Fully All-optical Multi-input Logic Gates Based on Bandgap Solitons in Guiding Photonic Crystal Nanostructures

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Abstract— Photonic crystals (PhCs) are multilayered periodic structures in which electromagnetic wave propagation is forbidden within a large frequency range (so-called photonic band-gap) [1]. A photonic crystal waveguide (PCW) is formed by introducing a defect into the original PhC by removing one or several rows. As a result, electromagnetic waves whose frequency lies in the photonic band-gap are confined and guided along the defect channel. If two or three PCWs are placed in close proximity, a coupled PCW is formed and the optical power is transferred from one PCW to another.

Nonlinear PhCs are promising candidates to enable dense full-optical signal processing on the same chip. In optically nonlinear media, the refractive index is modified by the light signal and it can be exploited to influence another light signal that passes the same medium, hence performing an all-optical signal processing operation. All-optical logic gates, which fulfill various logical operations in all-optical circuits, have received much attention for their application in ultrafast optical signal processing, e.g., for future optical computing systems. In this regard, we propose a novel working scheme to realize all-optical multi-input — cascade system — of logic gates in nonlinear PCWs. The proposed topology is advantageous due to the travelling-wave nature of the bandgap transmission [2]. It demonstrates a realistic pulse operation in the time domain that conforms very well to digital signal processing [3]. The optical signal pulses — i.e., the temporal solitons — maintain a stable pulse envelope while propagating along different logic gates. Note that an idea of bandgap transmission was already successfully applied within earlier conceptual studies, where we proposed an alloptical amplification effect in coupled pillar-type PCWs [4].

Formation of the bandgap solitons in coupled PCWs composed of a realistic planar air-hole type PhC with a nonlinear silicon background material is investigated together with the working concept of functional true all-optical NOT, AND and NAND logic gates. Since all logical operations can be performed using logical combinations of NOT, AND and NAND gates, future optical communication networks will require integrated all-optical logic gates with NOT, AND and NAND gates. Key to the realization of the proposed all-optical functional logic gates is the perfect "digitalization" in the process of bandgap transmission. Dispersion diagrams of the modes for the coupled PCWs are accurately calculated using our original, recently developed, numerically very fast full-wave modal analysis [5] to support a proper choice of the operation frequency that enables the bandgap transmission. Extensive theoretical and full-wave computational procedure demonstrates the efficiency and usefulness of the proposed operation principle.

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1. Yasumoto, K., ed., *Electromagnetic Theory and Applications for Photonic Crystals*, CRC Press, Boca Raton, FL, 2005.
2. Khomeriki, R., "Nonlinear bandgap transmission in optical waveguide arrays," *Phys. Rev. Lett.*, Vol. 92, 063905–063908, 2004.
3. Jandieri, V., R. Khomeriki, and D. Erni, "Realization of true all-optical AND logic gate based on the nonlinear coupled airhole type photonic crystal waveguide," *Optics Express*, Vol. 26, No. 16, 19845–19853, 2018.
4. Jandieri, V., R. Khomeriki, D. Erni, and W. C. Chew, "Realization of all-optical digital amplification in coupled nonlinear photonic crystal waveguides," *Progress In Electromagnetics Research*, Vol. 158, 63–72, 2017.
5. Jandieri, V., P. Baccarelli, G. Valerio, and G. Schettini, "1-D periodic lattice sums for complex and leaky waves in 2-D structures using higher-order Ewald formulation," *IEEE Transactions on Antennas and Propagation*, in press.

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Introduction

- Novelty of the Work.
- Photonic Crystals and Photonic Crystal Waveguides.
- Formulation of the Problem.
- Realization of All-Optical Logic Gates.
- Numerical Results and Discussions.

Novelty of the Work

- All-optical logic gates, which are responsible for various logical operations in all-optical circuits, play a key role in ultrafast optical signal processing.

