# Photonic Computing with Photorefractive GaAs PhC Nanobeam: Preliminary Analysis

J. Lopez Leyva, B. Shi, R. Stabile

EHCI, Eindhoven University of Technology, 5600MB Eindhoven, The Netherlands

***Abstract*** *- Conventional electronics based neural networks have recently made rapid advancements, but remains limited by large energy consumption. To address these issues, neuromorphic photonics rises as a new research fields that promises high computational density at lower energy consumption. In this paper we propose to execute the synaptic operation in photonic computing exploiting the photorefractive effect in GaAs Photonic Crystal (PhC) nanobeams, where for the first time the photorefractive effect in a GaAs PhC is simulated. The combination of photorefractive GaAs with 1D PhC nanobeams is utilized to detune the resonant wavelength by changing the refractive index via the self-interference pattern of the optical mode, and the redistribution of electrons and ionized donors in the GaAs PhC nanobeams, resulting in a built-in space charge field. The detuning of the resonant wavelengths would represent the synaptic weights in a neural network. We demonstrate the simulation via a FEM simulation using COMSOL, with a simplified photorefractive model where acceptors are removed and implemented. The polarizations of the optical mode suggest that a <111> orientation must be used instead of <001>, because the photorefractive space charge field and polarizations are parallel. Additionally, the drift and diffusion processes are shown to separate electrons and ionized donors.*

## Introduction

Artificial neural networks have made significant breakthroughs, but these advancements come with the drawback of requiring substantial electronic computing power [1]. To enhance both energy efficiency and processing speed, photonic computing has emerged as a promising alternative [2]. Key challenges for photonic computing are the small footprint and memory among others. For that reason, this work attempts to alleviate these problems by proposing the combination of the photorefractive effect (for fast memory) with a < 111 > Semi Insulating (SI) - GaAs Photonic Crystal (PhC) nanobeam (for small footprint).

An application of the photorefractive effect for analog matrix-vector multiplication was realized with integrated photonics using a cross-bar array with 2D slab waveguides [3]. This work shows that using integrated photonics can lead to faster writing times attributing to stronger light-matter interaction than in free space. This hints that using PhCs could provide fast writing times due to the large Q/V (quality factor over volume). To that purpose, besides MRRs, the use of the photorefractive effect with PhCs has been demonstrated in 1D and 2D PhCs using LiNbO3 [4,5]. Lastly, a recent work where the photorefractive effect is exploited in a microtoroid is shown [6].

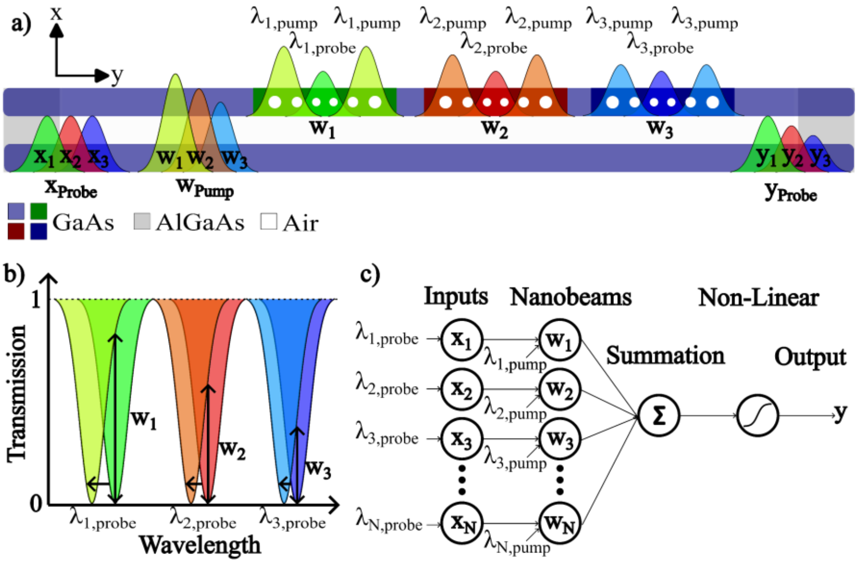



***Figure 1.*** *a) Schematic of the device operation using a pump and probe setup to encode different PhCs. b) Detuning mechanism of the PhC to realize a weight. c) Device representation as a perceptron to realize a simple neural network.*

