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Threshold reduction and spin filtering in spin lasers

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Abstract:

The paper includes a numerical study of spin lasers by introducing a spin VCSEL. In this article we focus on the spin laser threshold reduction and the spin filtering in it. The obtained results show that the threshold reduction and spin filtering affected strongly by the polarization injection.

Keywords: Spintronics, Spin lasers, VCSEL, Spin polarization, Laser dynamics

Introduction:

In conventional lasers the population inversion in the active medium is reached by pumping the laser with light or by electrical injection to reach the lasing threshold. In this procedure the carriers injected into the active medium are with arbitrary spin state and the light emitted will be unpolarized. Conventional lasers dynamics were widely studied, see for example [1,2].

Spin lasers or spin polarized lasers are the new in the component of semiconductor lasers where the vertical cavity surface emitting lasers (VCSELs) are mostly used to achieve spin lasers, their properties such as low threshold, selectivity of its circularly polarized output make it used widely in communication [3], signal processing, magnetic stores and in 3D TVs, which need two light sources with orthogonal polarizations [4]. Spin lasers are an application of spintronics (emerging electronic charge and spin properties). Spintronics is of more interesting field of nanoscience which deals with the spin of electron in addition to its charge [5]. The injected carriers can made with a specific spin (spin up or spin down) by adding a ferromagnetic layer to the active medium and magnetic poles, as illustrated in figure (1).

There are two major differences between conventional and spin lasers, (1) injected carriers are spin polarized. (2) light emitted from spin laser is circularly polarized [6]. It was found that injected spin polarized carriers can enhance the laser properties, it can reduce the threshold current as compared with the conventional one [7].

In present article we study the dynamics of spin VCSEL, and the effect of the injection current, polarization injection and the enhancement in the threshold reduction, spin filtering of spin VCSELs.

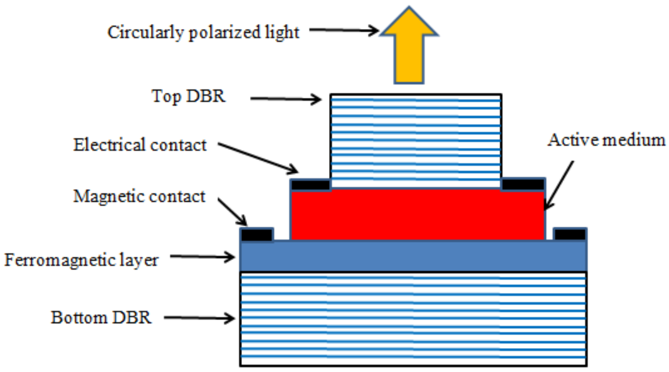


Fig. (1) A schematic view of spin polarized VCSEL.

The model :

The spin polarized rate equations that describe the laser time evolution in the presence of spin polarized electrons (holes) injected to the active layer are given by [7-8] :-

$$\frac{dn_{\pm}}{\mathrm{dt}} = J_{\pm} - g_{\pm}(n_{\pm}, S)S^{\mp} - \frac{(n_{\pm}-n_{\mp})}{\tau_s^n} - R_{sp}^{\pm} \quad (1)$$

$$\frac{dS^{\pm}}{dt} = \Gamma g_{\mp}(n_{\pm}, S)S^{\pm} - \frac{S^{\pm}}{\tau_{ph}} + \beta\Gamma R_{sp}^{\mp} \quad (2)$$

where $n=n_{+}+n_{-}$, + (-) denotes spin up (down) electrons, $n_{\pm}$ is the carriers density, S is the photon density, S=$S^{+} + S^{-}$, where + (-) denotes right (left) circularly polarized components, $J_{\pm}$ is the injection current density of spin up and spin down carriers, with the overall injection $J = J_{+} + J_{-}$. The polarization injection is $P_J = (J_{+} - J_{-})/J$. The optical gain, $g_{\pm}$, for spin polarized case is given by [6]:

$$g_{\pm}(n_{\pm}, p_{\pm}, S^{\pm}) = g_0(n_{\pm}+p_{\pm} - n_{tr})/(1 \quad \epsilon S) \quad (3)$$

g_o is the differential gain, ϵ is the gain compression factor and n_{tr} is the carriers density at transparency. τ_s^n is the spin relaxation time of the electrons, $p=p_{+}+p_{-}$, the density of holes and + (-) denotes spin up (down) cases.

