Optical Pattern Switching in Semiconductor Microresonators as All-Optical Switch

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In this paper, we present a spatial perturbation method to control the optical patterns in semiconductor microresonators in the far-field configuration. We propose a fast all-optical switch which operates at a low light level. The switching beam controls the behavior of output beams with strong intensities. The method has been applied successfully to different optical patterns such as rolls, squares, and hexagons.

Keywords: Optical switch, semiconductor microresonator, optical pattern, spatial perturbation, high-speed switching.

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I. Introduction

It would be highly beneficial to have a strong and nearly instantaneous interaction of light with light, preferably in a minimal volume for important applications, such as quantum information processing, integrated all-optical signal processing, and so on. In principle, this can be achieved by exploiting intrinsic material nonlinearities, that is, by all-optical switching. Optical switches are crucial components of communication networks, where light is redirected from channel to channel [1], and of general computational machines, where they can act as logic elements [2]. For all-optical switches, where light controls the flow of light, there has been a continual push to increase the sensitivity of switches so that it can be actuated with lower powers, thus decreasing the system complexity. With the advent of quantum information systems, it is important to increase the sensitivity to the point at which a single switching photon is effective [3].

Optical switching is strongly preferred because by replacing existing electronic network switches with optical ones, the need for optical-to-electronic-to-optical (OEO) conversion is removed as well as the need for the time and energy consuming conversion of light to electricity. There have been numerous proposals as to how to implement light switching between optical fibers, such as semiconductor amplifiers, liquid crystals, holographic crystals, and tiny mirrors [1].

Building an all-optical switch from transverse optical patterns combines several well-known features of nonlinear optics in a novel way. Using the different orientation of a transverse pattern as the distinct state of a switch allows maximization of the sensitivity of pattern forming instability.

The promising experimental results of pattern switching in atomic vapor (gaseous) systems have raised the question as to whether similar effects can be expected in solid state systems, in particular, semiconductors. One obvious advantage of semiconductors over atomic systems is that they can be more easily integrated in optoelectronic communication networks. Generally, semiconductor systems offer great flexibility in terms of epitaxial system growth (including active layers and mirrors), and, of course, they are mechanically robust.

In this work, we describe an all-optical switch which combines the extreme sensitivity of instability-generated transverse optical patterns with tiny perturbations. The formation of dissipative structures far from equilibrium has been widely studied since the early 1970s. In the late 1980s, the main focus in this field shifted gradually from purely temporal effects to spatial and spatio-temporal phenomena, especially spontaneous spatial pattern formation in the structure of the electromagnetic field in the section of broad-area radiation beams, when they interact with nonlinear media.

Great attention has recently been paid to the control of spatiotemporal dynamics in spatially extended nonlinear systems. As with the previous studies of controlling, there are two main schemes for manipulating pattern formation: feedback and non-feedback methods.

In this paper, we present a non-feedback technique which consists of applying external spatial perturbation to the system in order to break the symmetry and then to enhance the stability of the desired pattern in a semiconductor microresonator at the far-field configuration. This method allows us to rotate and select spatial patterns of related systems. Our method is based on applying a weak perturbation to the system in the spatial dimension. We control patterns with a beam the intensity of which is several hundred times smaller than the intensity of the pattern itself and is as fast as 0.5 to 100 ns for different values of perturbation coefficients. It is important that our non-feedback technique can be easily realized in practical spatially extended systems. In an optical system, for instance, both the amplitude and the phase of the injected field can easily be spatially perturbed with an optical mask. Of course, it is also possible to rotate the different patterns by injecting just a tilted wave, which is characterized by a single spot in the Fourier space instead of the target pattern. This is experimentally much easier to realize and corresponds to using a plane wave with a tilt.

In section II, the general model adapted to study semiconductor micro-resonators and the method used for pattern selection are described. In section III, we show the main numerical results on pattern switching obtained from integration of the dynamical equations. Finally, some conclusions and perspectives are reported in section IV.

