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Polarization self-modulated lasers with circular eigenstates

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A polarization self-modulated laser made of a semiconductor laser with an external cavity containing a Faraday rotator is investigated theoretically and experimentally. It is shown that the Faraday rotator yields circularly polarized eigenstates for the laser. Stable optical pulses at a frequency equal to one half of the free spectral range are observed through a polarizer, independently of the Faraday rotator orientation. The pulses are generated through beating between the phase-locked lasing modes associated with the two circular eigenstates of the laser. © *1999 American Institute of Physics.* [S0003-6951(99)04422-8]

Polarization self-modulation mechanisms in external-cavity semiconductor lasers lead to the generation of stable high frequency optical pulses.[1] These lasers have promising applications in optical clocking and integrated opto-electronic devices. The polarization modulation occurs thanks to an intracavity quarter-wave plate (QWP) whose neutral axes are oriented at 45° with respect to the semiconductor transverse electric (TE) and transverse magnetic (TM) mode polarization directions.[2] These devices therefore do not require high speed electronics. Moreover, the modulation frequency, which is strictly equal to one half of the free spectral range of the extended cavity, can be increased by reducing the length of the external cavity, and frequencies as high as hundreds of gigahertz have been theoretically predicted.[3] The temporal modulation of the polarization has been experimentally demonstrated both in edge-emitting semiconductor lasers[1,2,4] and in vertical-cavity surface emitting lasers.[5–7] A theoretical investigation of the laser dynamics[8] has shown that this behavior is due to a self-phase locking of the eigenmodes associated with the two eigenstates. Namely, owing to the π retardation during one roundtrip through the quarter-wave plate, the laser spectrum contains two combs of eigenfrequencies (each comb being associated with one polarization eigenstate), shifted by one half of the free spectral range. This leads to an efficient coupling between modes associated with different eigenstates and therefore to a phase-locking process.[8] Nevertheless, if the neutral axes of the quarter-wave plate are not strictly oriented at 45° with respect to TE and TM directions, or if the plate is tilted,[9] the two combs are no longer equally spaced. This results in unlocking of the laser eigenstates and, experimentally, the modulation frequency of the output polarization is no longer stable. The orientation of the quarter-wave plate is thus critical. The aim of this letter is to propose a different scheme of polarization self-modulated laser which circumvents this drawback by using an intracavity Faraday rotator (FR) in place of the quarter-wave plate. Namely, if the rotation angle associated with FR is set to 45°, one roundtrip through FR leads to a π retardation for the two circular components of the intracavity field. Polarization dynamics similar to the ones observed in the case of the quarter-wave plate may then be expected.

To test this proposal, we build the experimental setup shown in Fig. 1. A buried heterostructure laser diode (LD) provides the gain at 1.55 μm. One facet of LD is antireflection coated, with an intensity reflectivity smaller than 10^{-4}. Two antireflection-coated molded microlenses collimate the output beams. The external cavity of length L is closed with a flat mirror M_E, whose intensity reflectivity is equal to $R_E = 0.9$. The intracavity Faraday rotator FR (Optics for Research IO-4-1550) consists of an antireflection-coated bismuth-iron-garnet in a magnet. The single-pass Faraday rotation is equal to 45°. The laser oscillates between M_E and the cleaved facet M_C, with a free spectral range $c/2L$. The polarization of the output beam is analyzed by using a quarter-wave plate followed by an optical isolator (OI), that acts as a linear polarizer while circumventing spurious feedback. The fast axis of QWP (respectively, the passing axis of OI) makes an angle α (respectively β) with respect to the x axis. The beam is then sent onto a fast InGaAs photodiode FPD. At the same time, one part of the beam is sent via a

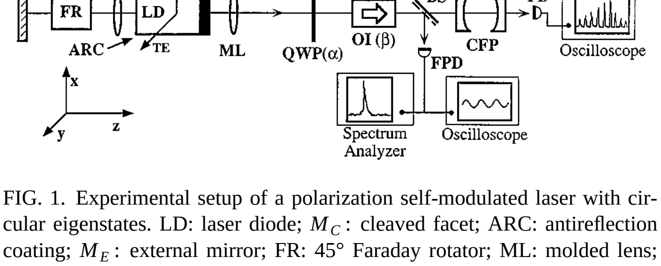

FIG. 1. Experimental setup of a polarization self-modulated laser with circular eigenstates. LD: laser diode; M_C: cleaved facet; ARC: antireflection coating; M_E: external mirror; FR: 45° Faraday rotator; ML: molded lens; QWP(α): quarter-wave plate with the fast axis oriented at angle α relative to the x axis. OI: optical isolator with the input polarizer oriented at angle β relative to the x axis. BS: beam splitter; CFP: confocal Fabry–Perot analyzer; PD: photodiode; FPD: fast photodiode.

