Frequency Bistability of a Semiconductor Laser under a Frequency-Dependent Feedback

B. Farias, T. Passerat de Silans, M. Chevrollier, and M. Oriá

Laboratório de Física Atômica e Lasers - D.F. - Universidade Federal da Paraíba, Cx. Postal 5008, 58051-970 João Pessoa-PB, Brazil

(Received 9 July 2004; published 4 May 2005)

The emission frequency of a diode laser submitted to a frequency-dependent optoelectronic feedback is observed to have more than one stable operation point together with a stable power emission. This is, to our knowledge, the first observation of bistability exclusively in the frequency of an optical system. The experiment was carried out with a semiconductor laser coupled to the cesium D_2 line by an orthogonally polarized frequency-sensitive optical feedback.

DOI: 10.1103/PhysRevLett.94.173902 PACS numbers: 42.55.Px, 42.50.Gy, 42.65.Pc, 42.79.Ta

Feedback is an important control mechanism whose applications occur in such various disciplines as biology [1], economics [2], and chemistry [3]. In physics, feedback has been used, for instance, as a control mechanism of fundamental quantum properties [4]. Optical cavities (OC: Fabry-Pérot, ring, or laser) with nonlinear media inside are physical systems adapted to studies of feedback manifestations, bistability being one of the most important behaviors resulting from feedback in such nonlinear systems [5].

The bistability in OC [6] has been demonstrated in experiments where both dispersive [7] and absorptive [8] responses of the nonlinear medium to the radiation field were explored. Recently multistability has been observed in an optical ring configuration [9] where the system explored both regimes, following an absorptive bistability curve during the up scanning of the input intensity and returning along the dispersive response of the atomic medium.

Semiconductor lasers also are largely used for studies of the dynamic response of the emitted radiation when these nonlinear systems are in the presence of feedback [10,11]. As a consequence, diode lasers (DL) have been employed to investigate bistability in power [12], polarization [13], and operation between different oscillating modes [14] in experiments where the frequency is a key parameter to the observation and control of such bistable states. However, no observation of an equivalent multistable behavior *only in the optical frequency* has been reported.

Actually, optical bistability has meant possible operation over two output *intensities* and presents potential applications, in all-optical logic gates and optical computing, as a switch (between two states of the output power), memory, converser, etc. We report here the first observation of bistability in the *frequency* response of a stable-power single-mode laser under frequency-sensitive feedback. This bistability in frequency opens the way to applications where optical digital information may be carried with a constant intensity level but using the switch between the two frequency branches, completing the analogy, in the optical domain, with the existent FM and AM radio frequency communication technology. Indeed, a recent demonstration [15] of frequency oscillation in a stable-power semiconductor laser achieved with a filtered feedback already paves the path for these all-optical FM applications.

The observation, reported in this Letter, of the hysteretic behavior of the laser frequency is due to our ability to separately (i) control the carrier density (and consequently the emission frequency) of the semiconductor directly through its *linear* dependence to an orthogonal (TM-polarized) feedback power, which does not interfere with the oscillating field (TE-polarized) in the semiconductor cavity and (ii) use the spectral nonlinear response of a filter to modulate the optical field reinjected into the laser cavity (see Fig. 1).

Obviously one should expect less sensitivity of the laser behavior (dynamical response, frequency shift, and emission linewidth) to TM than to TE feedback. Systematic studies of the laser dynamics mainly use TE feedback, whose operations are usually described by the Lang-Kobayashi equations [16], and the phase of the returned TE beam is a very important parameter as shown, for example, by different results obtained with coherent and delayed TE feedback [17]. Conversely, TM feedback essentially acts on the carrier density in the diode junction "saturated" by the oscillating TE field and does not interfere with this field [18]. We emphasize then the different nature of the results presented here from previous studies of frequency dependence of the *intensity* dynamics in semiconductor lasers submitted to a constant [19] or to a filtered [20] feedback, as well as from two modes bistability [21].