Γ is the optical confinement coefficient ,$\tau_{ph}$is the photon lifetime , β is the spontaneous emission factor and the spontaneous emission is $R_{sp}^{\pm} = \frac{n_{\pm}}{\tau_r}$ for linear recombination (LR) or $R_{sp}^{\pm} = Bn^2$ for quadratic recombination (QR).

τ_r is the recombination time and B is a time dependent constant.

The threshold reduction in spin lasers is given by [6,8]:

$$r = 1 - \frac{J_{T1}}{J_T} \quad (4)$$

where J_{T1} is the majority spin threshold ($J_{T1} < J_T$), see fig. (2)

The spin filtering is the spin- dependent transport of carriers in semiconductors nanostructure, that means the semiconductor acts like spin polarizer or spin filter [9]. This filtering is measured by spin filtering interval (SFI) [6,8], which is given by:

$$SFI = (J_{T2}-J_{T1})/J_T \quad (5)$$

where J_{T2} is the minority of spin threshold and $J_{T1} < J_T < JT_2$

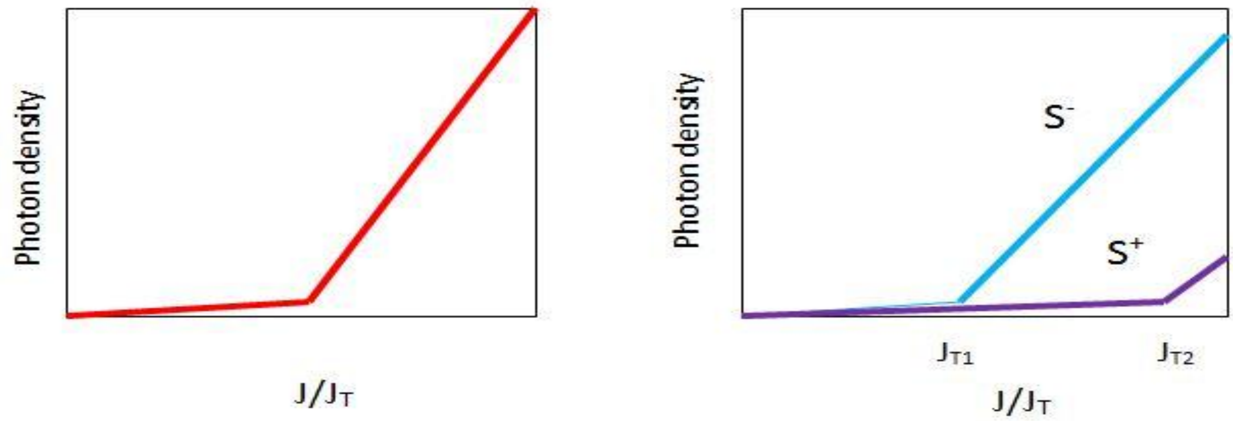


Fig. (2): The thresholds of conventional (left) and spin (right) lasers.

Results and discussion:

The rate equations describe the spin VCSEL (S-VSCEL) were solved numerically using 4th-order Runge - Kutta method and MTLAB software. The values of the parameters that appear in the simulation are given in table (1) .

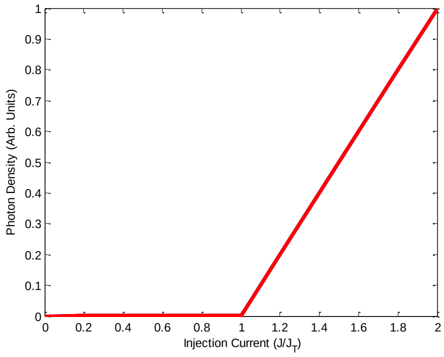
Table (1): Parameters used in the simulation [7-8].

