Light Polarization of a Quasi-isotropic Laser with Optical Feedback

Guy Stephan and Dominique Hugon
Laboratoire de Spectroscopie, Université de Rennes, F-35042 Rennes, France
(Received 23 May 1985)

The light of a quasi-isotropic, single-mode gas laser is linearly polarized for a line $J_a = 1 \rightarrow J_b = 2$. However, the azimuth of polarization can vary inside the line. Among the many different effects which cause these variations, we describe the role played by the detector optical feedback. We show experimentally that its amplitude and phase can be varied in a controlled manner in order to obtain abrupt switches between two perpendicular polarization states. Polarization bistability and hysteresis effects can then be commanded and studied from the outside of the laser.

PACS numbers: 42.55.Bi, 42.60.He

As early as 1966, it was discovered[1,2] that a single-mode He-Ne laser with internal mirrors may operate with a polarization of light which can flip abruptly between two orthogonal states while the frequency is scanned. A great amount of work followed, showing first that atomic properties[3–6] give a preferential polarization (circular or linear) and then describing the phenomenon both theoretically[7–10] and experimentally.[11–16] The subject has never been abandoned and now receives a renewal of interest in relation to laser instabilities,[17,18] optical bistability,[19] and vectorial tristability[20] studied in passive resonators. The commonly accepted idea is that the condition for bistable behavior in lasers is the presence of intracavity birefringence, generally attributed to the mirrors. We prove below that this requirement is not necessary, for this purpose we have divided the different causes of the polarization flip into three categories: (a) the properties of the gain medium, especially its anisotropy[21] or its longitudinal inhomogeneity of saturation,[22] (b) the cavity optical components, which are windows,[16] mirrors,[12] and diffracting objects[23]; and (c) the anisotropic feedback of the outside.

Up to now the third cause has been unseen in experimental studies. The new result in this Letter is the demonstration that one can command the polarization of light of a quasi-isotropic laser via the optical feedback of the detector system. The more isotropic the laser, the more sensitive it is to the feedback anisotropy. We study here a He-Ne laser working at 3.39 μm where causes (a), (b), and (c) are in the following hierarchy: (a) is negligible, (b) is weak and controlled by the use of an amplifying tube which is closed by windows inclined 86° with respect to the laser axis, and (c) can be varied and increased enough to impose its anisotropy on the laser. We then obtain as many polarization flips as wanted in the emission line. Moreover, their positions are easily controlled. Applications include a new use of the laser as a means to determine the eigenvectors of an external device, the study of atomic properties via a measurement of regions of bistability, and an extension to multimode lasers in order to explain some controversial results.[24]

Let us consider a monomode, internal-mirrors gas laser [Fig. 1(a)] having a gain medium with a preferentially linearly polarized emission line. This is the case for the 632.8-nm, 1.15-μm, and 3.39-μm neon lines. Let R_a and R_b be the isotropic reflectivity coefficients of the mirrors. This laser is initially symmetric around the propagation axis z. The detector system consists of a y-axis polarizer, a lens, and a photodiode. It reflects or diffuses a small amount of light back into the laser through the mirror R_b in a nonisotropic way because of the polarizer. Therefore, the laser cylindrical symmetry is broken. This can be accounted for by writing an anisotropic reflectivity for the mirror R_b as follows:

