Polarization- and Transverse-Mode Dynamics in Optically Injected and Gain-Switched Vertical-Cavity Surface-Emitting Lasers

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Abstract—In this paper, we summarize our recent results on nonlinear polarization- and transverse-mode dynamics of vertical-cavity surface-emitting lasers (VCSELs) induced by optical injection (OI) or current modulation. Due to the surface emission and cylindrical symmetry, VCSELs lack strong polarization anisotropy and may undergo polarization switching (PS). Furthermore, VCSELs may emit light in multiple transverse modes. This provides new features to the rich nonlinear dynamics induced in VCSELs by an external perturbation. We demonstrate for the case of orthogonal OI that new Hopf bifurcation on a two-polarization-mode solution delimits the injection locking (IL) region and that PS and IL of first-order transverse mode lead to a new resonance tongue for long positive detunings. Similarly, the underlying polarization-mode competition leads to chaotic-like behavior in case of gain switching and the presence of two transverse modes additionally reduces the possibility of regular dynamics.

Index Terms—Bifurcation, chaos, current modulation, gain switching, optical injection, polarization switching, vertical-cavity surface-emitting laser (VCSEL).

I. INTRODUCTION

VERTICAL-CA VITY surface-emitting lasers (VCSELs) present significant advantages over their edge-emitting counterparts, such as single longitudinal mode emission, low cost, circular output beam, and easy fabrication in two-dimensional arrays. However, emission in multiple transverse modes is usually found in VCSELs [1] as a result of spatial hole burning effect [2], [3]. Furthermore, due to the surface emission and cylindrical symmetry VCSELs lack strong polarization anisotropy and may undergo polarization switching (PS) [1], [4]. Different physical mechanisms can lead to PS, such as microscopic spin-flip processes in the presence of birefringence and linewidth enhancement factor [5], [6], thermal lensing [7], spatial hole burning [8], or the relative modification of the net modal gain and losses with the injection current [4], [9]. The lack of polarization anisotropies and the multitransverse-mode behavior of VCSELs provide new features to the rich nonlinear dynamics induced by optical injection (OI) and gain switching (GS). Locking of the frequency of the injected (slave) semiconductor laser to the one of the injecting (master) laser has long been known [10], [11] and is of great interest from an application point of view. It can be used for reduction of the laser linewidth [11], the mode partition noise [12] or for an enhancement of the modulation bandwidth [13], and for synchronizing an array of lasers onto a unique master [14]. Furthermore, OI dynamics is also of interest from a fundamental point of view and rich dynamics as period-doubling route to chaos [15]–[17], resonance tongues [18], and excitability [19] have been reported. Orthogonal OI in VCSELs, i.e., the linear polarization of the injected light is orthogonal to the one of the VCSEL, was first reported by Pan et al. [20] in 1993. It was shown that by increasing the injection strength, the VCSEL switches its polarization to that of the injected light through a region of bistability and may exhibit an injection locking (IL) depending on the frequency detuning between the two lasers [21]. Hong et al. [22] have shown that the otherwise depressed LP mode may be excited by orthogonal OI and regions of chaotic competitions in the two linearly polarized (LP) modes of the VCSEL have been shown experimentally both for positive and negative detunings. The case of parallel OI has been investigated by Li et al. [23]. Transverse-mode dynamics of a VCSEL with OI have been analyzed numerically [24] and experimentally [25], [26] for different configurations of the polarization of the injected light with respect to the light polarization of the free-running VCSEL.

GS of semiconductor lasers has received a lot of attention, considering its potential to generate ultrafast sharp pulses but also because it can lead to complex dynamics such as period doubling and possibly chaotic pulsating [27]–[30]. Just a few reports of chaotic behavior can be found in the literature [29], [30] since only lasers with relatively small gain saturation and spontaneous emission noise parameters might undergo period-doubling route to chaos under current modulation [31]. Studies of nonlinear dynamics in directly modulated VCSELs remain scarce [32]–[34]. Nonlinear dynamics have been theoretically analyzed for LP single transverse-mode [32], [33] and multimode VCSELs [33], [34]. Chaotic behavior appears in the multimode regime due to transverse-mode competition [33], [34].
Only recently theoretical and experimental studies have been undertaken with special attention on the role of light polarization [35]–[38].