II. The Model

The dynamical equations, suitable to describe a broad area semiconductor heterostructure in a passive (without population inversion) configuration, where the semiconductor microresonator is of the Fabry-Perot type, with a multi-quantum-well (MQW) structure, can be cast in the same form as in [4] to [8] as

$$\frac{\partial E}{\partial t} = -\kappa\left[\zeta E - E_{\mathrm{I}} + \Theta E - i\nabla_{\perp}^{2} E\right], \tag{1}$$

$$\frac{\partial N}{\partial t} = -\gamma_{\parallel}\left[N + \beta N^{2} + \left(N-1\right)\left|E\right|^{2} - d\nabla_{\perp}^{2} N\right], \tag{2}$$

where E and N are the normalized electric field and the carrier density normalized to the transparency value, respectively; κ is the cavity damping constant; and $\gamma_{\parallel}$ is the carrier nonradiative recombination rate. Here, $\zeta = 1+\eta+i\theta$ with $\eta = 2\alpha_i L/T$ is proportional to the linear absorption coefficient per unit length due to the material in the region between the QWs and the reflectors, and $\theta = (\omega_c - \omega_0)/\kappa$, which is the cavity detuning parameter, with ω_0 being the frequency of the holding field, and ω_c is the longitudinal cavity frequency closest to ω_0. The transverse Laplacian, defined as usual as $\nabla_{\perp}^{2} = \partial^2/\partial x^2 + \partial^2/\partial y^2$, represents diffraction in (1), and carrier diffusion in (2) through the diffusion parameter d, $\beta = BN_0/\gamma_{\parallel}$ where B is the coefficient of radiative recombination involving two carriers, and N_0 is the carrier density at transparency. The transverse coordinates x and y are scaled to the diffraction length. The parameter E_I is the normalized injected field (taken real and positive), $\Theta = 2C[(1-i\Delta)/(1+\Delta^2)](1-N)$ with C being the bistability parameter, and $\Delta = (\omega_e - \omega_0)/\gamma_e$ where ω_e is the central frequency of the excitonic absorption line, approximated by a Lorenzation curve, and γ_e is its half–width. To ensure that our analysis would be as realistic as possible in comparing our proposed switch with the devices currently available, the choice of numerical values of the physical quantities characterizing our model was inspired by experimental works on optical bistability in GaAs MQW structures [7]-[11] (see [8] for a more detailed discussion of the model equations and of the calculations of the homogeneous stationary solutions and their stability analysis).

Typical values of physical parameters common to both configurations are

$$\lambda_0 = \frac{2\pi c}{\omega_0} = 850\ \text{nm}, \quad n = 3.5,\ T = 4\times10^{-3},\ L = 2\ \mu\text{m}.$$

With this choice of physical quantities, we are led to a cavity decay rate of $\kappa = 8.57\times10^{10}\ \text{s}^{-1}$ and a diffraction coefficient of $a = 19.3\,\mu\text{m}^2$. These values imply that the time unit is

$\kappa^{-1} = 11.7\,\text{ps}$, and the space unit is $\sqrt{a} = 4.39\,\mu\text{m}$. In a broad-area device with a cross section $S \approx 5000\,\mu\text{m}^2$ (for example, a square of about $70\times 70\,\mu\text{m}^2$) which we used in our simulations, the active volume V_A is about $250\,\mu\text{m}^3$.

In our controlling method, the direction of the bright output beams is controlled by applying a weak switching laser beam. Orientation of the output beams is extremely sensitive to perturbations, and their azimuth angle can easily be rotated to the direction of the switching beam.

To illustrate pattern switching mathematically, we consider the control parameter E_I of the system to which, in our algorithm, the spatial perturbation is exerted as

$$E_I = E_{I0}\left[1+\alpha f(r)\right], \tag{3}$$

where E_{I0} is the unperturbed control parameter, α is the amplitude of the perturbation, and $f(r)$ with $r = (x, y)$ is the spatial perturbation function. Here, α should be smaller than 1. The function $f(r)$ should be designed to reflect the signature of the target pattern; therefore, the most natural form of this function is chosen as that of the basic harmonics of the target pattern.

The results presented in this paper were obtained by numerically integrating (1) and (2) with the spatially perturbed pump defined in (3). Using a split-step method with periodic boundary conditions, we performed the numerical integration of the dynamical equations.