Fig. 1a shows the device operation we propose. Two air suspended <111> SI-GaAs waveguides (blue) are deposited on AlGaAs (grey) and stand next to each other. One waveguide contains multiple multimode PhCs (green, red, dark blue), each with a different lattice spacing such that the resonant wavelength is different. Initially, pump pulses are sent. Each pump wavelength couples into a different PhC, and within the PhC, they couple into the 2nd order mode. This will then induce the photorefractive effect, which is done by changing the refractive index of the cavity, such that the resonant wavelength is shifted (detuned) as shown in Fig 1b. This corresponds to a written weight in the PhC and the effect is measured by the probe pulses, which also is coupled into only one PhC.

After coupled into the PhC, the input probe pulse is coupled back into the bus waveguide, where the change in transmission (dependent on the pump intensity) determines the results of multiplying the data encoded in the probe, by the photorefractive effect induced wavelength shift in the PhC as $y_i = w_i \cdot x_i$. To elaborate on the weight part, we consider first the situation where almost no light is transmitted at the fudamental wavelength as shown in Fig 1b (blue case). After pumping the PhC, the photorefractive effect is produced, which changes the refractive index and thus detunes the resonant wavelength (spectrum follows a Lorentzian shape). The detuned fundamental wavelength is coupled less efficiently to the PhC, implying the transmission through the bus waveguide is increased instead. In this way, it can be seen that the stronger the photorefractive effect (green case), the larger the cavity shift, and the more light is transmitted through the bus waveguide. As shown in Fig. 1c, this setup can represent the linear part of a perceptron (non-linearity is not a yet addressed). In the following we will describe a simplified photorefractive model, the simulation approach in COMSOL, as well as preliminary results.

**Theory**

The photorefractive (simplified) mechanism is given in Fig 2. The diagram (bottom) shows the well-known (and thus not elaborated here) band diagram of the photorefractive mechanism in SI-GaAs. The diagram (top) shows the redistribution of electrons (blue dots) and ionized donors (green dots) in the PhC from the bright regions to the darker regions. To describe the photorefractive effect, the Kukhtarev model is typically used [7]. A simplified version of this model (without acceptors) is introduced in equations (1)-(4):

$$\frac{dN_D{}^+}{dt} = \left(\frac{s}{hf}I + \beta\right)(N_D - N_D{}^+) - \gamma n N_D{}^+, \qquad \frac{dn}{dt} = \frac{dN_D{}^+}{dt} + \nabla \cdot \vec{J} \tag{1,2}$$

$$\vec{J} = \frac{\mu k_B T}{e}\nabla n + \mu n \vec{E}, \qquad \nabla \cdot \vec{E} = \frac{e(N_D{}^+ - n)}{\varepsilon \varepsilon_0}, \tag{3,4}$$

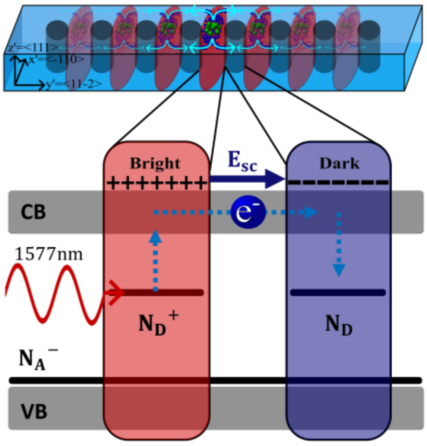
where $N_D{}^+$is the ionized donor concentration, $N_D$ the donor concentration, $n$ the electron concentration, $t$ is time, $s$ the photoionization constant, $h$ planck costant, $f$ the photon frequency, $I$ the optical intensity, $\beta$ the thermal generation rate, $\gamma$ the recombination rate, $\vec{J}$ the total current, $\mu$ the electron mobility, $k_B$ Boltzmann constant, $T$ the temperature, $e$ fundamental charge, $\vec{E}$ the space charge field, $\varepsilon_0$ the vacuum permittivity and $\varepsilon$ the permittivity of GaAs. This model neglects the acceptors, two photon absorption, holes and single photon dynamics among others for simplicity. Regarding the modified model without acceptors, it is derived from charge neutrality using the Fermi-Dirac distribution for ionized donors and Boltzmann approximation for electrons, expressed as follows:

