Spin Modulation in Semiconductor Lasers

Jeongsu Lee,1, William Falls,1 Rafal Oszwaldowski,1,2 and Igor Žutić1
1 Department of Physics, State University of New York at Buffalo, NY, 14260, USA
2 Instytut Fizyki, Uniwersytet Mikołaja Kopernika, Grudziądzka 5/7, 87-100, Toruń, Poland

We provide an analytic study of the dynamics of semiconductor lasers with injection (pump) of spin-polarized electrons, previously considered in the steady-state regime. Using complementary approaches of quasi-static and small signal analyses, we elucidate how the spin modulation in semiconductor lasers can improve performance, as compared to the conventional (spin-unpolarized) counterparts. We reveal that the spin-polarized injection can lead to an enhanced bandwidth and desirable switching properties of spin-lasers.

Practical paths to spin-controlled devices are typically limited to magnetoresistive effects, successfully employed for magnetically storing and sensing information. However, spin-polarized carriers generated in semiconductors by circularly polarized light or electrical injection can also enhance the performance of lasers, for communications and signal processing. While such spin-lasers already demonstrate a lower threshold current as compared to their conventional (spin-unpolarized) counterparts, many theoretical challenges remain. Even in the steady-state regime, several surprises have only recently been revealed. For example, a very short spin relaxation time of holes can be advantageous with the maximum threshold reduction larger than what was theoretically thought possible.

Some of the most attractive properties of conventional lasers lie in their dynamical performance. Here we explore novel opportunities offered by spin-polarized modulation. We generalize the rate equation (RE) approach to describe spin-lasers with a quantum well (QW), typically GaAs or (In,Ga)As, used as the active region. However, our analytical approach allows considering other materials for spin-lasers. Spin-resolved electron and hole densities are \( n_\pm, p_\pm \), where \(+(-)\) denotes the spin up (down) component; the total carrier densities are \( n = n_+ + n_- \), \( p = p_+ + p_- \). For photon density we write \( S = S^+ + S^- \), where \(+(-)\) is the right (left) circularly-polarized component. Spin-polarized electrons, injected/pumped into the QW can be represented by a current \( J = J_+ + J_- \) and the corresponding current polarization \( P_J = (J_+ - J_-)/J \). Each of these quantities, \( X \), can be decomposed into a steady-state \( X_0 \) and a modulated part \( \delta X(t) \), \( X = X_0 + \delta X(t) \).

We focus here on the harmonic amplitude and polarization modulation \( (AM, PM) \). \( AM \) for a steady-state polarization implies \( J_+ \neq J_- \) (unless \( P_J = 0 \), as in conventional lasers),

\[
AM : J = J_0 + \delta J \cos(\omega t), \quad P_J = P_{J0}, \quad \tag{1}
\]

where \( \omega \) is the angular modulation frequency. \( AM \) is illustrated schematically in Fig. 1. Similar to the steady-state analysis, \( P_J \neq 0 \) leads to unequal threshold currents \( J_{T1} \) and \( J_{T2} \) (for \( S^+, \) majority and minority photons). For the injection \( J_{T1} < J < J_{T2} \), we expect a modulation of fully polarized light, even for a partially polarized injection. Such a modulation can be contrasted with \( PM \) which also has \( J_+ \neq J_- \), but \( J \) remains constant

\[
PM : J = J_0, \quad P_J = P_{J0} + \delta P_J \cos(\omega t). \quad \tag{2}
\]

While an experimental implementation of the idealized \( PM \) [a fully time-independent \( J \), in Eq. (2)] remains a challenge, we analyze it theoretically to note its potential advantages. Just as a decade ago there was an early progress towards electrical spin injection in semiconductors (now well-established), a recent progress in electrically tunable \( P_J \) is encouraging that \( PM \) could be realized in future spin-lasers. Currently, optically injected...
lasers with a controllable degree of circular polarization are more promising for implementing PM\textsuperscript{4.6.14}.