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beam splitter to a 1-cm-long confocal Fabry–Perot interferometer in order to monitor the laser spectrum.

The polarizations and frequencies of the eigenstates are deduced from the Jones matrix **M** for one round trip inside the cavity starting from mirror M_C. We denote by G_{TE} and G_{TM} the single-pass complex gain associated with the TE and TM axes of LD. In the $x-y$ frame, the matrix of FR is equal to $1/\sqrt{2}\left[\begin{smallmatrix}1 & -1\\ 1 & 1\end{smallmatrix}\right]$. It follows that $\mathbf{M} = \sqrt{R_E R_C} G_{\mathrm{TE}} G_{\mathrm{TM}} e^{2ikL}\left[\begin{smallmatrix}0 & -1\\ 1 & 0\end{smallmatrix}\right]$, where k is the wave number of the intracavity field and R_C the intensity reflection coefficient of M_C. The diagonalization of **M** determines the laser eigenstates: the two eigenstates correspond to left and right circularly polarized light components denoted in this letter by a σ^+-polarized and a σ^--polarized light. The corresponding eigenvalues show that their frequency difference is $\nu_+ - \nu_- = c/4L + (p-q)c/2L$, if p and q are the longitudinal mode orders of the considered σ^+ and σ^- eigenstates, respectively. Similar to the case of polarization self-modulated lasers made using an intracavity quarter-wave plate, we expect the spectrum of the laser to consist of two $c/2L$-periodic combs of longitudinal modes associated with the two eigenstates, with a $c/4L$ shift with respect to one another.

To test these predictions with our experiment, the passing axis of OI is first set at 45° (respectively −45°) with respect to the fast axis of QWP, i.e., $\alpha = 0°$ and $\beta = +45°$ (respectively −45°). The optical isolator therefore selects the σ^+ (respectively the σ^-) circular component of the output field, i.e., only one eigenstate is transmitted through OI. Figures 2(a) and 2(b) display the corresponding spectra obtained using the Fabry–Perot interferometer. The spectrum of each eigenstate is a comb of successive longitudinal modes spaced by $c/2L$, in agreement with the theory. Here, L is equal to 39 cm, leading to a free spectral range of 386 MHz. Moreover, when the input polarizer of OI is aligned with the fast axis of QWP, i.e., $\beta = 0°$, both eigenstates are transmitted through OI. Figure 2(c) displays the corresponding spectrum. It consists of a $c/4L$ periodic comb, due to the superposition of the two combs associated with the two eigenstates. It thus shows that the two combs are shifted by $c/4L$ with respect to one another. The same behavior is observed for different values of the cavity length L. For parallel orientation of QWP and OI ($\beta = 0°$), we also send the output beam onto a fast photodiode (FPD). The two eigenstates recombine onto FPD, leading to beatnotes in the intensity with a period equal to $4L/c$, as shown in Fig. 3 for $L = 1.32\,\mathrm{m}$. As expected, the value of the period is equal to $4L/c = 17.5\,\mathrm{ns}$. Moreover, the shape of the intensity modulation shows that only odd harmonics are present in the spectrum of the intensity. This is confirmed by Fig. 4, where the typical intensity spectrum is displayed. Finally, when QWP and OI are removed, the beats almost disappear. This shows that the two eigenstates are indeed orthogonal. The residual modulation in the output beam intensity is actually due to the anisotropy of M_C which slightly recombines the two eigenstates.

Surprisingly, changing the polarization of the laser eigenstates from linearly to circularly polarized does not seem to affect their dynamics. Indeed, similar to the case of linearly polarized eigenstates, for σ eigenstates, the following features are obtained: (i) the optical spectra consist of a superposition of two $c/2L$ periodic combs spaced by $c/4L$, (ii) the recombination of the two eigenstates leads to beatnotes at $c/4L$ featuring only odd harmonics of $c/4L$. Moreover, the present laser exhibits the most important property of polarization self-modulated lasers, i.e., the phase-locking of all modes. This is clear from (i) the experimental stability