A single-mode, current- and temperature-stabilized, AsAlGa diode laser, emitting around 852 nm, is placed

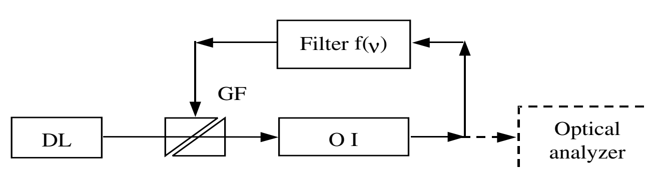

FIG. 1. Scheme to inject an orthogonal-polarization filtered optical feedback in a semiconductor laser. DL: diode laser, GF: Glan-Foucault, OI: optical isolator. Optical analyzer: Fabry-Pérot cavity and room-temperature Cs-vapor cell.

in a configuration that allows returning a fraction of the laser output back into the DL cavity. The laser is operated within its commercial characteristics, i.e., with no special coating on its faces. The experimental setup (Fig. 1) is essentially the same as described in Ref. [22]. The collimated output beam with a slightly elliptical polarization (the ratio between the two orthogonal polarizations is 800:1) is sent through a Glan-Foucault polarizer. The TE component is transmitted and the TM one is laterally reflected. A beam with orthogonal polarization is returned into the DL through the ejection axis of the polarizer and a half-wave plate allows the control of the feedback intensity. An optical isolator blocks residual coherent feedback, particularly from the Fabry-Pérot of analysis, and guarantees the one-way character of the feedback loop. A frequency-sensitive device placed in the way of the feedback beam spectrally modulates its intensity.

Initially, we characterize the laser response to an orthogonal incoherent feedback by measuring the frequency shift $\delta = (\nu_0 - \nu)$ of the laser as a function of P_f, the fraction of the power sent back to the laser. ν is the emission frequency and ν_0 is the solitary (no feedback) laser frequency, depending linearly on the laser current j [11]:

$$\nu_0 - \nu_{\mathrm{th}} = k(j - j_{\mathrm{th}}), \tag{1}$$

where ν_{th} and j_{th} are the laser threshold frequency and current, respectively, and $k = -3.75$ GHz/mA in our system. All the measurements related in the following are carried out for a laser current around 100 mA and an emission power of approximately 40 mW. The optical power P_{eff} effectively returning into the laser cavity is related to P_f through a geometrical coupling factor χ that we did not measure [23]. We measure a linear dependence of δ as a function of P_f [24]:

$$\delta = \beta P_f. \tag{2}$$

The shift depends on the effective coupling of the reinjected beam with the semiconductor cavity so that a judicious alignment is necessary to optimize the effective feedback level. With $\beta = 1.76$ GHz/mW, this frequency shift is obtained, in a very reproducible way, up to values of $\delta \approx 10$ GHz for a feedback level of -7.7 dB [25]. β is the coefficient to be considered to operate this kind of system as an AM $\leftrightarrow$ FM converser [26].

For further studies and applications, such as the dynamical stabilization of the diode laser [22] or the observation of a bistable behavior, as discussed below, the laser frequency is scanned around the resonance of the filter. The feedback power becomes then a frequency-dependent fraction of the total laser power,

$$P_f = \kappa(\nu)P, \tag{3}$$

where $\kappa(\nu)$ accounts for the line shape of the filter.

Considering the laser linewidth of about 40 MHz we chose as a filter the Doppler-broadened absorption line of the Cs D_2 transition at 852.1 nm ($6S_{1/2} - 6P_{3/2}$). This system presents advantages such as the fact that an atomic line constitutes an absolute, yet versatile [27], frequency reference. The loop transmission coefficient κ takes the form:

$$\kappa = \kappa_0[1 - \epsilon f(\nu)], \tag{4}$$

where κ_0 stands for the nonresonant losses and attenuations in the different optical elements of the setup (transmission through beam splitters, spurious reflections by optical elements, attenuation by the $\lambda/2$ wave plate, etc.), ϵ is the absorption coefficient at line center ν_{at}, and $f(\nu)$ is the amplitude-normalized absorption line shape. We slightly heat the vapor cell so that $\epsilon \approx 0.5$, allowing a contrasted transmission spectrum together with a high level of nonresonant loop transmission, κ_0, and consequently feedback powers comparable to the laser output power [see Eq. (2) and the value of β]. We show in Fig. 2(a) a transmission spectrum of the Cs D_2 line for $\epsilon = 0.5$, with zero feedback level, i.e., the free spectrum of the