$$N_{D,0}{}^+ = \frac{N_D}{1 + g_D exp\left(\frac{E_D - E_F}{k_B T}\right)} = n_0 = N_C exp\left(-\frac{E_C - E_F}{k_B T}\right), \tag{5}$$

where $N_{D,0}{}^+$and $n_0$ are the initial concentrations of ionized donor and electrons respectively, $g_D$ the degeneracy, $E_D$ the donor energy, $E_F$ the fermi energy, $E_C$ the conduction band energy, $N_C$ the effective density of states. Placing these expressions into equation 1, gives the new thermal generation coefficient:

$$\beta = \frac{N_{D,0}{}^+}{N_D}\gamma N_C \; exp\left(-\frac{E_C - E_F}{k_B T}\right). \tag{6}$$

This gives a value of $\beta$ = 0.746 $s^{-1}$. To obtain this expression, only the first time step is considered at t=0, and dark illumination is assumed as $I = 0$. Additionally, the Boltzmann approximation is used, since $N_D \gg N_{D,0}{}^+$ such that $N_D - N_D{}^+ \approx N_D$.




| Coefficient | Ionized donor PDE ($u = N_D^+$) | Electron PDE ($u = n$) | Electric Potential PDE ($u = V$) |
|---|---|---|---|
| $f$ | $\frac{sI(x,y,z,t)N_D}{hf} + \beta N_D$ | $\frac{\partial N_D^+}{\partial t}$ | $\frac{e(N_D^+ - n)}{\varepsilon\varepsilon_0}$ |
| $a$ | $\frac{sI(x,y,z,t)}{hf} + \gamma n + \beta$ | | |
| $d_a$ | 1 | 1 | |
| $c$ | | $\frac{\mu k_B T}{e}$ | $-1$ |
| $\alpha$ | | $\mu V_{x,y,z}$ | |

**Figure 2.** (left) Sketch of photorefractive effect in an air-suspended SI-GaAs PhC nanobeam at the top, and the band diagram of photorefractive effect in SI–GaAs at the bottom. **Table 1** (right) of coefficients of the coefficient form PDE used in equation 1,2,4 for the ionized donors, electrons and electric potential.

## Simulation approach

Next, the simulation framework using Finite Element Method (FEM) in COMSOL 6.2 is presented. First, the optical modes of the PhC nanobeam are simulated with the Eigenvalue solver (ARPACK). The PhC structure is adopted from literature and converted from Si to GaAs using scale invariance [8]. The solver gives an arbitrary electric field magnitude, which is normalized in order to apply to the correct intensity magnitude as

$$I(x,y,z,t) = I_{peak}\frac{E_x^2 + E_y^2 + E_z^2}{max(E_x^2 + E_y^2 + E_z^2)} exp\left(-\frac{t}{\tau_p}\right), \qquad (7)$$

where $I(x,y,z,t)$ is the intensity spatio-temporal distribution, $I_{peak}$ is the magnitude of maximum intensity. An important approximation is the decoupling of optical and carrier simulations. This is done by applying an exponential decay to the optical intensity according to the photon lifetime $\tau_p$ of the first optical mode of 628 ps, which corresponds to a Quality factor (Q factor) of $7.5 \cdot 10^5$. Now that the intensity is spatially and temporally known, the photorefractive model is implemented in COMSOL by redefining the Kukhtarev equations as a system of coupled Partial Differential Equations (PDEs), where each PDE represents an equation from the Kukhtarev model. The general coefficient form is given by