In this paper, we summarize our recent results on nonlinear polarization and transverse-mode dynamics of VCSELs for the case of OI or GS. In Section II, we demonstrate that, for the case of orthogonal OI, a new Hopf bifurcation on a two-polarization-mode solution delimits the IL region and that PS and IL of first-order transverse mode lead to a new resonance tongue for large positive detunings. In Section III, we show that the underlying polarization-mode competition leads to chaotic-like behavior in case of GS and the presence of two transverse modes additionally reduces the possibility of regular dynamics as shown. Finally, in Section IV, a brief summary of the results is presented.

II. NONLINEAR POLARIZATION- AND TRANSVERSE-MODE DYNAMICS IN VCSEL WITH ORTHOGONAL OI

The experiments on orthogonal OI have been performed with oxide-confined GaAs quantum-well VCSEL emitting at 845 nm as a slave laser (SL). The solitary VCSEL is polarization bistable in the injection current region 2.25–4.60 mA, displaying type II PS (from the low to the high frequency LP mode [9]). It is biased below the bistable region, at $I = 2.105$ mA, and emits fundamental transverse mode with horizontal polarization (x-LP) and output power of $P_{\text{out}} = 1.28$ mW. An external cavity tunable laser is used as a master laser (ML) and is set to emit vertically polarized light (y-LP).

In Fig. 1, we show a typical route to PS through IL by presenting high-resolution Fabry–Perot spectra for different injected powers and fixed negative detuning of $-4$ GHz. For very low injected power, the VCSEL keeps emitting in x-LP but is pulled toward the ML frequency proportionally to the strength of the injection. An increase of the injected power leads to undamping of relaxation oscillations—small side peaks appear on each side of the SL peak [Fig. 1(a)]. For still larger injection strength, PS with injection frequency locking of the fundamental transverse mode is achieved [Fig. 1(b)]. The locking region is exited by excitation of a limit cycle dynamics [Fig. 1(c)]. Harmonics of the limit cycle are resolved for higher injection power and further the SL frequency is progressively pushed from the ML frequency [Fig. 1(d)].

Fig. 2 presents the boundaries of qualitatively different dynamics experimentally mapped in the plane of frequency detuning (master minus the SL frequency)—injection power (normalized to the solitary VCSEL power). The polarization switch OFFand switch ON points of the x-LP mode for increasing (decreasing) the injected power are represented by the dark blue and violet (light blue and black) lines. In the regions S1 and S2, the frequency of VCSEL emission is locked to the ML. However, in the case of S2, it is the first-order transverse mode rather than the fundamental transverse mode (as is the case of the S1 region) that locks to the ML, the fundamental transverse mode being then suppressed when crossing the dark green line. The unlocking of the first-order transverse mode happens at smaller values of $P_{\text{inj}}$, describing bistable region B2 between the fundamental and the first-order transverse mode both with the same polarization (B2 is delimited by the dark green and red lines).

In Fig. 3, the mapping of the VCSEL subject to OI is extended toward large positive detuning up to 180 GHz. When the injection strength is increased, different PS scenarios are resolved depending on the frequency detuning. A switching from x-LP to y-LP fundamental transverse mode is observed for the whole frequency detuning range—denoted by black triangles in Fig. 3. This boundary exhibits two minima for the switching power:
the first located at a detuning of 2 GHz and the second one at a detuning of 150 GHz with injection powers of 7.1 μW and 623.9 μW, respectively. IL of the first-order transverse mode together with suppression of the fundamental mode is observed for frequency detuning range from 60 to 120 GHz, denoted by black diamonds in Fig. 3.

It is possible to reproduce theoretically the experimental results on the base of a set of rate equations that accounts for the polarization properties of VCSELs, namely the spin-flip model (SFM) [5]. The SFM equations [5], [6], extended to the case of IO are given in [6], [39]–[42] for a single-transverse-mode VCSEL and in [43] for a multitransverse-mode VCSEL. For completeness, we list the SFM equations for the case of IO in a single-transverse mode VCSEL, namely

$$\frac{dE_x}{dt} = - (\kappa + \gamma_d)E_x - i(\kappa \alpha + \gamma_p + \Delta \omega)E_x + \kappa (1 + i \alpha)(N E_x + i N E_y) \quad (1)$$