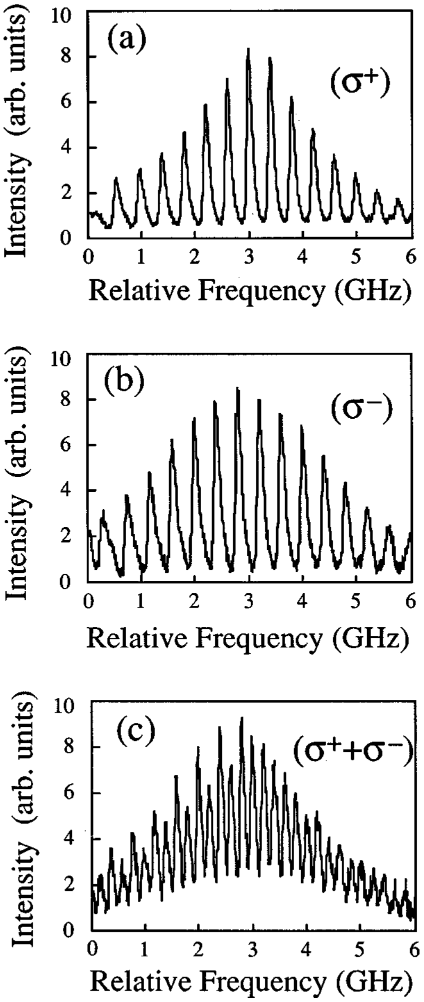

FIG. 2. Analysis of the external cavity laser output spectrum through the Fabry–Perot analyzer for three different angles of the input polarizer of OI: (a) $\beta = 45°$; (b) $\beta = -45°$; (c) $\beta = 0°$. (a) and (b) correspond to the combs of frequencies associated with the σ^+ and σ^- circularly polarized lasing modes, respectively. (c) shows the superposition of the two combs. L is equal to 39 cm.

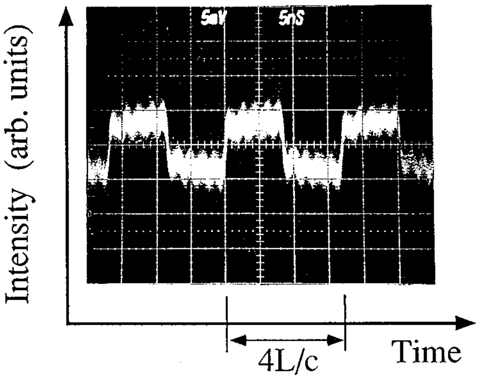

FIG. 3. Observation of the typical beatnote between the two oscillating eigenstates through the polarizer oriented at $\beta = 0$. Horizontal axis: 5 ns per division. L is equal to 1.32 m.

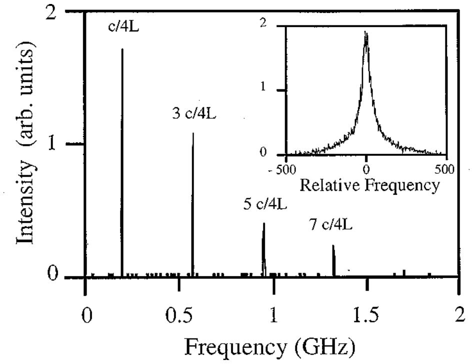

FIG. 4. Intensity spectrum showing the fundamental frequency $c/4L$ and three odd harmonics. As for Fig. 2, L is equal to 39 cm. Inset: spectrum of the $c/4L$ beatnote at 193 MHz. The FWHM is equal to 92 kHz. Both vertical axes are linear.

of the waveform of Fig. 3, (ii) the experimental stability of the optical spectra of Fig. 2, and (iii) the amazingly high spectral purity of the beat note at $c/4L$, as evident from the insert of Fig. 4. Indeed, the width of the $c/4L$ peak is equal to 92 kHz fullwidth at half–maximum (FWHM), which is almost twice smaller than the width obtained from the same laser chip when an intracavity quarter-wave plate is used instead of a Faraday rotator.[4] We suspect the better stability of the intracavity Faraday rotator laser compared to the intracavity quarter-wave plate laser to be due to two properties of the Faraday rotator. First, the rotation angle does not depend on the orientation of the Faraday rotator, which makes it not sensitive to mechanical vibrations. Second, the dependency of the rotation angle versus the wavelength is lower than 6×10^{-3} deg/nm, which permits to rigorously adjust the rotation angle at 45° for the whole spectrum of the intracavity field. The surprising aspect of our experiment is that the phase-locking mechanism does not only occur for different active media (such as gas, bulk semiconductors, and quantum wells[2]), but also seems independent of the polarizations associated with the eigenstates of the cavity modes. It is well known that the coupling constant for two-mode lasers depends drastically on the polarization of the intracavity fields.[10] In the case of polarization self-modulated lasers, the equal spacing of the modes appears to be the dominant process for the phase locking of the modes to occur.

In conclusion, the theoretical and experimental analysis of the eigenstates of external cavity semiconductor lasers containing a Faraday rotator have been performed. The circular polarized eigenstates for such a laser have been shown to lead to polarization self-modulation. The intrinsic qualities of σ eigenstates together with the high spectral purity of their beat note make such lasers very promising candidates for the realization of optical clocks.

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