$$e_a\frac{\partial^2 u}{\partial t^2} + d_a\frac{\partial u}{\partial t} + \nabla \cdot (-c\,\nabla u - \alpha u + \gamma) + \beta \cdot u + au = f, \qquad (8)$$

where $u$ is a general variable which in this case represents either ionized donors, electrons $n$, or electric potential $V$ (potential addresses the space charge field via $\vec{E} = \nabla V$). The coefficients are given in table 1. To simulate transient dynamics, the time domain study is used after the eigenfrequency solver. This calculates the intensity, charge generation/movement, and space charge fields. A tolerance factor of $10^{-3}$ and 25 iterations were used, together with a nonlinear controller and a fully coupled system of equations. A direct solver (PARADISO) is used for simulation speed. To speed up the simulation further, four-fold symmetry is exploited by using Perfect Electric Conductor (PEC) and Perfect Magnetic Conductor (PMC) boundary conditions. Additionally, the zero flux boundary is added to the ionized donor and electron PDEs to control the flow of charges against the GaAs-air interfaces. Lastly, the Dirichlet boundary condition ($V = 0$) is implemented in the space charge field PDE at the air-PML interfaces to simulate open boundaries.

## Preliminary results and discussion

The orientation of the space charge field (DC electric field due to charges) and optical polarizations must be considered. Fig 3 a) and b) shows that both of these develop in plane, meaning they are parallel. This poses a major problem, as the traditionally used <001> crystal orientation has a weak Electro-Optic Pockels effect when they are non-orthogonal.

This could potentially explain why in the past, no works of photorefractive GaAs resonators have been realized. However, here we propose the use of a <111> crystal configuration, since this allows the Pockels effect to exist for parallel space charge field and polarizations. Lastly, due to limitations of the model without acceptors, the shared results are narrowed. Fig c), d), e) show the spatial distribution of ionized donors, electrons and electron current density. Fig b), shows the space charge field, where it can be seen that the shape is a direct consequence of the electron diffusion towards the dark regions of the PhC. This demonstrates the capability of the approach to solve complex temporal dynamics, and gives the first hint of the photorefractive mechanism in PhCs. To obtain the magnitude of the wavelength shift due to the photorefractive effect, perturbation theory is used by including all three polarizations and the full dielectric constant matrix change instead of only the scalar change (necessary due to anisotropic Pockels effect in <111>). This gives a preliminary tuning efficiency of 6.3 fm/photon with an approximate maximum shift of 300 fm. Note that these results are possibly worse due to the simplifications of the model mentioned previously.