$$\frac{dE_y}{dt} = - (\kappa - \gamma_d)E_y - i(\kappa \alpha - \gamma_p - \Delta \omega)E_y + \kappa (1 + i \alpha)(N E_y - i N E_x) + \kappa \gamma_n E_{inj} \quad (2)$$

$$\frac{dN}{dt} = - \gamma_n \left[ N \left(1 + |E_x|^2 + |E_y|^2\right) - \mu \right. + i N (E_y E_x^* - E_y E_y^*) \quad (3)$$

$$\frac{dn}{dt} = - \gamma_n n - \gamma_n \left[ n \left(1 + |E_x|^2 + |E_y|^2\right) + i N (E_y E_x^* - E_y E_y^*) \right]. \quad (4)$$

In addition to the coupling of the polarizations states through the carrier density (3), the SFM accounts for a coupling due to the finite spin-flip rate $\gamma_n$ of the carriers [5], which together with the linewidth enhancement factor $\alpha$ and the inherent small VCSEL birefringence $\gamma_p = (\omega_y - \omega_x)/2$ and dichroism $\gamma_d$ leads to PS in a solitary laser [6]. The variable $N$ is related to the total inversion between conduction and valence bands while $n$ accounts for the difference in the carrier numbers with opposite spins. The rest of the parameters are $\mu$, the normalized injection current; $\kappa$, the photon decay rate; and $\gamma_n$, the carrier decay rate. OI of y-LP light is accounted for by $\kappa_{inj}$ the coupling coefficient, $E_{inj}$ the injected field amplitude, and $\Delta \omega = \omega_{inj} - (\omega_x + \omega_y)/2$, the frequency detuning between the master and the mean of the VCSEL LP mode frequencies.

Fig. 4 shows a typical bifurcation mapping for a single-transverse mode VCSEL with parameters: $\mu = 1.5$, $\kappa = 300$ ns$^{-1}$, $\gamma = 1$ ns$^{-1}$, $\gamma_p = 30$ ns$^{-1}$, $\gamma_d = 0.5$ ns$^{-1}$, and $\gamma_n = 100$ ns$^{-1}$. Qualitative changes in the VCSEL dynamics are detected and followed using the continuation package AUTO 97. Different bifurcation curves are plotted: a saddle node (SN), two Hopf ($H_1$ and $H_2$), and a torus (TR). The supercritical and subcritical parts of each bifurcation curve are represented in black and gray, respectively. When increasing the injection strength, the VCSEL switches its polarization to that of the injected field; these “PS off” (x-LP mode off) points are shown with circles. The PS curves interplay with the bifurcation curves. SN and $H_1$ are bifurcations on a stationary injection-locked state and have also been reported in the case of optically injected edge-emitting laser. In the conventional case of EEL, the locking region is then delimited by the codimension-two point $G_1$ where SN and $H_1$ intersect [44]. In our VCSEL system, the locking region is delimited by SN, $H_1$ but also by a new bifurcation $H_2$ [see Fig. 4(b)]. The maximum detuning leading to IL therefore stays well below the codimension-two SN-Hopf point $G_1$. Apart
from its effect on the locking, $H_2$ also affects the PS mechanism. The smallest injection strength needed to achieve PS is located on $H_2$ and corresponds to a dramatic change in the PS curve [$m_1$, see the thick dot vertical arrow in Fig. 4(c)]. The regions of more complicated, possibly chaotic dynamics bounded by $PD_1$ and $PD_2$ also affect the switching mechanism leading to a second local minimum denoted by $m_2$ in Fig. 4(c). As a result, the PS curve exhibits a wobbling shape with local minima of the injected power required for switching. The observed shape agrees qualitatively with the experimental results presented in Fig. 2. The torus bifurcation TR corresponds to the excitation of two-polarization-mode dynamics in the route to PS and IL—a limit cycle in the x-LP and a wave mixing in the y-LP—which is also in agreement with the experiment [42].

The impact of the spin-flip rate on the new Hopf bifucation curve $H_2$ is investigated in Fig. 5 by superimposing four bifurcation diagrams for $\gamma_s$ ranging between 50 ns$^{-1}$ and 300 ns$^{-1}$. For the sake of clarity, the PS curve, TR, $PD_1$, and $PD_2$ bifurcations curves are omitted. While the SN and first Hopf ($H_1$) bifurcations do not change, the second Hopf bifurcation $H_2$ changes considerably, approaching and passing the codimension-two point $G_1$ (see the green curve for $\gamma_s = 300$ ns$^{-1}$). At this point there is no supercritical part of $H_2$ and it does not influence the VCSEL polarization dynamics anymore.