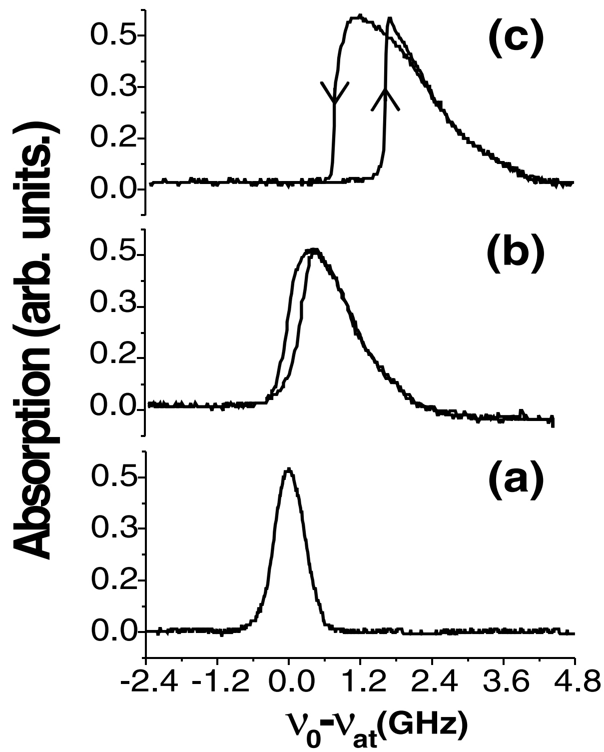

FIG. 2. Laser transmission through the atomic filter. The x axis is scaled in terms of the solitary laser frequency ν_0. (a) Doppler profile of the Cs D_2 line used as a filter to modulate the feedback beam; the fit by Eq. (5) gives $\alpha = 7.7$ GHz^{-2}. (b)–(c) Emission frequency probed by the Cs D_2 absorption when the laser is under filtered orthogonal-polarization optical feedback: (b) $\kappa_0 = 5.81 \times 10^{-3}$; (c) $\kappa_0 = 3.43 \times 10^{-2}$. The arrows indicate the direction of each scan.

atomic filter. We fit this curve with a spectral Gaussian profile,

$$f(\nu) = \exp[-\alpha(\nu - \nu_{\mathrm{at}})^2]. \tag{5}$$

Increasing P_f, the emission frequency decreases so that the resonance occurs at a lower current (at a correspondingly higher solitary frequency), and the absorption line shape changes dramatically [22], as can be observed in Figs. 2(b) and 2(c). The signal of the derivative of the absorption spectrum determines the laser response in such a way that the scanning of the positive flank of the absorption ($dP_f/d\nu < 0$) provokes instability and the negative flank stability [22,25]. A laser "locked" at the stable flank has its linewidth reduced by a factor determined by the loop time delay and not by the semiconductor relaxation oscillation frequency [28]. In our setup the round trip length of the feedback beam is $L = 180$ cm, meaning a delay of 6 ns or a modulation frequency of 167 MHz. The measurements reported here are carried out at an operation current around $j = 2.3 j_{\mathrm{th}}$ where no amplitude modulations, due to the orthogonal feedback, are expected [29]. An up-down frequency scanning allows the observation of the hysteretic cycle shown in Figs. 2(b) and 2(c) [30]. There the laser power is constant and its amplitude and frequency noise are comparable to the solitary laser operation; i.e., without a frequency discriminator we cannot distinguish between the two states of this bistability. There is also no observable effect in the emission polarization, which could be easily detected in the laser output, through the Glan polarizer. The hysteresis range is controlled through the feedback level κ_0 and the absorption coefficient, ϵ. We summarize in Fig. 3 the measurements of the hysteresis range as a function of κ_0.

