Study of all optical switching behaviour in semiconductor microresonator with nano-active layer

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Abstract. In this paper the behaviour of carriers in spontaneous patterns formation and patterns switching has been studied. Results demonstrate that with increasing length of cavity the range of required input field amplitude for patterns formation increased slightly and also the minimum perturbation coefficient for switching decreased greatly. Increasing nonradiative recombination rate of carriers about ten percent appeared that required input field amplitude for patterns formation raised more than before, albeit the minimum perturbation coefficient for switching and switching and switching time dose not vary considerably.

1. Introduction

Recently, a switching technique that is based on sensitivity of transverse optical patterns has been developed in both atomic and semiconductor systems [1-6]. A transverse optical pattern is the spatial structure of the electromagnetic field in the plane perpendicular to the propagation direction [3]. In semiconductor micro resonator devices optical patterns emerge from the coupling of the nonlinear medium response, diffraction, and the feedback action of mirrors. In atomic system, Gauthier and his group have developed a switching technique experimentally and theoretically that uses a very weak beam of light to control a much stronger beam [3].

In this paper, we investigate a non-feedback technique [11-13], which allows selecting the orientation of spatial patterns in a semiconductor microresonator system. Our method is based on injecting a weak perturbation into the system to control patterns with a beam whose intensity is much smaller than the intensity of the pattern itself.

In reference [7-12], an all optical switch based on sensitivity of transverse optical patterns to tiny perturbation in a semiconductor microresonator in passive configuration had been discussed. In recent article for pattern generation an semiconductor optical cavity have been used that a holding beam has been imposed, they control patterns with a beam whose intensity is smaller than the intensity of the pattern itself and as fast as nanosecond scale for different values of perturbation coefficients. In semiconductor devices behavior of carriers determine the behavior of devices, also a powerful principle that could be explored to implement all-optical transistors, switches, logical gates, and memory is the concept of optical bistability. In systems that display optical bistability, the outgoing intensity is a strong nonlinear function of the input intensity, and might even display a hysteresis loop. Thus equations in homogeneous stationary state for field and carriers have been considered and with numerical calculations and by choosing proper physical parameters bistable behavior have been studied.

In each system some fundamental parameters have substantial rule in behavior of system, thus in this paper we perused the effects of some cavity parameters on the response manner of all optical switches. For this reason we studied the variation of cavity length on switching response time and required amplitude of perturbation for switching.
2. Model
Similar with our previous model [4,5], we consider a broad area semiconductor device but in active configuration (i.e., with population inversion). The semiconductor microresonator is of the Fabry-Pérot type, with a MQW structure perpendicular to the direction Z of propagation of the radiation inside the cavity. The dynamical equations for the slowly varying coherent field and carrier density, in the paraxial and mean field limit approximation are as in [4, 5].

2.1. Homogeneous Solution and Carriers Bistable Behavior
The homogeneous solution \((E_s, N_s)\) of dynamical equations are obtained by setting equal to zero the time derivatives and neglecting the Laplacian. For appropriate choices of the parameters the curves of \(|E_s|\) as a function of \(|E_i|\) and also the curves of \(|N_s|\) as a function of \(|E_i|\) had been studied. As it has shown in Figure (1), the behavior of \(|E_s|\) and \(|N_s|\) as a function of \(|E_i|\) is bistable. Also from their comparison at this Figure it is perspicuous that as well as mentioned with increasing injected field, output field increases with an S shape and carriers density decreases with an inverse S shape and the behavior of electric filed intensity and carrier density are on the contrary with each other.

![Figure 1](image_url)  
**Figure 1.** \((E_s - E_i)\) and \((N_s - E_i)\) curves for two different currents below threshold with these parameters \(\beta = 0, \eta = 0, \alpha = 5, C = 0.45, \theta = -2, d = 0.052\). Ascendant curves depend on \((E_s - E_i)\) curves and falling curves depend on \((N_s - E_i)\) curves.