The SFM model further predicts a two-mode injection-locked solution, i.e., elliptically polarized injection-locked state for frequency detuning close to the VCSEL birefringence [39]. The bifurcation route to such solution has been studied in detail in [41]. As evidenced from Fig. 5, the spin-flip rate $\gamma_s$ strongly influences the position of the new Hopf bifurcation curve $H_2$. Experimentally detecting the $H_2$ curve would not, however, determine $\gamma_s$ unambiguously as $H_2$ also appears in a simpler two-mode gain-saturation VCSEL model, which does not account for the spin dynamics [45]. For a reliable determination of $\gamma_s$, the region of elliptically polarized injection-locked states [41] needs to be experimentally determined.

We now model the effect of the orthogonal OI on both the polarization- and transverse-mode dynamics of VCSELs by expanding the SFM model to account for two transverse modes with two orthogonal linear polarizations [43]. The injection current is set at 1.7 times the threshold current; slightly below the polarization bistable region. The parameter $k_s$, the relative loss of first-order mode with respect to the fundamental mode—is set to $k_s = 1.2$, so that the x-LP first-order transverse mode starts lasing at about 4.7 times the threshold current as in the experiment. Furthermore, the birefringence of $\Delta n_{p} = 2.084 \times 10^{-5}$, the refractive indices of core $n_c = 3.5$ and clad $n_{cl} = 3.489$ region of the VCSEL, its cavity length of $L_c = 1 \text{ mm}$, and radius $a = 3 \text{ mm}$ are chosen in such a way that the frequency splitting between $x$- and $y$-fundamental and first-order modes are 2 and 193 GHz, respectively, and correspond to the experimental values of the solitary VCSEL. We consider that a polarization switch-on or switch-off is obtained when the averaged total $y$-polarized power becomes larger or smaller than the averaged total $x$-polarized power. The SFM parameters are taken as $\kappa = 300 \text{ ns}^{-1}$, $\gamma_s = -0.81 \text{ ns}^{-1}$, $\gamma = 0.55 \text{ ns}^{-1}$, $\gamma_\phi = 91 \text{ ns}^{-1}$, and the carrier diffusion coefficient is $D = 10 \text{ cm}^2/\text{s}$.

The boundaries of PS in the plane of injection power frequency detuning are shown in the Fig. 6. As can be seen from this figure, there are two minima in the injected power required for switching. The detuning of about 155 GHz at which the second minimum appears is near the frequency difference between the fundamental and the first-order transverse modes of the solitary VCSEL. Very good agreement with experiment is evident when comparing this figure with Fig. 3.

### III. NONLINEAR POLARIZATION- AND TRANSVERSE-MODE DYNAMICS IN GAIN-SWITCHED VCSEL

Polarization dynamics of gain-switched VCSELs was first investigated in [35] based on the SFM for a single-transverse-mode VCSEL, namely

$$
\frac{dE_x}{dt} = -(\kappa + \gamma_\alpha)E_x - i(\kappa \alpha + \gamma_y)E_x + \kappa(1 + i\alpha)(NE_x + inE_y)
$$

(5)

$$
\frac{dE_y}{dt} = -(\kappa - \gamma_\alpha)E_y - i(\kappa \alpha - \gamma_y)E_y + \kappa(1 + i\alpha)(NE_y - inE_x)
$$

(6)

Fig. 6. Theoretical mapping of PS and transverse-mode competition extended toward large positive detunings.
The depressed x-LP mode is given. The bias current is $I_{dc} = 1.1$ and the modulation frequency is $\nu_M = 1$ GHz. The VCSEL parameters are specified in the text.

\[
\frac{dN}{dt} = -\gamma N(1 + |E_x|^2 + |E_y|^2) - (\mu_{dc} + \Delta \mu \sin(2\pi \nu_M t)) + i\hbar \left( E_y E_x^* - E_y E_x^* \right)
\]

\[
\frac{dh}{dt} = -\gamma_i n \left( |E_x|^2 + |E_y|^2 \right) - i\hbar \left( E_x E_y^* - E_y E_x^* \right). \tag{8}
\]

Here $\mu_{dc}$ is the bias current, $\Delta \mu$ and $\nu_M$ are the amplitude and the frequency of modulation of the injection current, respectively.