In QWs the spin relaxation time for holes $\tau_{ph}^h$ is much shorter than for electrons $\tau_{ph}^e$, so holes can be considered unpolarized, $p_h^e = p/2$. The charge neutrality condition, $p_\pm = n/2$, can then be used to decouple the REs for holes from those for electrons which become\textsuperscript{7}

$$dn_\pm/dt = J_\pm - g_\pm(n_\pm, S)S^\mp - (n_\pm - n_\mp)/\tau_\pm - R_{sp}^\pm, \quad (3)$$

$$dS^\mp/dt = \Gamma g_\mp(n_\mp, S)S^\mp - S^\mp/t_{ph} + \beta R_{sp}^\mp. \quad (4)$$

where $g_\pm$ is the spin-dependent optical gain, $\tau_{ph}$ is the photon lifetime, $\Gamma$ is the optical confinement coefficient, $\beta$ is the spontaneous-emission coefficient.

We consider the linear form of radiative spontaneous recombination\textsuperscript{22} $R_{sp}^\pm = n_\pm/\tau_\pm$, where $\tau_\pm$ is the recombination time. In conventional lasers ($P_J = 0$), the optical gain term, describing stimulated emission, can be modeled as $g(n, S) = g_0(n - n_{tran})/(1 + \epsilon S)$, where $g_0$ is the density-independent coefficient, $n_{tran}$ is the transparency density, and $\epsilon$ is the gain compression factor.\textsuperscript{7}

For $P_J \neq 0$, even at $\epsilon = 0$, the correct generalization $g(n, S) \rightarrow g_\mp(n_\pm, p_\mp, S) = g_0(n_\pm + p_\pm - n_{tran})$ differs from the previous expression\textsuperscript{22} but, combined with the charge neutrality condition ($p_\pm = n/2$), it leads to the correct maximum threshold reduction.\textsuperscript{22} With small experimental values of $\epsilon$ in spin-lasers,\textsuperscript{22} the gain compression at moderate pumping intensities is almost negligible. Given the typical range of $\beta \sim 10^{-5} - 10^{-3}$, we mostly focus on the limit $\beta = 0$, for which the operating regimes of the spin-lasers can be simply described.

To develop a preliminary understanding of AM and PM in spin-lasers, we study analytically the quasi-static regime ($\omega \ll 1/\tau_{ph}, 1/\tau_\pm$). This implies that the steady-state results\textsuperscript{22} can be used to obtain AM (PM) with $J_0 = (P_{J0})$ substituted by $J(t)$ ($P_J(t)$) and the injection $J_\pm$ will be in phase with the response $n_\pm$ and $S^\pm$. For typical parameters\textsuperscript{22} we confirmed numerically that this regime is valid up to $\omega/2\pi \sim 10$ MHz. The steady-state results ($\epsilon = 0$) for the two threshold currents (see Fig.\textsuperscript{1})

$$J_{T1} = J_T/(1 + |P_J|/(1 + 2w)), \quad J_{T2} = J_T/(1 - |P_J|), \quad (5)$$

remain directly applicable for AM and PM. Here $J_T = N_T/\tau_\pm$ is the unpolarized threshold current, $N_T = nJ \geq J_T = (\Gamma g_0)_{\tau_{ph}}^{-1} - n_{tran}$ is the electron threshold density, and $\tau_\pm \sim \tau_\pm^{\text{re}}$ is the ratio of the recombination and spin relaxation times. $J_{T1}$ and $J_{T2}$ in Eq.\textsuperscript{5} delimit three regimes of a spin-laser: (i) For $J < J_{T1}$, the laser operates as a spin light-emitting diode (LED)\textsuperscript{19} (ii) For $J_{T1} \leq J < J_{T2}$, there is a mixed operation: lasing only with one circular polarization (only $S^-$, if $P_J > 0$), while the other circular polarization is still in the spin-LED regime, and (iii) For $J \geq J_{T2}$, the laser is fully lasing with both $S^\pm > 0$.