$$R_x = R_b \quad \text{on the } x \text{ axis},$$

$$R_y = R_b + \epsilon \exp(i\phi) \quad \text{on the } y \text{ axis}.$$

$\epsilon \exp(i\phi)$ represents the detector feedback. Generally

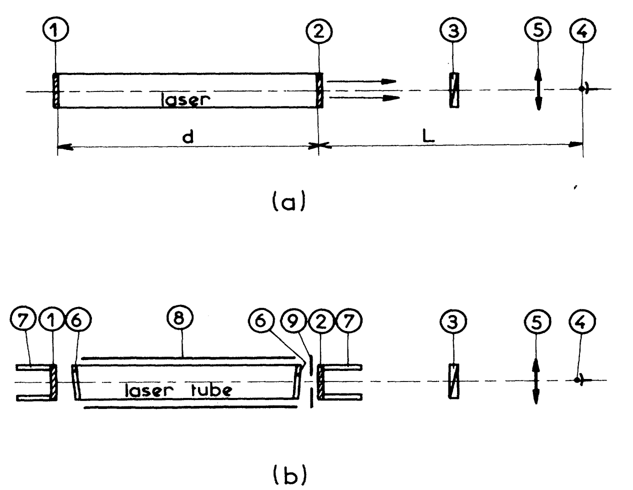

FIG. 1. (a) Theoretical model. (b) Experimental arrangement. 1, mirror R_a (plane mirror); 2, mirror R_b (concave mirror); 3, polarizer; 4, detector (InAs); 5, lens; 6, tube window; 7, piezoelectric ceramic; 8, magnetic shielding; and 9, diaphragm.

one has $\epsilon << R_b$, and therefore $|R_y| \sim R_b + \epsilon \cos\phi$. Let E_x, E_y be the modes having, respectively, x,y polarizations and frequencies ω_x, ω_y. Theory[22] shows that the polarization switch $E_x(\omega_x) \to E_y(\omega_y)$ occurs when the expression

$$\Delta v = \dot{E}_y/E_y - \dot{E}_x/E_x = \tfrac{1}{2}\omega\{1/Q_x(\omega_x) - 1/Q_{xy}(\omega_y) + [(\alpha_x^i(\omega_x) - \alpha_y^i(\omega_y)]/\epsilon_0\} \tag{1}$$

becomes positive. This expression contains the frequency-dependent components $Q_x(\omega_x)$ and $Q_{xy}(\omega_y)$ of the quality factor and the imaginary part of the anisotropic polarizability tensor.[25] If we neglect saturation effects and cavity anisotropies, this expression shows that the azimuth of polarization will be along the larger-reflectivity axis. For the moment let us forget the imaginary part $\epsilon \sin\phi$, which will influence the laser frequency.[26] Then, following the sign of $\cos\phi$ the light will be polarized along the y ($\cos\phi > 0$) or the x ($\cos\phi < 0$) axis.

Now it can be seen that ϕ is a function of the frequency ν,[27]

$$\phi = 4\pi\nu L/c, \tag{2}$$

where L is the optical path between the mirror R_b and the detector. ν can be scanned by a variation of the position of one mirror. Suppose first that the mirror R_a is moving. Then

$$\delta\phi = 4\pi\,\delta\nu\, L/c.$$

Consider the spectral range $\Delta\nu = c/2d$, where d is the laser length. For this range $\delta\phi = 2\pi L/d$ and ϕ shows L/d cycles. Therefore when ν moves continuously within the interval $c/2d$, there are $N_1 = L/d$ regions with preferential polarizations x or y, with $2N_1$ possible polarization switches. The farther away the detector, the more polarization switches within the line (Fig. 2). A second possibility is to vary the position of the mirror R_b. In this case ν and L vary together and $\delta\phi = (L\,\delta\nu + \nu\,\delta L)4\pi/c$. As $\delta L = -\delta d$ and $\delta d/d = -\delta\nu/\nu - \delta n/n$, we get

$$\delta\phi = (4\pi/c)[\delta\nu(L+d) + \nu d\,\delta n].$$

Here n is the frequency-dependent index of refraction whose value is close to unity. Thus a 2π cycle for ϕ corresponds to the spectral range

$$\delta\nu = \frac{c}{2(L+d)} - \frac{d}{L+d}\nu\,\delta n$$

and polarization periods no longer have the same width.

Consider now the laser free spectral range $\Delta\nu'$ which corresponds to a $\lambda/2$ variation of its optical length. That is, $\Delta\nu' = \Delta\nu - \nu\,\Delta n$. Δn is the index difference for the two frequencies (each belonging to a different longitudinal mode labeled N and $N+1$) which can oscillate for the same length d. Inside of this range the variation of ϕ is $\Delta\phi := 2\pi N_2$ and the expression for $\delta\phi$ gives

$$\Delta\nu' = (N_2\Delta\nu - \nu\,\Delta n)/(N_1+1).$$

One can the obtain Δn from an experimental determination of N_1 and N_2:

$$\Delta n = \frac{\Delta\nu}{\nu}\left(1 - \frac{N_2 - 1}{N_1}\right).$$

If the mirror R_a oscillates the range $\Delta\nu'$ is split into N_2' periods, and $\Delta\nu' = N_2' c/2L$ which must give the same value for Δn. One then obtains $N_2 - 1 = N_2'$, which means a supplementary cycle when the mirror R_b oscillates.