To describe the observed hysteresis we turn to account that far from threshold and in the presence of TM feedback the output power of the laser is almost constant and its frequency is shifted linearly with the injected power [Eq. (2)]. Then, from Eqs. (2)–(4), we can write the frequency of the laser as

$$\nu = \nu_0 - \beta\kappa_0[1 - \epsilon f(\nu)]P. \tag{6}$$

The curves in Figs. 4(a)–4(e) show the calculated spectral response of a diode laser submitted to an orthogonal feedback filtered by the Doppler-broadened Gaussian absorptive line shape given by Eq. (5) and plotted in Fig. 4(f). The linear curve Fig. 4(a) represents the laser frequency for zero feedback ($\kappa_0 = 0$, $\nu = \nu_0$). For a constant, nonzero feedback $\kappa = \kappa_0$ ($\epsilon = 0$), this line is shifted by an amount $\beta\kappa_0 P$ [Fig. 4(b)]. Curves 4(c)–(e) show the evolution of ν versus ν_0 for $\epsilon = 0.5$ and for different values of κ_0, i.e., when changing the amount of the out-of-resonance feedback in the laser cavity. For small orthogonal coupling [$\kappa_0 \ll 1$, Fig. 4(c)] the derivative $d\nu/d\nu_0$ is always positive, and no hysteresis cycle occurs. The hysteretic behavior appears for feedback levels such that $\kappa_0 > \kappa_1$, where κ_1 is derived from the condition that the derivative $d\nu/d\nu_0$ be negative:

$$\frac{1}{\kappa_1} = \sqrt{2\alpha}\epsilon\beta P \exp\left(-\frac{1}{2}\right). \tag{7}$$

We show on curve (e) in Fig. 4 the path followed by the laser. The hysteresis observed in Fig. 2 is due to the fact that the laser avoids the instability regions ($d\nu/d\nu_0 < 0$, as discussed above). In Fig. 3 the hysteresis range as a function of κ_0 is best fitted by a theoretical curve with β

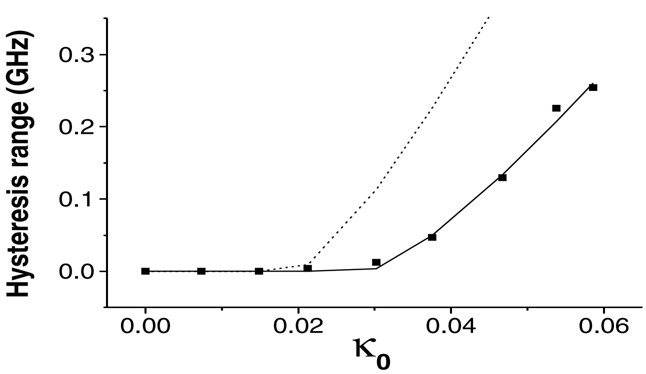

FIG. 3. Hysteresis range as a function of κ_0. Experimental parameters: $\epsilon = 47.5\%$, $P = 42.4$ mW, $\alpha = 8.27\ \mathrm{GHz}^{-2}$, $\beta_{\mathrm{exp}} = 1.035$ GHz/mW. Squares: experimental data. Full line: calculated curve, with $\beta = 0.7$ GHz/mW. Dotted line: calculated curve, with $\beta = 1.035$ GHz/mW (see text).