These operating regimes, for large AM and PM, determine the time-dependence of electron and photon densities, normalized to $N_T$ and $S_T = J_T\Gamma \tau_{ph}$, shown in Fig.\textsuperscript{2} AM in the upper panel reveals $S^\pm$ near $\omega t = 0, 2\pi$, corresponding to $J > J_{T2}$ (a fully lasing regime) and a constant $n_\pm = n_\mp$. With time evolution the laser enters the mixed regime $J_{T1} < J < J_{T2}$ (only lasing with $S^-$, Fig.\textsuperscript{1}). If $P_J > 0$, for both AM and PM (discussed below) the photon densities in Fig.\textsuperscript{2} can be expressed as

$$S^-/S_T = (2/3) [J/J_T(1 + P_J/2) - 1], \quad S^+/S_T = 0, \quad (6)$$

where $J$ and $P_J$ are given by either Eq.\textsuperscript{1} or\textsuperscript{2}. For $P_J \leq 0$, the expressions for $S^+$ and $S^-$ in Eq.\textsuperscript{6} are simply exchanged. Finally, near $\omega t = \pi, 3\pi$, no emitted $S^\pm$ implies $J < J_{T1}$ (the spin-LED regime). PM in the lower panel shows only $J > J_{T1}$ ($S^-$ is present). The fully lasing regime, near $\omega t = \pi, 3\pi$, corresponds to constant $n$, even as $P_J(t)$ varies.

The quasi-static approach allowed us to consider analytically large signal modulation (both for AM and PM), usually only studied numerically. We next turn to the complementary approach for laser dynamics, i.e., small signal analysis (SSA), limited to a small modulation ($|\delta J/J_0| \ll 1$ for AM and $|\delta P_J| \ll 1, |P_{J0} + \delta P_J| < 1$ for PM\textsuperscript{22}) but valid for all frequencies. We confirmed that the two approaches coincide in the common region of validity. Our SSA for spin-lasers proceeds as in conventional lasers\textsuperscript{22} The decomposition $X = X_0 + \delta X(t)$ for $J_{T1}, n_\pm, S^\pm$ is substituted in Eqs.\textsuperscript{3} and\textsuperscript{4}. The modulation terms can be written as $\delta \lambda(t) = Re[\delta \lambda(t)] = Re[\delta X(t)e^{-i\omega t}]$. We then analytically calculate $\delta n_\pm(\omega), \delta S_\pm(\omega)$ and the appropriate generalized frequency response functions $R_{\pm}(\omega) = |\delta S^{\pm}(\omega)/\delta J^\pm(\omega)|$, which reduce to the conventional form $R(\omega) = |\delta S(\omega)/\delta J(\omega)|$, in the $P_J = 0$ limit. From SSA we obtain the resonance
in the modulation response $R_{\pm}(\omega)$, also known as “relaxation oscillation frequency,” $\omega_R/2\pi$. For $P_{J0} = 0$ and $J > J_{T2}$, we find

$$\omega_{R}^{AM} \approx \sqrt{2\omega_{R}^{PM}} \approx |\Gamma_0 N_T(\tau/\tau_r)(J_0/J_T - 1)|^{1/2}$$
$$= (g_0 S_0/\tau_{ph})^{1/2},$$

(7)

where $\omega_{R}^{AM}$ recovers the standard result.\(^2\) For $P_{J0} \neq 0$ and $J_{T1} < J < J_{T2}$

$$\omega_{R}^{AM} = \omega_{R}^{PM} \approx |\Gamma_0 N_T(\tau/\tau_r)(1 + |P_{J0}|/2)J_0/J_T - 1|^{1/2}$$
$$= (3g_0 S_0/2\tau_{ph})^{1/2}.$$

(8)

Such $\omega_R$ correspond to a peak in the frequency response and can be used to estimate its bandwidth\(^2\) a frequency where the normalized response $R(\omega/2\pi)/R(0)$ decreases to $-3$ dB.