By use of this simple model we can predict the appearance of extinction slots in the line when observed through a polarizer. Let us examine now the positions of the slots within the line Eq. (2) shows that a variation of L modifies ϕ and therefore changes this position. L can be slightly modified by a tilt of the detector, the lens, or the polarizer. Shifting a mirror changes the laser frequency by $\delta\nu$. Therefore if one mirror is vibrating, a tilt on that mirror will not change

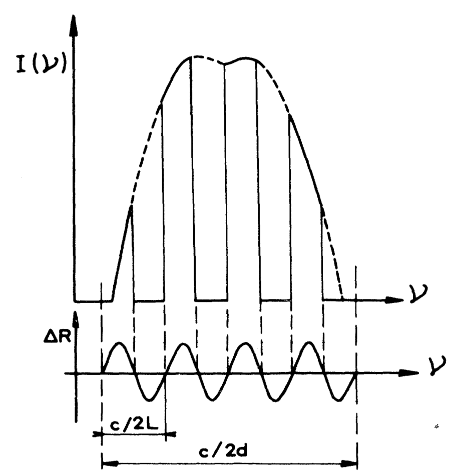

FIG. 2. Preferential perpendicular polarization domains give a crenelated signal when observed through the polarizer. If $\Delta R = \epsilon \cos\phi > 0$ the light oscillation is along the y axis, otherwise along the x axis. The larger L, the larger the number of slots. Their position in the line changes with the origin of ϕ, which can easily be driven by changing L. When $L < d$, one can or cannot observe polarization switches depending on this origin. Spectral width $c/2L$ or $\delta\nu$ (see text) is obtained depending on which mirror oscillates. It can also be seen that in the case where the cavity shows a constant anisotropy $\Delta R = R_{by} + \epsilon\cos\phi - R_{bx}$, the sinusoid is vertically translated and the width of bright and dark domains are not equal anymore.

the positions of the dark slots. They will be shifted by a tilt on the other mirror. Let us assume, for instance, that the mirror R_a vibrates in such a way that

$$\delta\phi = \phi - \phi_0 = (4\pi L/c) d\nu \sin(\Omega t),$$

with $\Delta\phi = 0$ when $\nu = \nu_0$. Here $d\nu$ and Ω are the amplitude and angular frequency of the frequency modulation. If a static variation $\Delta_1\nu$ is introduced by a tilting of the mirror R_b, the frequency modulation becomes centered on $\nu_0 + \Delta_1\nu$. Now

$$\delta\phi = (4\pi L/c)[\Delta_1\nu + (\Delta_1\nu + \nu\,\delta n)d/L + d\nu \sin(\Omega t)]$$

is centered on $\nu_0 + \Delta_1\nu + (\Delta_1\nu + \nu\,\delta n)d/L$, and this leads to a shift $(\Delta_1\nu + \nu\,\delta n)/N_1$ of the dark-slot positions inside the line.

Consider now the role of the imaginary term $\epsilon \sin\phi$: The optical length of the laser becomes anisotropic and the resonance condition[26] when applied to the two fields E_x and E_y shows that their frequencies are related by

$$\omega_y - \omega_x = -\Delta\nu(\epsilon/R_b)\sin[2(L+nd)\omega_y/c]$$

for the same length d. The switches $E_x(\omega_x) \rightarrow E_y(\omega_y)$ and $E_y(\omega_y) \rightarrow E_x(\omega_x)$ are then shifted from the position given by $R_y - R_x = 0$ to another one, obtainable from Eq. (1). Inclusion of saturation effects introduce hysteresis via $1/Q_{xy}(\omega_y)$ and $\alpha^i_{x,y}(\omega_{x,y})$. These effects are easily observed when L is of the order of d and are described elsewhere.