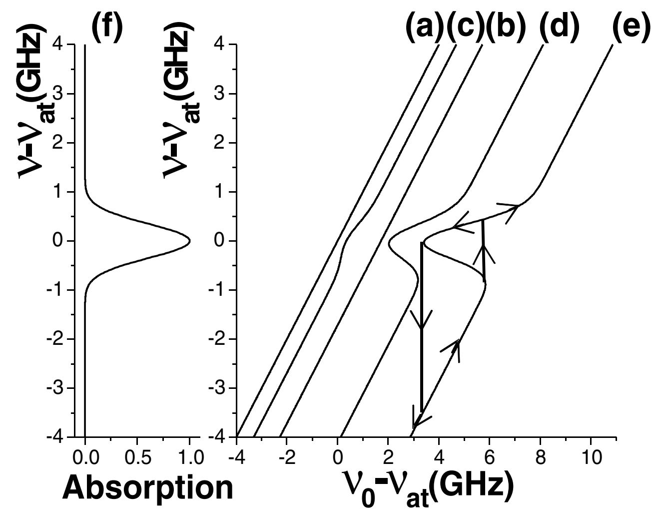

FIG. 4. Calculated laser emission frequency ν as a function of the solitary laser frequency ν_0 [Eqs. (5) and (6)], for $P = 39$ mW, $\alpha = 4.1\ \mathrm{GHz}^{-2}$, and $\beta = 1.76$ GHz/mW. (a) Without feedback. (b) With a constant level feedback $\kappa_0 = 2.5 \times 10^{-2}$ and $\epsilon = 0$. (c)–(e) with filtered feedback ($\epsilon = 0.5$): (c) $\kappa_0 = 1.0 \times 10^{-2}$; (d) $\kappa_0 = 6.0 \times 10^{-2}$; (e) $\kappa_0 = 1.0 \times 10^{-1}$. The emission frequency path is indicated by arrows in the two directions of the scans. The instability region is avoided, resulting in bistability. (f) Filter spectral profile [Eq. (5)].

slightly smaller than the value measured without the frequency filter (all other values of parameters as measured, see caption), which corroborates our suspicion of resonant propagation effects affecting the power coupling factor χ and consequently the effective power sent back into the laser [29]. The hysteresis range scales as $(\kappa_0 - \kappa_1)^x$, with x a function of all the parameters of the system. For instance, with the parameters values of the experiments of Fig. 3 we have $\kappa_1 = 2.87 \times 10^{-2}$ and $x \approx 1.35$.

In summary, we present a technique to optically control the frequency of a semiconductor laser. Using an atomic-filtered orthogonal feedback we observe a bistable behavior in the laser frequency in a regime of stable output intensity. The system is easily controllable and completely described by a simple model. It constitutes a new paradigm for the study of frequency optical bistability and future developments may use other frequency discriminators as diffraction gratings, atomic beams, or cold atoms to achieve sub-Doppler resolution narrowing the frequency operation range, or yet, use a second laser to control the transmission in the vapor cell [9]. One can also expect that the frequency switch presented here may be employed in combination with frequency modulation obtained with TE feedback [15]. The system presented here is robust, stable, and reproducible and can be built in a compact way, necessary characteristics for applications in all-optical FM logic circuits.

The authors thank A. Freire de Araújo and P. Segundo for their help in the early stage of this experiment. This research was supported by FINEP (Fenix Project), CAPES-COFECUB project 456/04, and CNPq.