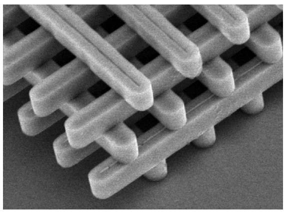
- **We, actually for the first time, demonstrate the realization of true all-optical NOT, AND and NAND logic gates using bandgap solitons in photonic crystal waveguides composed of an experimentally feasible planar air-hole type hexagonal structure.**

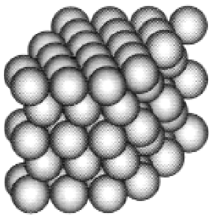
- **A key element in the working concept of the proposed all-optical logic gates is the virtually "perfect digitalization" of the involved time-domain signals inherent to the process of bandgap transmission.**

- All investigated gate topologies operate with temporal bandgap solitons having stable pulse envelopes during signal processing, which is considered as one of the main advantages of the proposed working concept of the device.

- In the proposed setup, there is no need to amplify the output signal after each logial operation, and can be directly use it as a new input signal for another logical operation.

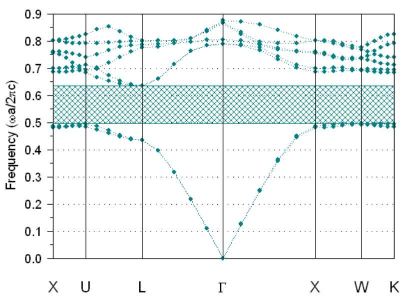
Photonic Crystals and Photonic Crystal Waveguides (1)





Unique feature to localize electromagnetic waves to specific arrays and to guide along certain directions at restricted frequencies.

1. K. Yasumoto, H. Toyama and T. Kushta, *IEEE Transaction on Antennas and Propagation*, vol.52, pp. 2603-2611, 2004.
2. K. Yasumoto, V. Jandieri and Y. Liu, *JOSA A*, vol.30, no.1, pp. 96-101, 2013.
3. V. Jandieri, K. Yasumoto and J. Pistora, *JOSA A*, vol.31, no.3, pp. 518-523, 2014.
4. P. Baccarelli, V. Jandieri, G. Valerio, and G. Schettini, EuCAP 2017, Paris, France, 19-24/03/2017, pp. 3222-3223.
5. V. Jandieri, P. Baccarelli, G. Valerio and G. Schettini, *IEEE Transaction on Antennas and Propagation*, vol. 67, no. 4, 2019.



Modal field is represented as a superposition of an *infinite* number of space harmonics

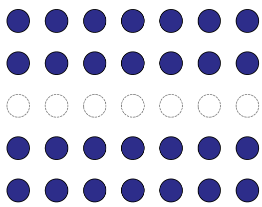
$$k_{xn} = \beta_n + i\alpha, \quad n = 0, \pm 1, \pm 2, ..$$

$$\beta_n = \beta_0 + \frac{2\pi n}{h}$$

Space-harmonic phase constant

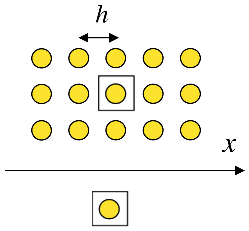
Modal attenuation (leakage) constant

Photonic Crystal Waveguide

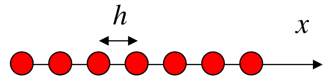


Photonic Crystals and Photonic Crystal Waveguides (2)

2D Electromagnetic-Band-Gap (EBG) Structure

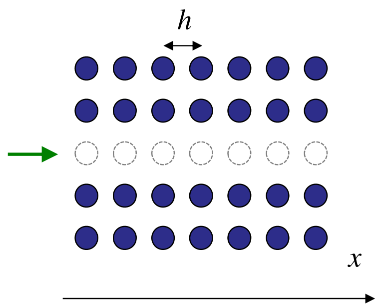


Periodic chain



Modal analysis of 2D periodic dielectric or metallic structures composed by *cylindrical inclusions* in a hosting dielectric medium

Planar 2D waveguide structure



The modal field is represented as a superposition of an *infinite* number of space harmonics

Space-harmonic complex wavenumber

$$k_{xn} = \beta_n + i\alpha, \quad n = 0, \pm 1, \pm 2, ..$$

Goal: Derivation of the complex wavenumbers for *bound* modes in their stop-band regimes and *leaky* modes in their physical and non-physical regions