Symbol	Description	Value	Units
n_{tr}	Carriers density at transparency	1×10^{14}	cm^{-3}
β	Spontaneous emission factor	1×10^{-5}	-
ϵ	Compression factor	2×10^{-18}	cm^3
τ_r	Recombination time	200	ps
τ_{ph}	Photon life time	1	ps
Γ	Confinement factor	0.003	-
g_o	Differential gain	2000	cm^{-1}
τ_s^n	Spin relaxation time	600	ps
B	Quadratic recombination constant	1.43×10^{-7}	$cm^3 sec^{-1}$

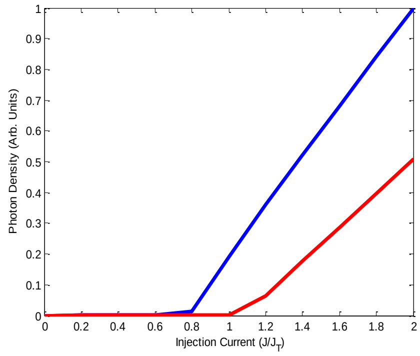
The threshold current of the lasing is an important factor in the laser operation , where in S-VCSEL there are two threshold currents [7]. The effect of the polarization injection on these threshold were studied and abstracted in figure (3) .It is seen that at p=0 the S-VCSEL acts as a conventional laser, i.e. single threshold as can be seen in figure (3a) , while as P increased there is a reduction in the S^- threshold on other hand the S^+ threshold still at 1.2 J_T , see figure (3 b – e).

Another way to show the effect of P_J is by fixing J at a certain value and increasing P_J from 0 and 1.

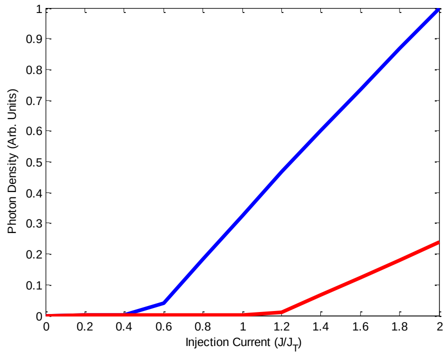
Figure (4) shows the results of this procedure , it can be seen that at J/J_T =0.25 as shown in figure (4 a).The laser action starts at P≈0.75 with full circularly polarized (S^-). Increasing J to 0.5 J_T the laser still operates with S^-, as figure (4 b) shows that the threshold value shrinks to 0.55 J_T. At J=1.2J_T, the laser will operation in the mixed state (S^- and S^+) especially at low P_J , as can be seen in figure (4 c).



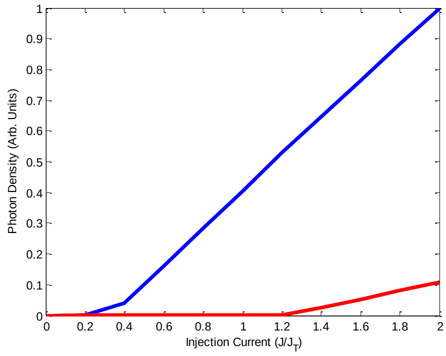
(a)



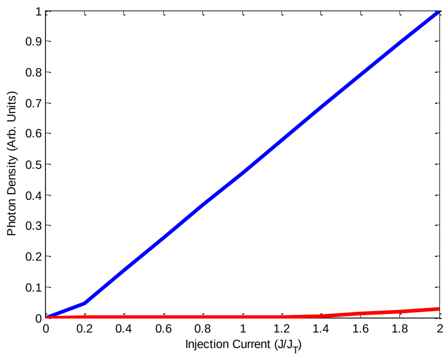
(b)



(c)

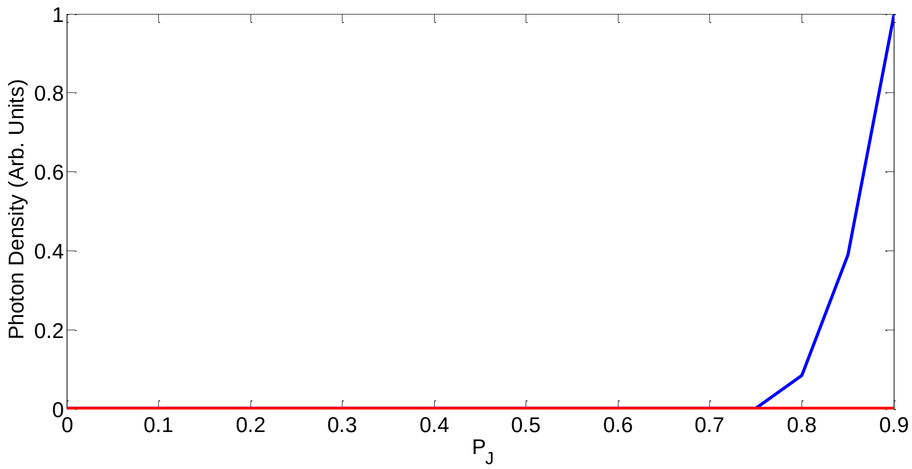


(d)