[1] S. Serizawa, K. Miyamichi, H. Nakatani, M. Suzuki, M. Saito, Y. Yoshihara, and H. Sakano, Science **302**, 2088 (2003).
[2] J. A. Holyst, M. Zebrowska, and K. Urbanowicz, Eur. Phys. J. B **20**, 531 (2001).
[3] S. Grill, V. S. Zykov, and S. C. Müller, J. Phys. Chem. **100**, 19082 (1996).
[4] J. M. Geremia, J. K. Stockton, and H. Mabuchi, Science **304**, 270 (2004).
[5] See, for example, L. A. Lugiato, in *Progress in Optics*, edited by E. Wolf (North-Holland, Amsterdam, 1984), Vol. 21, p. 71, and references therein.
[6] H. M. Gibbs, *Optical Bistability: Controlling Light with Light* (Academic, New York, 1985).
[7] H. M. Gibbs, S. L. McCall, and T. N. C. Venkatesan, Phys. Rev. Lett. **36**, 1135 (1976).
[8] A. T. Rosenberger, L. A. Orozco, and H. J. Kimble, Phys. Rev. A **28**, R2569 (1983).
[9] A. Joshi and M. Xiao, Phys. Rev. Lett. **91**, 143904 (2003).
[10] H. Kawaguchi, *Bistabilities and Nonlinearities in Laser Diodes* (Artech House, Boston, 1994).
[11] G. P. Agrawal and N. K. Dutta, *Long-Wavelength Semiconductor Lasers* (Van Nostrand Reinhold, New York, 1986).
[12] P. Pakdeevanich and M. J. Adams, Opt. Commun. **176**, 195 (2000); M. J. Adams, Solid-State Electron. **30**, 43 (1987).
[13] Y. C. Chen and J. M. Liu, Appl. Phys. Lett. **46**, 16 (1985); S. Cecchi, G. Giusfredi, E. Petriella, and P. Salieri, Phys. Rev. Lett. **49**, 1928 (1982).
[14] Y. Hong and K. A. Shore, Opt. Lett. **23**, 1689 (1998).
[15] A. P. A. Fischer, M. Yousefi, D. Lenstra, M. W. Carter, and G. Vemuri, Phys. Rev. Lett. **92**, 023901 (2004).
[16] R. Lang and K. Kobayashi, IEEE J. Quantum Electron. **16**, 347 (1980).
[17] O. Ushakov, S. Bauer, O. Brox, H.-J. Wünsche, and F. Henneberger, Phys. Rev. Lett. **92**, 043902 (2004); F. Ishiyama, J. Opt. Soc. Am. B **16**, 2202 (1999).
[18] Optoelectronic feedback also permits the dynamical control of the laser emission through the carrier density. See, for instance, A. Fischer, J.-P. Goedgebuer, and H. Porte, Opt. Lett. **24**, 765 (1999). However, this technique has limitations if compared to the optical one described here (cf. Ref. [25]).
[19] J. Mørk, B. Tromborg, and P. L. Christiansen, IEEE J. Quantum Electron. **24**, 123 (1988).
[20] M. Giudici, L. Giuggioli, C. Green, and J. R. Tredicce, Chaos Solitons Fractals **10**, 811 (1999).
[21] Amplitude modulation occurs simultaneously with mode jumps. See, for instance, L. Xu, B. C. Wang, V. Baby, I. Glesk, and P. R. Prucnal, IEEE Photonics Technol. Lett. **14**, 149 (2002).
[22] A. F. A. da Rocha, P. C. S. Segundo, M. Chevrollier, and M. Oriá, Appl. Phys. Lett. **84**, 179 (2004).
[23] While the value of χ is not important for our purpose here, it can indeed be determined. See, for instance, P. A. Judge, C. H. L. Quay, and J. A. Hudgings, Appl. Phys. Lett. **81**, 3933 (2002).
[24] It can be shown (see Ref. [11]) that an increase in the number of photons inside the cavity results in an increase in the index of refraction through a decreasing of the carrier density, so that the frequency of the lasing mode decreases. All these relations are linear.
[25] H. Yasaka, Y. Yoshikuni, and H. Kawaguchi, IEEE J. Quantum Electron. **27**, 193 (1991).
[26] The linear response of the laser to the intensity feedback makes it a candidate as a frequency generator/AM-FM converser. For this application, it may appear as a complementary technique of that of Ref. [15], but one must first characterize the frequency range for this conversion, i.e., the operation passband, which is beyond the purpose of this work.
[27] The dynamics of the laser depends on the line shape, which may be strongly modified through the control of the medium thickness. See, for instance, S. Svanberg, G. Y. Yan, T. P. Duffey, and A. L. Schawlow, Opt. Lett. **11**, 138 (1986).
[28] H. Yasaka and H. Kawaguchi, Appl. Phys. Lett. **53**, 1360 (1988).
[29] T. Heil, A. Uchida, P. Davis, and T. Aida, Phys. Rev. A **68**, 033811 (2003).
[30] The structure appearing in Fig. 2(c) is due to a dispersive contribution of the filter transmission and is currently being investigated.