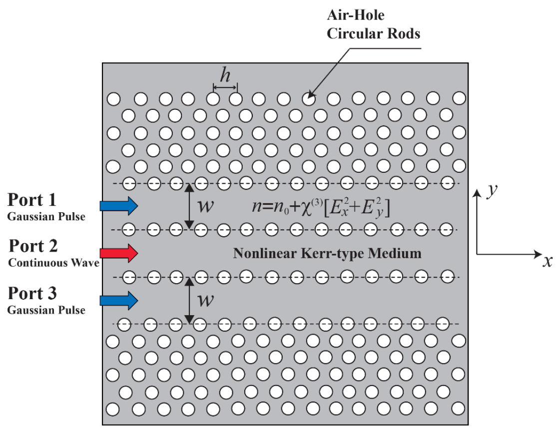
$$\beta_n = \beta_0 + \frac{2\pi n}{h}$$

Space-harmonic phase constant

Modal attenuation (leakage) constant

V. Jandieri, P. Baccarelli, G. Valerio and G. Schettini, *IEEE Transaction on Antennas and Propagation*, vol. 67, no. 4, 2019.

Formulation of the Problem (1)



For the realization of true all-optical signal processing, the optical system needs to have ***nonlinear properties***.

In optically nonlinear media, the index of refraction is modified by the presence of a light signal and this modification can be exploited to influence another light signal, thereby performing an all-optical signal processing operation.

Nonlinear Photonic Crystals (PCs) are one of the most promising candidates to enable dense full-optical signal processing *on the same chip* leading to much lower production and operating costs.

V. Jandieri, R. Khomeriki and D. Erni, "Realization of True All-Optical AND Logic Gate based on the Nonlinear Coupled Air-hole Type Photonic Crystal Waveguide," *Optics Express* , vol. 26, no. 16, 2018.

$n_0 = 2.95$ (linear refractive index)

$r = 0.32h$ (radius of the rods)

$w = 1.73h$ (width of the waveguide)

Bandgap for H-modes (H_z, E_x, E_y). Air-Hole type PhCs. Length of the device is 30*h*.

Typical semiconductor material (*Si*, *GaAs*, *InP*) with relative high refractive index is studied.

For practical application would be better to use modified material systems with enhanced third order nonlinearities based on amorphous *Si*, or hybrid organic-*Si*-on-insulator compounds [1]:

[1] J. Leuthold, C. Koos, W. Freude, 'Nonlinear silicon photonics,' Nature Photonics, 4, 535, 2010.

Formulation of the Problem (2)

Using the "multiple-scale" analysis, Maxwell equations are reduced to the nonlinear Schrödinger equation for the slowly-varying wave amplitude:

$$2i\frac{\partial F_{S,A}}{\partial t}+\frac{\partial^2 \omega_{S,A}}{\partial k_{x0}^2}\frac{\partial^2 F_{S,A}}{\partial \xi^2}+\gamma F_{S,A}\left|F_{S,A}\right|^2=0$$

which has a soliton solution: Amplitude of soliton.

$$F_{S,A}(z,t)=\frac{F_{S,A}^0 \exp(i\delta\omega_{S,A}t)}{\cosh\left[\left(z-v_{S,A}t\right)/\Lambda_{S,A}\right]}$$

Width of soliton.

$$\Lambda_{S,A}=\frac{1}{F_{S,A}^0}\sqrt{\frac{2\omega''_{S,A}}{\gamma}},$$

Nonlinear coefficient proportional to optical susceptibility $\chi^{(3)}$.

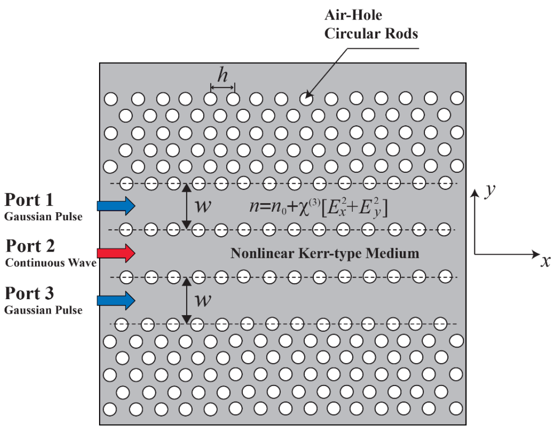
Group velocity of soliton.