Bifurcation diagrams of the polarization-resolved output power $I_x$ and $I_y$ are shown in Fig. 7 as a function of amplitude of modulation $\Delta \mu$ for $\nu_M = 1$ GHz and $I_{dc} = 1.1$. The VCSEL parameters are $\alpha = 3$, $\gamma_a = 0.1$ ns$^{-1}$, $\gamma_\nu = 1$ ns$^{-1}$, $\gamma_\alpha = 50$ ns$^{-1}$, $\kappa = 300$ ns$^{-1}$, and $\gamma = 1$ ns$^{-1}$. The modulation frequency $\nu_M$ is smaller than the relaxation oscillation frequency of the VCSEL $\nu_{RO} = [2\pi\gamma(\mu-1)]^{1/2}/2\pi = 1.23$ GHz. As can be seen from Fig. 7, the VCSEL initially lases in the y-LP mode, with increasing amplitude of sinusoidally modulated intensity at the modulation period with increasing $\Delta \mu$. For large enough $\Delta \mu$, such that the injection current goes from below to above the threshold current, GS occurs. In certain regions of $\Delta \mu$, the two LP modes coexist with chaotic or time-periodic dynamics and for still larger $\Delta \mu$ the VCSEL lases only in the y-LP mode with a period-doubling route to chaos.

The LP mode dynamics is detailed in Fig. 8, which shows time traces of the polarization-resolved intensities for specific values of $\Delta \mu$. At $\Delta \mu = 0.04$, the depressed x-LP mode is also lasing, i.e., the direct current modulation has excited the LP mode that was depressed in the VCSEL under dc operation. The two LP modes exhibit chaotic-like dynamics with a fast modulation of their intensities at the modulation frequency complemented by a slower envelope. Interestingly, the two LP modes emit in phase at the modulation frequency but the envelopes of their pulses are in partial antiphase: when one LP mode fires a large pulse, the other LP mode fires a small pulse. The partial antiphase dynamics is better seen in Fig. 8(b), which presents the averaged over the modulation period output power in the two LP modes. For a slightly larger $\Delta \mu = 0.07$, Fig. 8(c), the two LP modes exhibit in-phase time-periodic pulsing at the modulation frequency. For larger $\Delta \mu$, the y-LP mode is only lasing. At $\Delta \mu = 0.18$, Fig. 8(e), the y-LP mode exhibits a period-3 time-periodic pulsing dynamics, which is followed by chaotic single-mode dynamics at $\Delta \mu = 0.2$, Fig. 8(f). For increasing modulation depth, the dynamics is single period one, Fig. 8(g), followed by a period-doubling route to chaos—the period 2 is shown for $\Delta \mu = 0.24$ in Fig. 8(h).

These theoretical predictions have been experimentally confirmed in [36]. A GaAs quantum-well oxide-confined VCSEL emitting at 851 nm is used in the experiments biased close to the PS point and then driven by an RF signal through a bias-T. The temporal traces of the total and polarized powers are shown in Fig. 9 for a modulation frequency of 2.88 GHz and current amplitude of $\Delta I = 0.89 I_{dc}$. A regular stream of pulses at each two periods of modulation is found for the total power. Small shoulders appear that are remnants of the period-1 dynamics. When the amplitude of the modulation decreases those shoulders become larger until similar heights are obtained for all the pulses in such a way that only one pulse appears each modulation cycle (period-1 dynamics). Pulses in individual polarizations also appear with that periodicity but their heights are very irregular with wide temporal regions in which pulses in one polarization are very small while in orthogonal polarization are very high—as deduced from the regularity of the total power. Another indication for the regularity of the pulse dynamics is the statistical distribution of the residence times $\tau_x$ ($\tau_y$) given by the time between consecutive crossings of the corresponding $P_x$ ($P_y$) output power, from below to above, of certain reference level chosen as half of the total power maximum (see Fig. 9). Both the experimental and theoretical probability density distributions of the residence times for the individual polarizations.
Fig. 9. Experimental time traces of the intensities of (a) the total, (b) \(x\)-polarized, and (c) \(y\)-polarized powers. The current modulation is such that \(\mu_M = 2.88 \text{ GHz}, I = 1.26 I_{th}\), and \(\Delta I = 0.89 I_{th}\).

present a multipeaked structure with a long exponential envelope [36]. This long exponential tail is a signature of the irregularity of the stream of pulses—in contrast with the absence of such a tail for the total power.