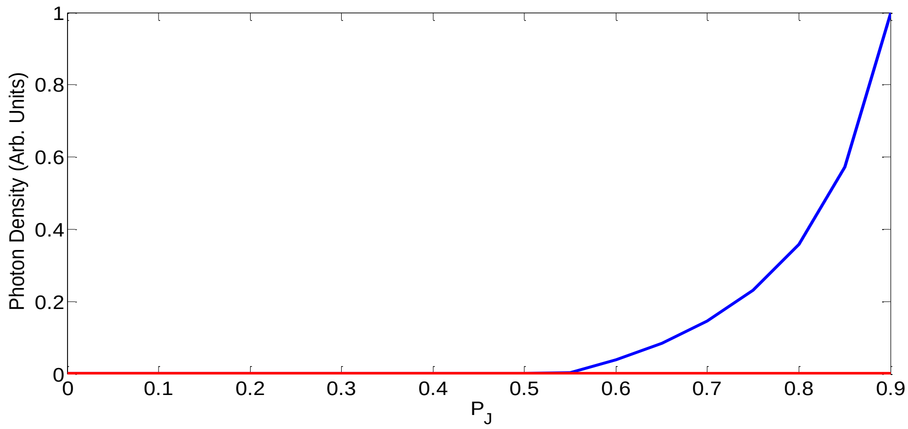


(e)

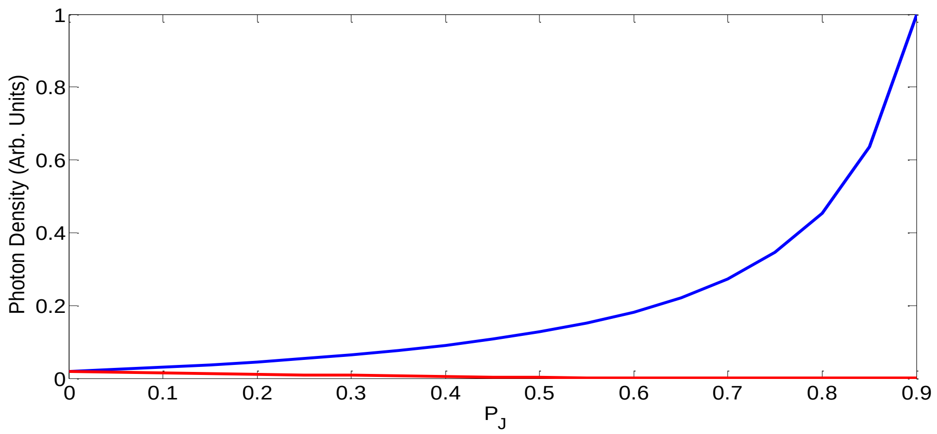
Fig.(3): The effect of the current injection on threshold of the S-VCSEL (red line for S^+ and blue line for S^-) for: (a) P_J=0, (b) P_J =0.25, (c) P_J = 0.5, (e) P_J =0.7 and (f) P_J =0.9



(a)



(b)



(c)

Fig.(4): Effect of polarization injection on threshold of the S –VSCEL (red line for S^+ and blue line for S^-) at: (a) $J= 0.25J_T$, (b) $J=0.55J_T$ and (c) $J =1.2J_T$

Fig. (5) shows the threshold reduction in spin VCSEL, it can be seen that the reduction increases with increasing the polarization injection and the reduction in the case of quadratic recombination is greater than the linear one.