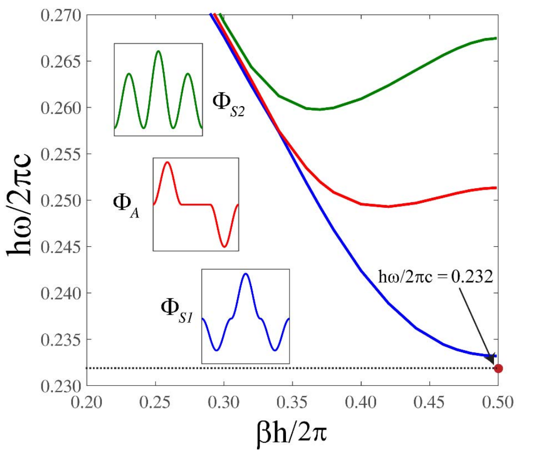
$$\delta\omega_{S,A}=\frac{1}{4}\gamma\left(F_{S,A}^0\right)^2$$

Frequency shift due to Kerr type Nonlinearity.

V. Jandieri, R. Khomeriki and D. Erni, "Realization of True All-Optical AND Logic Gate based on the Nonlinear Coupled Air-hole Type Photonic Crystal Waveguide," *Optics Express* , vol. 26, no. 16, 2018.

Realization of All-Optical Logic Gates (1)





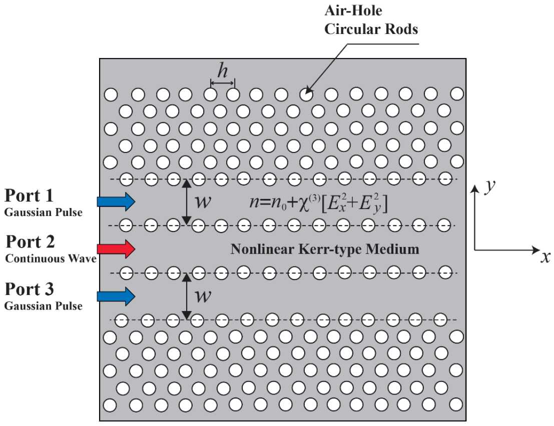
n_0 = 2.95 (linear refractive index)
r = 0.32h (radius of the rods)
w = 1.73h (width of the waveguide)

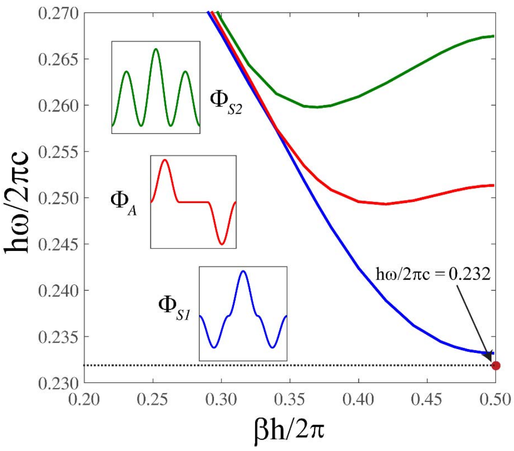
Bandgap for H-modes (H_z, E_x, E_y). Air-Hole type PCs. Length of the device is 30h.

[1] K. Yasumoto, V. Jandieri and Y. Liu, *JOSA A*, vol.30, pp. 96-101, 2013.
[2] V. Jandieri, K. Yasumoto and J. Pistora, *JOSA A*, vol.31, pp. 518-523, 2014.
[3] V. Jandieri, P. Baccarelli, G. Valerio and G. Schettini, *IEEE Transaction on Antennas and Propagation*, vol. 67, no. 4, 2019.

To realize Bandgap Transmission - gap soliton propagation - an excitation frequency of the injected signal should be properly chosen very close to band edge (red dot in the dispersion diagram). In the linear regime no propagation (all the modes evanescent).

Realization of All-Optical Logic Gates (2)





n_0 = 2.95 (linear refractive index)

r = 0.32h (radius of the rods)

w = 1.73h (width of the waveguide)

Bandgap for H-modes (H_z, E_x, E_y). Air-Hole type PCs.
Length of the device is 30h.

$$\omega(\beta) = \omega_{S1}(\beta) - \gamma\left(F_{S1}^0\right)^2/4$$

Frequency shift due to the Kerr effect.