The perturbation control function $f(r)$, generally (for all roll, square, and hexagonal patterns), is defined as

$$f(r) = \exp\ i\Big(\sum_j (K_{jx}x + K_{jy}y + \phi_j)\Big) + C.C., \tag{4}$$

$$j = 1, 2, 3, \cdots, 8,$$

where $K_{jx}x = |K_j|\,x\cos(\gamma)$, and $K_{jy}y = |K_j|\,y\sin(\gamma)$ with $|K_j| = K_C$, which is the critical wave vector; γ is the wave vector-tilting angle in respect to the x-axis; and ϕ_1 is an arbitrary phase. For different types of patterns, j is different, where rolls are formed by wave vectors $\vec{K}_{1,5}$, squares by $\vec{K}_{1,3,5,7}$, and hexagons by $\vec{K}_{1,2,4,5,6,8}$ [5].

III. Numerical Results

The numerical integration of dynamical equations with the spatially perturbed pump defined in (3) was performed by using a split-step method with periodic boundary conditions. This method implies the separation of the algebraic and 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 an FFT algorithm.

When the input field E_I is a plane-wave (that is, it does not depend on the transverse variables x and y) the dynamical

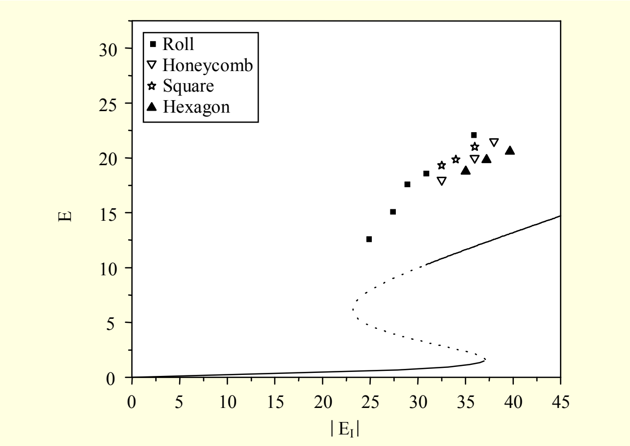

Fig. 1. Steady-state curve of the homogeneous solution and results of numerical simulations. The dotted line indicates the unstable part of the curve. Different patterns are indicated by different symbols. The ordinate of the symbol corresponds to the maximum intensity in the pattern. The parameters are η=0.25, β =1.6, d=0.2, θ=–3, Δ=–1, and C=40.

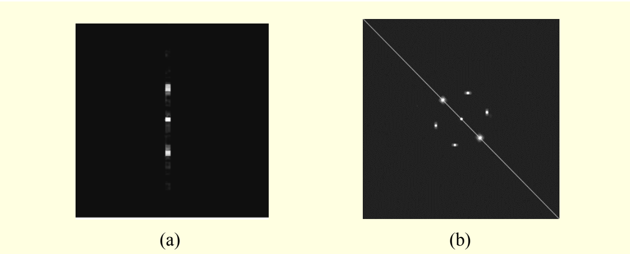

Fig. 2. (a) Horizontal roll and (b) hexagon H^+ patterns in the far-field case. The parameters are η = 0.25, β = 1.6, d = 0.2, θ = –3, Δ = –1, C = 40, and E_I = 31 and 39 in the two frames, from left to right.

equations admit homogeneous (that is, x- and y-independent) stationary solutions. In all cases considered in this paper, the steady-state curve of $|E_S|$, where E_S is the stationary value of the field E as a function of E_I, is S-shaped (see Fig. 1) and its lower branch is stable. On the contrary, the negative-slope branch and part of the upper branch are unstable against the growth of spatially modulated perturbations.

First, the roll, square, and hexagons H^+ and H^- (honeycomb) patterns are produced with different values of $|E_S|^2$ in a far-field configuration. Figure 2 shows roll and hexagonal patterns which were created spontaneously in a far-field case of passive configuration. The far field of a roll pattern should be two points, placed on an ideal line oriented orthogonally to the rolls. We also have the central component (the bright spot at the center), which corresponds to the homogeneous PW component.

By adding a perturbation term, we controlled the direction of spontaneously created roll patterns using tilting wave vector K.

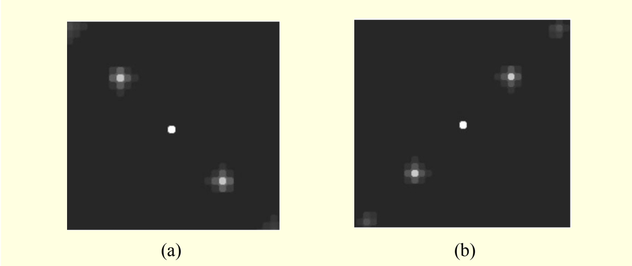

Fig. 3. Roll patterns in the far-field case (a) before switching and (b) after switching. The strength of perturbation α which we have used is equal to 0.05 and $\gamma = \pi / 2$.