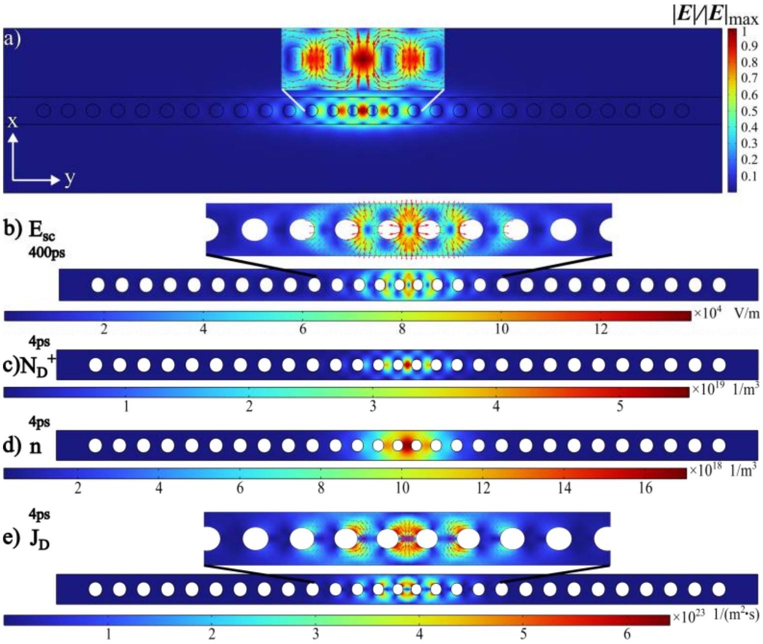



**Figure 3.** 2D spatial distributions in the PhC nanobeam. a) The normalized optical polarizations of the 1st order mode is shown with the normalized electric field in the x-y plane at a wavelength of $\lambda = 1577\ nm$. The inset shows the vectorial plot of the electric field components $E_x$ and $E_y$. b) The magnitude of the space charge field at 400ps (inset shows a zoom-in with the arrows indicating the direction of the space charge field). c), d) spatial distribution of ionized donor and electrons at 4 ps respectively. e) Spatial distribution of electron diffusion current density at 4 ps (inset shows arrows indicating direction of current).

## Conclusions

The present work shows a new photonic computing architecture using photorefractive PhC nanobeams. Also, a simple approach to perform transient photorefractive FEM simulations in complex structures such as a PhC nanobeam is shown. A (simplified) model is recasted to a coupled system of PDEs, where optical and carrier simulations are decoupled. The preliminary simulation results show an in-plane space charge field. This suggests that a <001> crystal orientation has a weak Pockels effect, and hence a <111> orientation is suggested in this work. This gives a preliminary tuning efficiency of 6.3 fm/photon with an approximate maximum shift of 300 fm.


**Acknowledgments**

The authors would like to thank Prof. Dr. Andrea Fiore for his contributions in the conceptualization of the device physics.


**References**


[1]. H. An, M. A. Ehsan, Z. Zhou, and Y. Yi, "Electrical modeling and analysis of 3D synaptic array using vertical RRAM structure," in Proc. 18th Int. Symp. Quality Electronic Design (ISQED), Mar. 2017, pp. 1-6.

[2]. B. J. Shastri, A. N. Tait, T. F. de Lima, W. H. P. Pernice, H. Bhaskaran, C. D. Wright, and P. R. Prucnal, "Photonics for artificial intelligence and neuromorphic computing," Nature Photonics, vol. 15, no. 2, pp. 102–114, 2021.

[3]. E. A. Vlieg, L. Talandier, R. Dangel, F. Horst, and B. J. Offrein, "An Integrated Photorefractive Analog Matrix-Vector Multiplier for Machine Learning," Applied Sciences 2022, Vol. 12, Page 4226, vol. 12, no. 9, p. 4226, 4 2022.

[4]. Y. He, R. Luo, H. Liang, Q. Lin, and H. Jiang, "High-quality lithium niobate photonic crystal nanocavities," Optica, Vol. 4, Issue 10, pp. 1251-1258, vol. 4, no. 10, pp. 1251–1258, 10 2017

[5]. M. Li, H. Liang, R. Luo, Y. He, and Q. Lin, "High-Q 2D Lithium Niobate Photonic Crystal Slab Nanoresonators," Laser & Photonics Reviews, vol. 13, no. 5, p. 1800228, 5 2019.

[6]. J. Hou, J. Zhu, R. Ma, B. Xue, Y. Zhu, J. Lin, X. Jiang, X. Chen, Y. Cheng, L. Ge, Y. Zheng, and W. Wan, "Subwavelength Photorefractive Grating in a Thin-Film Lithium Niobate Microcavity," Laser & Photonics Reviews, p. 2301351, 2024

[7]. A. L. Smirl, G. C. Valley, K. M. Bohnert, and T. F. Boggess, "Picosecond photorefractive and free-carrier transient energy transfer in GaAs at 1 µm," IEEE J. Quantum Electron., vol. 24, no. 2, pp. 289-303, Feb. 1988.

[8]. P. B. Deotare, M. W. McCutcheon, I. W. Frank, M. Khan, and M. Lončar, "High quality factor photonic crystal nanobeam cavities," Applied Physics Letters, vol. 94, no. 12, p. 121106, 3 2009.