The irregular behavior of individual polarizations, in contrast to the regular one of the total power, is also manifested in the corresponding RF spectra shown in Fig. 10. Large peaks appear half of the modulation frequency and its multiples. These peaks are an indication of the period-doubling dynamics observed in the time series in Fig. 9. The large pedestals that appear around the peaks of the spectra of individual polarizations indicate that the polarization-resolved dynamics is quite irregular. The power levels at low frequencies are much larger for the individual polarizations than for the total power, as a result of the anticorrelation between the two polarizations.

We now consider a model of a gain-switched multitransverse-mode VCSEL [37] similar to the one for the case of OI in the previous section. The calculated bifurcation diagrams for the total and polarization-resolved powers of the fundamental and first-order transverse modes are shown in Fig. 11. Periodic and chaotic dynamics are now found for all transverse modes of different polarization and for the total intensity. The \(LP_{11}\) mode is now excited with a significant power for all the modulation amplitudes. Time-periodic dynamics is now restricted to low values of \(\Delta \mu\), i.e., the excitation of the higher order transverse mode causes a disappearance of the windows of time-periodic regular pulsating dynamics found in the single-mode case.

In order to experimentally check these theoretical predictions, we performed current modulation experiments using GaAs quantum-well VCSEL with medium oxide aperture size, such that it can operate on two transverse modes simultaneously [38]. The optical spectra of the VCSEL, taken at several values of the injected current, are shown in Fig. 12. The laser exhibits a single-transverse-mode operation with side-mode suppression ratio (SMSR) larger than 25 dB for bias currents less than
5.3 mA. First-order transverse mode can be clearly seen at 6 mA bias current with SMSR of 13.5 dB. Its power increases as the bias current increases and becomes similar to the one of the fundamental mode for a current of 10 mA. At that value of the current a third transverse mode is also appearing. We should mention that, in order to avoid the polarization-mode competition, which—as shown above—also leads to irregular dynamics, we have chosen VCSEL emitting in one linear polarization only.

A sinusoidal voltage is used to modulate the current around a bias value of 5.3 mA. Time traces obtained in the vertical polarization for a fixed amplitude of 20 dBm—large enough to achieve GS—and several modulation frequencies are shown in Fig. 13. Time-periodic response of the system, with a period equal to the period of the modulation is obtained when $\nu_M = 1.98$ GHz [Fig. 13(a)]. This situation is maintained in Fig. 13(b)–(d) but the pulse heights change in irregular way. 1T-periodic response with smaller modulation amplitudes again appears at $\nu_M = 3$ GHz [Fig. 13(e)] followed by irregular responses when increasing $\nu_M$ [Fig. 13(f) and (g)]. The difference with respect to the irregular responses of Fig. 13(b) and (c) is that now some of the pulses appear at 2T. For $\nu_M = 4.2$ GHz in Fig. 13(h), a more regular response but with a 2T periodicity is observed. We have measured a 2.4 GHz relaxation oscillation frequency at 5.3 mA, which roughly corresponds to the modulation frequency that separates the two situations in which the pulses switch OFF or do not switch OFF completely at each modulation cycle. In such a way, our experimental findings on the nonlinear dynamical behavior of a multitransverse-mode VCSEL when subject to high-frequency current modulation show that irregular pulsating dynamics can be obtained for a wide range of modulation frequencies as a result of the competition between the different transverse modes of the laser, in agreement with the theoretical predictions.

IV. CONCLUSION

Thus, we have shown that the nonlinear dynamics of VCSELS induced by OI or current modulation are drastically modified due to the underlying polarization- and transverse-mode competition. This provides new features to the rich nonlinear dynamics such as, for the case of OI, the new Hopf bifurcation on a two-polarization-mode solution that delimits the IL region and the new resonance tongue of PS and IL of first-order transverse mode for large positive detunings. Similarly, the underlying polarization-mode competition leads to chaotic-like behavior in case of GS, and the presence of two transverse modes additionally reduces the possibility of regular dynamics.

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