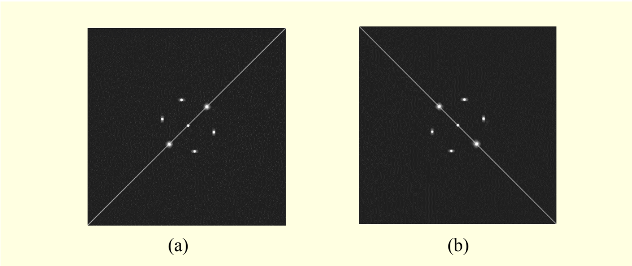

Fig. 4. (a) Spontaneously created hexagon pattern and (b) rotated. The strength of perturbation α which we have used is equal to 0.05, and $\gamma = \pi / 2$.

In this case the perturbation function *f*(*r*) with arbitrary γ has been added to E_{I0}. Figure 3 shows the roll pattern before and after switching. In this case, we used a general perturbation function where *j*=1, 5 with γ = π/2 and $|K_1| = K_C = 1.72$.

In order to switch the hexagon H^+ pattern, we used the perturbation function *f*(*r*) in (3) as follows:

$$f(r) = \frac{1}{2}\left[e^{i(K_1.r+\phi_1)} + e^{i(K_4.r+\phi_4)} + e^{i(K_6.r+\phi_6)} + C.C.\right], \quad (5)$$

where, $K_{jx}x = |K_j| x\cos(\gamma)$, and $K_{jy}y = |K_j| y\sin(\gamma)$ with $|K_j| = K_C$, and K_1, K_4, and K_6 make an angle of $2\pi/3$ with each other.

As seen in Fig. 4, honeycomb patterns can also rotate at an arbitrary angle γ . This figure shows a hexagonal pattern before and after switching with $\gamma = \pi / 2$ in a counterclockwise direction.

Far-field studies of optical patterns shows a trade-off relation between switching time and perturbation strength *α*. Figure 5 shows switching time as a function of the perturbation coefficient α. The figure shows successful switching even for a perturbation amplitude as small as α = 0.05. This means that our switching technique is able to control the behavior of output beams at higher intensities.

IV. Conclusion

We have conducted a far-field study of optical pattern selection in a semiconductor microresonator based on small spatial perturbations which is important from a practical viewpoint. Using the proposed spatial perturbation method, a pattern is generated either spontaneously or by using an optical mask, and a weak driving signal (switching beam) generated by a target mask causes the initial pattern to rotate to the new orientation. The method has been successfully applied to various optical patterns.

Our investigation was inspired by [1], and demonstrates that, by using a semiconductor instead of an atomic medium, the rotation is much faster, occurring on the scale of nanoseconds instead of microseconds. Using the proposed all-optical switch, patterns can be controlled using a beam, the intensity of which is 400 times lower than the intensity of the pattern itself, and the switching time varies as an inverse function of perturbation coefficients in the range of 0.5 to 100 ns. Therefore, in area of high-speed switching, the proposed switch is a practical alternative to electrical switches.

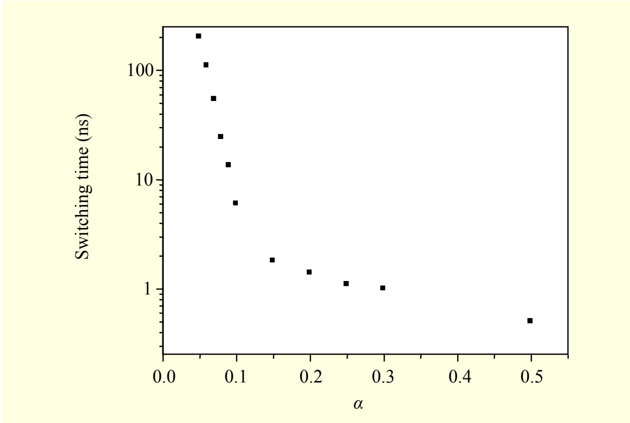

Fig. 5. Switching time variation with perturbation coefficient *α*.

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