3. Simulations and numerical analysis
The results we will present here were obtained by numerically integration dynamical equations with the spatially perturbed injected field defined before. The numerical integration of dynamical equations was performed by using a split-step method with periodic boundary conditions. This method implies the separation of the algebraic and the Laplacian terms in the right-hand side of dynamical equations. The first part is integrated via a Runge-Kutta algorithm, while the linear operator (Laplacian) is integrated via a two-dimensional 2D-FFT. For the aim of achieving the initial condition of switching, what we typically do is to follow the pattern branch by changing the input intensity, starting from a case where the pattern was spontaneously formed.
3.1. The response time and sensitivity dependence on VCSEL parameters

Now in this section we investigate the effects of variation of physical parameters of microresonator on spontaneous patterns formation in system and also on switching performance. For the aim of switching performance and making comparison between different cases we just consider roll patterns switching in all cases. As mentioned before, physical characteristics that we study their variation in our system is: cavity length ($L$)

We study the effect of the cavity length by varying this parameter from ±20 to ±30 percent. Some important parameters which on the cavity length: diffraction coefficient $a = v / 2\kappa k_z$ which $v = c / n$, $k = \sqrt{T}/2L$ is the cavity half-width, and $k_z = \omega_0 n / c$; diffusion coefficient $d = l_0^2 / a$ which $l_0 = \sqrt{D\tau_r}$ is diffusion length; adimensional decay rate $\gamma = (2\kappa\tau_r)^{-1}$ which $\tau_r$ is the nonradiative recombination rate of carriers; and the cavity detuning $\theta = \omega_l - \omega_0 / \kappa$ which $\omega_0$ being the frequency of the holding field and $\omega_l$ the longitudinal cavity frequency closest to $\omega_0$. Thus with variation of the cavity length all of these parameters will change. Depends on different cavity length, bistable curve of $|E_S|$ as a function of $|E_I|$ and their Turing unstable region will be different which has shown in Figure (2). Thereupon region of injected field for patterns formation and also output patterns intensity will be different.

![Figure 2. Steady-state curves of $|E_S|$ as a function of $|E_I|$ for different cavity length, dashed line refers to unstable Turing instability region.](image)

Simulations show no regular patterns in proper times in system with decreasing cavity length. Thus we start to increase this parameter by 10, 20, and 30 percent and obtain patterns for each of these states. Then for each cavity length we switch one spontaneous roll pattern. In the case of 10 percent increment successful switching performed with $\alpha = 0.1, 0.07, 0.03$ and also $\alpha = 0.02$. As could be seen in this case required perturbation coefficient is very smaller than its value in the case of initial cavity length. Switching with $\alpha = 0.01$ was not successful thus $\alpha = 0.02$ is the minimum perturbation coefficient in this case. Then we increased cavity length up to 20 percent. Results of switching in this case demonstrate that minimum perturbation coefficient is $(\alpha = 0.002)$ too. This perturbation coefficient is 250 times smaller than minimum perturbation coefficient for switching in
the case of initial cavity length. Also we switched roll pattern with perturbation that is 650 times weaker than injected field amplitude of roll pattern in this case ($E = 1.3$). This consequence leads us to produce all optical switches that operate in ultra low light levels. It should be pointed out; however, increment in switching time is the cost of decreasing perturbation amplitude (Fig 3).

![Figure 3](image)

**Figure 3.** Evaluation of electric field intensity for 20 and 30 percent increment, for both cases injected field amplitude is ($E = 1.3$) and perturbation coefficient is ($\alpha = 0.002$).

Results of switching for 30 percent increment case show that minimum perturbation coefficient in this case is almost similar to 20 percent increment case. We could deduce from this result that increasing microcavity length for this purpose to some extent could be beneficial. Albeit in this case switching time is a little faster than previous case but their switching times are in a same range (Fig 3). According to Figure (3), here switching times are longer than initial case, while the used amplitude of perturbation here is 250 times smaller than its initial value, and switch could be faster with stronger perturbation coefficient.

![Figure 4](image)

**Figure 4.** Comparing minimum perturbation coefficient for each cavity length.
In Figure (4) we plot the perturbation variation as a function of microcavity length. We defined the perturbation coefficient as the minimum coefficient needed for the pattern to rotate completely. It can be seen that, pattern can be controlled with very small coefficients of perturbations with enough larger length compared with initial length of the microresonator.

4. Conclusions
A spatial perturbation method has been used to select and control spontaneous optical pattern orientation in an active semiconductor microresonator. Our successful results have been demonstrated with a perturbation made by a tilted wave, corresponding in the Fourier space to only one of the spots of a roll pattern. The switching beam controls the orientation of output patterns with much stronger intensities: for example, we can rotate patterns with intensity 350 times stronger than the switching beam intensity. Also switching time is sensitive to the perturbation strength $\alpha$ and decreases by increasing $\alpha$. Also for founding more regular spontaneous pattern after shorter time in system we could increase cavity detuning to some extent.

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