To conclude the above discussion, one can question the validity of representing the feedback by the expression $\epsilon \exp(i\phi)$. Our motivation is simplicity: It is obvious that the modified reflectance has to be replaced by an Airy's formula[27] when ϵ is strong enough. This would lead to different widths for the two frequency domains alternatively polarized x or y in Fig. 2. We have experimentally verified the conclusions of this simple analysis on a monomode, quasi-isotropic laser [Fig. 1(b)] working at 3.39 μm: The amplifying tube is filled up with a mixture of ^{20}Ne and natural He. Its windows are antiparallel, making a 4° angle with the vertical y axis, and define a vertical incidence plane. The tube preferential polarization azimuth is therefore vertical. One of the mirrors is plane ($R_a \sim 1$) and the other concave ($R_b = 0.8$), with a 120- or 85-cm radius of curvature. The high transmittance (36% for intensity) of the coupling mirror allows a high feedback.

Figure 3 gives experimental results when $L = 11.30$ m and $d = 0.429$ m. First, the plane mirror R_a is oscillating [Figs. 3(a) and 3(b)]. The intensity is set up so that there is an extinction between two successive cavity modes. In Fig. 3(a) the line is observed without a polarizer: The intensity modulation reveals the feedback and can be adjusted with a rotation of the detector around the x or y axis. This modulation can be shaped differently following the characteristics of the feedback. We have also observed shapes describable by Airy's formula.[27] Figure 3(b) shows the expected line shape observed through the polarizer. We observe $N_2' = 21.5$ cycles within the line. Using $N_1 = 26.3$, $\nu = 88.4$ THz, and $\Delta\nu = 350$ MHz, we obtain $\Delta n = 7.3\times10^{-7}$. This value is in agreement with a first evaluation obtained from the gain. Let ν_1 and ν_2 be the two frequencies corresponding to Δn. If they are symmetrical with respect to the line center[28] one obtains $n(\nu_1) = 1 - 3.6\times10^{-7}$ and $n(\nu_2) = 1 + 3.6\times10^{-7}$. The precision on n obviously increases with the ratio L/d and one cannot expect any measurement when, for instance, $L = 2d$. Figure 3 shows that one can split a laser line $c/2L$ spectral ranges. This will al-

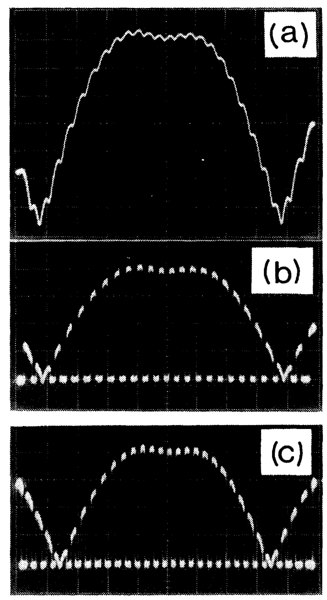

FIG. 3 (a) Line profile of the single-mode laser at 3.39 μm with use of the arrangement of Fig. 1(b) without the polarizer. Frequency increases from left to right. The gain has been set up such that the linewidth at zero intensity corresponds to a variation of the laser optical length $\lambda/2$ (successive longitudinal modes border on each other at zero intensity). The oscillating mirror is the plane one, R_a. The backward trace has been electronically rubbed out. The intensity modulation is due to the detector optical feedback. $L = 11.30$ m and $d = 0.429$ m. Twenty-two maxima can be observed. Light polarization is vertical as determined by the tube windows. (b) Mirror R_a is oscillating and 21.5 polarization cycles can be observed through the polarizer. (c) Mirror R_b is oscillating and 22.5 cycles can be counted. We have made this optical self-chopper working with the same efficiency for $L = 25$ m. We observed that the detector orientation was far from being critical, which allows a very easy observation of the phenomena.