We can now look for possible advantages in the dynamic operation of spin-lasers, as compared to their conventional counterparts. From Eq. \(8\)\(^\dagger\) we infer that the spin-polarized injection increases $\omega_R$ and thus increases the laser bandwidth — an important figure of merit.\(^2\) In Fig. \(3\) these trends are visible in the normalized frequency response. Results for $P_{J0} = 0$ (using finite $\epsilon$ and $\beta$) show that our analytical approximations for $\epsilon = \beta = 0$ are an accurate description of $AM$ and $PM$, at moderate pumping power. The increase of $\omega_R$ and the bandwidth with $P_{J0}$, for $AM$ and $PM$, can be understood as the dynamic manifestation of threshold reduction with increasing $P_{J0}$. With $\omega_{R} \propto (S_0/\tau_r)^{1/2}$ [Eq. \(8\)], the situation is analogous to the conventional lasers: $\omega_R$ and the bandwidth both increase with the square root of the output power\(^3\) ($S_0^+ = 0$ for $J_{T1} < J < J_{T2}$). An important advantage of spin-lasers is that the increase in $S_0^+$ can be achieved even at constant input power (i.e., $J = J_T$), simply by increasing $P_{J0}$. Additionally, a larger $P_{J0}$ allows for a larger $J_0$ (maintaining $J_{T1} < J_0 < J_{T2}$), which can further enhance the bandwidth, as seen in Eq. \(8\). For $P_{J0} = 0.9, J_0$ can be up to $10 J_T$, from Eq. \(8\).

We next examine the effects of finite $\tau_s^\alpha$, shown for $w = 1$ and $P_{J0} = 0.5$. AM results follow a plausible trend: $\omega_R$ and the bandwidth monotonically decrease and eventually attain “conventional” values for $\tau_s^\alpha \rightarrow 0$ ($w \rightarrow \infty$). The situation is rather different for $PM$: seemingly detrimental spin relaxation enhances the bandwidth and the peak in the frequency response, as compared to the long $\tau_s^\alpha$ limit ($w = 0$). A shorter $\tau_s^\alpha$ will reduce $P_T$ and thus the amplitude of modulated light. Since $\delta S^-(0)$ decreases faster with $w$ than $\delta S^-(\omega > 0)$, we find an increase in the normalized response function, shown in Fig. \(3\). The increase in the bandwidth comes at the cost of a reduced modulation signal.

The above considered trends allow us to infer some other possible advantages of $PM$ at fixed injection. In the quasi-static approximation, for $J > J_{T2}$, constant $n_+ = n_- = N_T/2$ (Fig. \(2\)) implies that $PM$ would be feasible at a reduced chirp ($\alpha$-factor), since $\delta n(t)$, which is a chirp of low-frequency and $\epsilon = \beta = 0$, can be combined with SSA in Fig. \(3\) revealing substantially smaller $\epsilon, \beta$ effects for $PM$ than $AM$, to suggest that the reduced chirp and therefore desirable switching properties of spin-lasers can be expected for a broad range of parameters.

In this work we predict an improved performance of spin-lasers and show how it can be understood from the threshold reduction experimentally demonstrated for the steady-state regime.\(^4\) Future advances in spin-lasers may depend on progress in magnetic memories and data storage. Answers to the key questions in these areas, about ultra-fast magnetization dynamics and timescales for magnetization reversal,\(^5\) may also determine the switching speed limit in the modulation of electrically pumped spin-lasers.

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\(^2\) SL operations at reduced chirp ($\alpha$-factor), since $\delta n(t)$, which is a chirp of low-frequency and $\epsilon = \beta = 0$, can be combined with SSA in Fig. \(3\) revealing substantially smaller $\epsilon, \beta$ effects for $PM$ than $AM$, to suggest that the reduced chirp and therefore desirable switching properties of spin-lasers can be expected for a broad range of parameters.

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