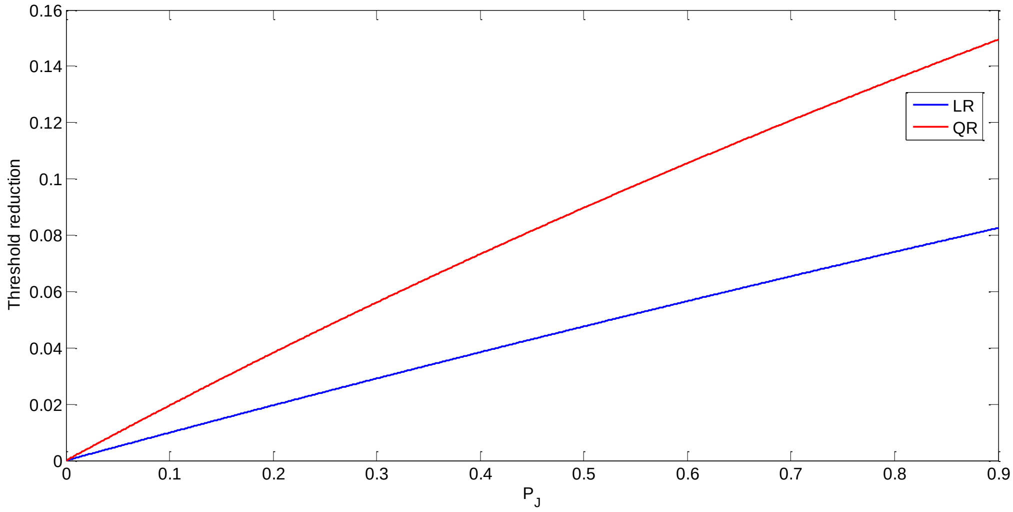


Fig. (5): Threshold reduction in spin VCSEL for LR and QR.

The relation between the spin filtering interval and the polarization injection is shown in fig. (6), it is seen that the SFI increased with increasing P_J and the maximum difference in SFI between QR and LR occurs around P_J=0.5.

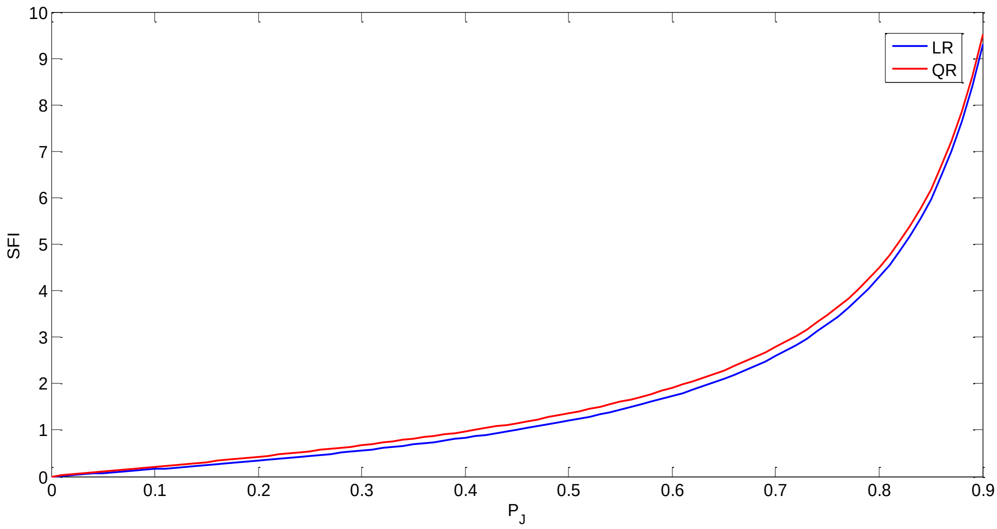


Fig. (6): The relation between SFI and P_J for QR and LR.

Conclusions:

From the simulation results we conclude that the polarization state of the spin laser depends on the injection current and the polarization injection. The threshold of the laser with right circularly polarized shrinks with increasing the polarization injection while the output power is increased. The threshold reduction for quadratic recombination, QR, is greater than the linear recombination LR. The spin filtering interval, SFI, increases with increasing the polarization injection and again it increases for quadratic recombination, QR, greater than for the linear recombination LR around P_J=0.5.

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تخفيض العتبة وترشيح البرم في ليزرات البرم

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الملخص:

يتضمن البحث دراسة عددية لليزرات البرم ممثلة بليزر الأنبعاث السطحي ذي التجويف الشاقولي البرمي. ركزنا في هذا العمل على تخفيض عتبة الليزر وترشيح البرم فيه. أوضحت النتائج المحصلة أن تخفيض العتبة وفلترة البرم تتأثر وبشدة بحقن الأستقطاب.

الكلمات المفتاحية: السبنترونكس، ليزرات البرم، ليزرات الانبعاث الشاقولي، حركيات الليزر.