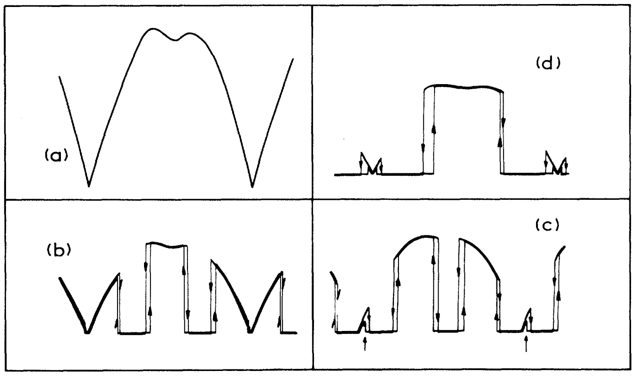

FIG. 4. Signals observed for $L=2d=86$ cm. Here backward traces have been preserved. For more clarity, drawings have been made from oscillograms. (a) Line profile without polarizer. The intensity modulation due to feedback is hardly seen and is replaced by a deformation. Other signals (b), (c), and (d) are all observed through the polarizer. (b), (c) Obtained with the mirror R_b vibrating. Three dark slots appear. The two figures correspond to two different (but close) positions of the plane mirror R_a. Adjusting the mirror R_b does not modify the slot positions. Note the variation of the bistability domains Δd across the line. (d) Obtained in the same manner but with the mirror R_a vibrating. Only two slots can now be seen. They can be moved across the line by tilting the mirror R_b or, more easily, by slightly modifying the position of a component of the detector system.

low an easy frequency calibration of the emission lines. It can also be split into variable domains $\delta\nu$ (as given above) which allows the direct measurement of index variations. Figure 3(c) is obtained with the mirror R_b oscillating: $N_2=22.5$ cycles can be observed which verifies the relation $N_2=N_2'+1$.

Figure 4 illustrates the preceding conclusions for $L/d=2$. A sinusoidal voltage[29] is applied on either of piezoceramics holding the mirrors in order to see the domain of bistability Δd. Figures 4(a)–4(c) correspond to a vibration of the concave mirror. Figure 4(a) shows the entire line shape, while Figures 4(b) and 4(c) show lines through the polarizer. As predicted, there are three extinction slots $(L/d+1=3)$. Their positions within the line were changed from Fig. 4(b) to 4(c) by slightly modifying the plane-mirror adjustment. Figure 4(d) was obtained by a vibration of the plane mirror and shows only two slots as predicted. Figures 4(b)–4(d) also show the bistability domains Δd whose width varies inside the line.

We would like to thank Dr. Y. V. Troitsky for a valuable correspondence. Laboratoire de Spectroscopie is unité de recherche No. 791 associée au Centre National de la Recherche Scientifique.

[1]W. Culshaw and J. Kannelaud, Phys. Rev. **141**, 237 (1966).

[2]R. L. Fork, W. J. Tomlinson, and L. J. Heilos, Appl. Phys. Lett. **8**, 162 (1966).

[3]D. Polder and W. Van Haeringen, Phys. Lett. **19**, 380 (1965).

[4]H. De Lang, G. Bouwhuis, and E. T. Ferguson, Phys. Lett. **19**, 482 (1965).

[5]C. V. Heer and R. D. Graft, Phys. Rev. **140**, A1088 (1965).

[6]W. M. Doyle and M. B. White, Phys. Rev. **147**, 359 (1966).

[7]W. Van Haeringen, Phys. Rev. **158**, 256 (1967).

[8]V. A. Smirnov and A. M. Tumaikin, Opt. Spektrosk. **40**, 1030 (1976) [Opt. Spectrosc. (USSR) **40**, 593 (1976)].

[9]I. P. Mazanko, Opt. Spektrosk. **36**, 552 (1973) [Opt. Spectrosc. (USSR) **36**, 318 (1974)].

[10]M. S. Borisova and I. P. Mazanko, Opt. Spektrosk. **47**, 126 (1979) [Opt. Spectrosc. (USSR) **47**, 69 (1979)].

[11]E. Yu Andreyeva, K. O. Teryokhin, and S. A. Fridrikhov, Opt. Spektrosk. **27**, 809 (1969) [Opt. Spectrosc. (USSR) **27**, 441 (1969)].

