "resonant" frequency Ω_{eff} of the driven pendulum. For larger mirror displacements, we observed again the appearance of a sequence of harmonics of Ω_{eff}. Theoretical and experimental spectra corresponding to this regime are shown in Fig. 2(a).

For appropriate choices of I_i, φ_0, and $F(t)$, the calculated audio-frequency spectrum could be changed from the simple pattern of harmonics to one in which the major frequency was split. This transition was observed in the experiments at a laser input power of about 200 mW; these experimental and calculated regimes are shown in Fig. 2(b). It is clear that it is ideally in this region that bistability will first occur: The radiation field, combined with the gravitational restoring force, both being position dependent, can be thought of as forming a potential presenting minima at the stable operating points of the system. Under the action of the noise force, the system can hop between the first well, with effective resonant frequency $\Omega_{\mathrm{eff}} < \Omega$, and the second one, with $\Omega_{\mathrm{eff}} > \Omega$, leading to a splitting of the major frequency of the system.

Although tempting, it was not possible to determine unambiguously that the bistability curve in Fig. 1 corresponded to this region. The possibility of noise "washing out" the relatively shallow first two minima during a long scan could not be excluded, and the observed bistability cycle may well involve a higher-order Fabry-Perot resonance.

As the intensity I_i was increased further in the computer calculations, still another characteristic solution type appeared. In this type, the mirror motion became no longer particularly sensitive to the driving force, but would damp into a steady-state mode in which it was weakly driven about one of the higher-order equilibrium points indicated by the static solution. That such a solution is possible is not surprising; the potential wells corresponding to higher-order resonances are increasingly narrower, and exhibit "resonant" frequencies Ω_{eff} quite different from the pendulum frequency Ω. The mirror, once captured in such a well, will no longer respond to frequencies about Ω. But that such a capture is common is not obvious. Such solutions, however, occurred persistently when a minimum value for I_i was attained.

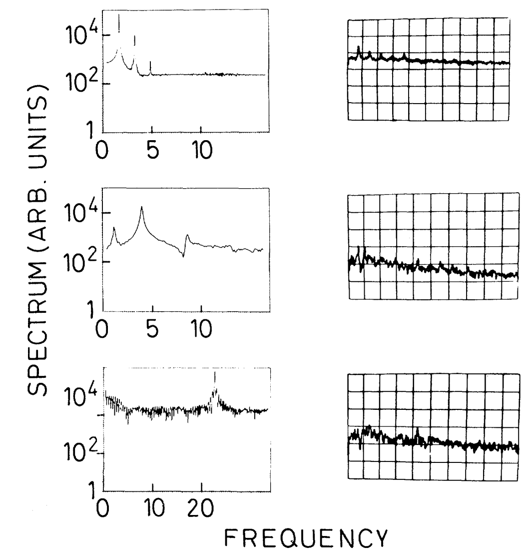

FIG. 2. Theoretical (left) and experimental (right) audio spectra illustrating (top) the appearance of harmonics of the driven pendulum frequency Ω_{eff}; (middle) the frequency splitting—bistable—regime; (bottom) the mirror confinement regime. Theoretical curves: arbitrary frequency scale; experimental curves: 2 Hz/division.

The experimental evidence for this effect is shown in Fig. 2(c). The suppression of the response of the system at the pendulum frequency is dramatic. It is difficult to predict what intensity is necessary to achieve this suppression, since it depends on the magnitude of the driving force, which is unknown in these experiments. But the effect is clearly a potentially useful way to control the position of the mirror.

These preliminary results demonstrate with certainty that bistability may be achieved without the use of nonlinear media. The general agreement of calculations including radiation pressure strongly indicate that this is the source of the nonlinear behavior. Perhaps the most interesting feature of these experiments, however, is the discovery of the mechanical stabilizing effect at higher laser power levels. An understanding of the nature and limits of this effect is now being gained both experimentally and theoretically, and will be reported in detail in the near future.

Radiation-pressure bistability and optical mirror confinement open the way to a number of novel applications where the measurement of very small displacements is desired. Our system can operate as an extremely sensitive transducer between mechanical and optical signals, and could be used in optoacoustic spectroscopy, e.g., of surfaces, and photoelectric effect studies: The momentum of the photoelectrons ejected by a metallic surface is about three orders of magnitude larger than that of the incident photons. Further possible applications include laser stabilization, an all-optical microphone, and seismometers, to list a few.

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[1]For a tutorial discussion, see, e.g., J. H. Marburger and F. S. Felber, Phys. Rev. A 17, 335 (1978).

[2]E. F. Nichols and G. F. Hull, Phys. Rev. 13, 307 (1901).