[12]A. G. Laguna-Ayala and C. Roychoudhuri, Bol. Inst. Tonantzintla, **2**, 109 (1976).

[13]A. P. Voitovitch and A. P. Shkadarevitch, Opt. Spektrosk. **41**, 627 (1976) [Opt. Spectrosc. (USSR) **41**, 368 (1976)].

[14]T. Yoshino, Jpn. J. Appl. Phys. **11**, 263 (1972).

[15]A. S. Lipatov and V. N. Parygin, Kvan. Elektron. (Moscow) **2**, 2571 (1975), and **5**, 2098 (1978) [Sov. J. Quantum Electron. **5**, 1400 (1976), and **8**, 1184 (1978)].

[16]A. Le Floch, G. Ropars, J. M. Le Normand, and R. Le Naour, Phys. Rev. Lett. **52**, 918 (1984).

[17]L. W. Casperson, in *Laser Physics, The Proceedings of the Third New Zealand Symposium, 1983,* edited by I. D. Harvey and D. F. Walls, Lecture Notes in Physics, Vol. 182 (Springer-Verlag, New York, 1983), p. 88.

[18]R. S. Gioggia and N. B. Abraham, Opt. Commun. **47**, 278 (1983).

[19]*Optical Bistability,* edited by C. M. Bowden, M. Ciftan, H. Robl (Plenum, New York, 1981).

[20]M. Kitano, T. Yabuzaki, and T. Ogawa, Phys. Rev. Lett. **46**, 926 (1981).

[21]M. Dumont and G. Durand, C. R. Acad. Sci. **257**, 2974 (1963). See also Y. C. Chen and J. M. Liu, Appl. Phys. Lett. **45**, 731 (1984), for the case of a semiconductor laser.

[22]D. Hugon, thése de troisieme cycle, Rennes, 1982 (unpublished).

[23]D. Belland, Infrared Phys. **24**, 381 (1984).

[24]E. Hasle, Opt. Commun. **31**, 206 (1979).

[25]G. Stephan, R. Le Naour, and A. Le Floch, Phys. Rev. A **17**, 733 (1978).

[26]P. J. Brannon, Appl. Opt. **15**, 1119 (1976).

[27]Th. H. Peek, P. T. Bolwijn, and C. Th. J. Alkemade, Am. J. Phys. **35**, 820 (1967).

[28]G. Stephan and M. Trümper, Phys. Rev. A **30**, 1925 (1984).

[29]Y. V. Troistsky, *Lasery s Perestraivaemoi Chastotoi* (Kiev, 1973), p. 280.

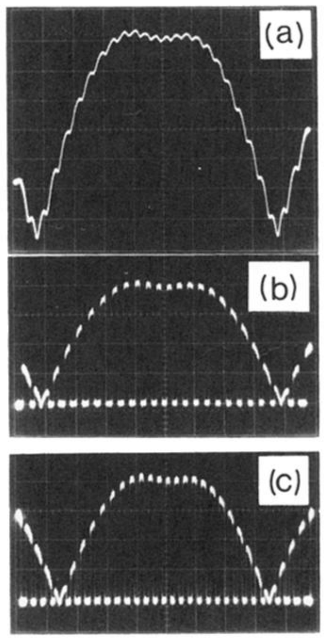

FIG. 3 (a) Line profile of the single-mode laser at 3.39 μm with use of the arrangement of Fig. 1(b) without the polarizer. Frequency increases from left to right. The gain has been set up such that the linewidth at zero intensity corresponds to a variation of the laser optical length $\lambda/2$ (successive longitudinal modes border on each other at zero intensity). The oscillating mirror is the plane one, R_a. The backward trace has been electronically rubbed out. The intensity modulation is due to the detector optical feedback. $L = 11.30$ m and $d = 0.429$ m. Twenty-two maxima can be observed. Light polarization is vertical as determined by the tube windows. (b) Mirror R_a is oscillating and 21.5 polarization cycles can be observed through the polarizer. (c) Mirror R_b is oscillating and 22.5 cycles can be counted. We have made this optical self-chopper working with the same efficiency for $L = 25$ m. We observed that the detector orientation was far from being critical, which allows a very easy observation of the phenomena.