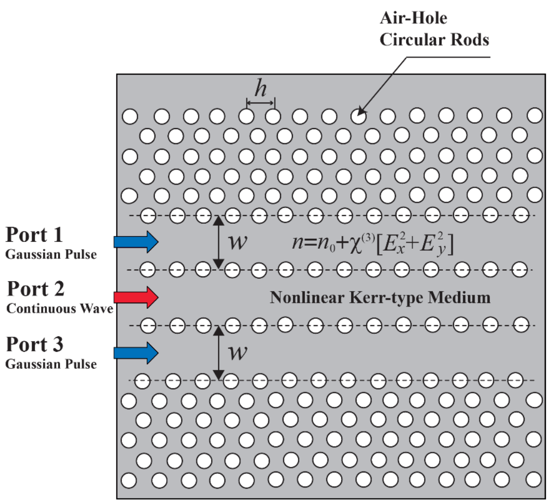
$$H_z^{S1} = \Phi_{S1}(x,y)\frac{F_{S1}^0 \exp[i(\beta_{S1}x - \omega t)]}{\cosh\left[F_{S1}^0 (x - v_{S1}t)\sqrt{\gamma/2\omega''}\right]}$$

Propagating Symmetric.

$$H_z^A = \Phi_A(x,y) F_A^0 \exp(-i\omega t - |\beta_A| x)$$

Evanescent Anti-Symmetric.

Numerical Results and Discussions (1)



The efficiency of the proposed logic gates as well as their scalability is demonstrated using our original rigorous analysis together with full-wave computational electromagnetics.

For numerical analysis, we use FDTD method.

The numerical grid has a spatial resolution of 18 cells per wavelength.

The Courant number for temporal resolution is chosen as 0.95.

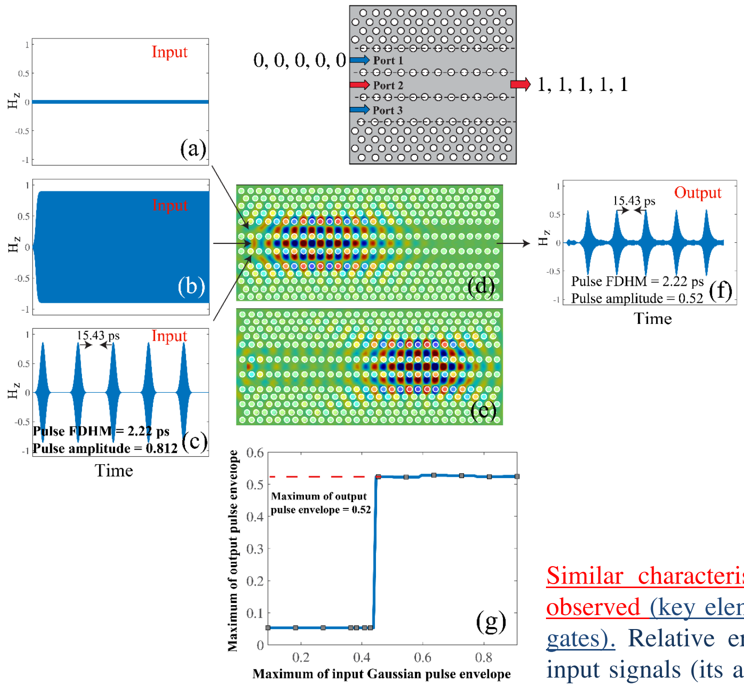
As an absorbing boundary condition we use U-PML.

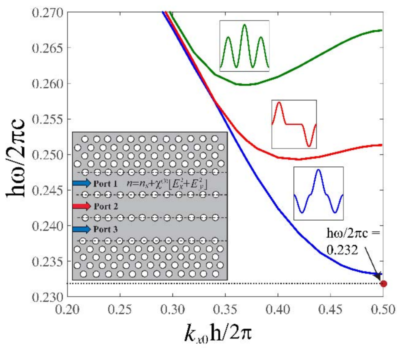
To represent the cylinders more accurately, we use the 2xGrid smoothing.

The simulation is created in MatLab™ and run on an intel-i7™ PC with 8.00 GB RAM.

Numerical Results and Discussions (2)

Realization of fully optical NOT logic gate





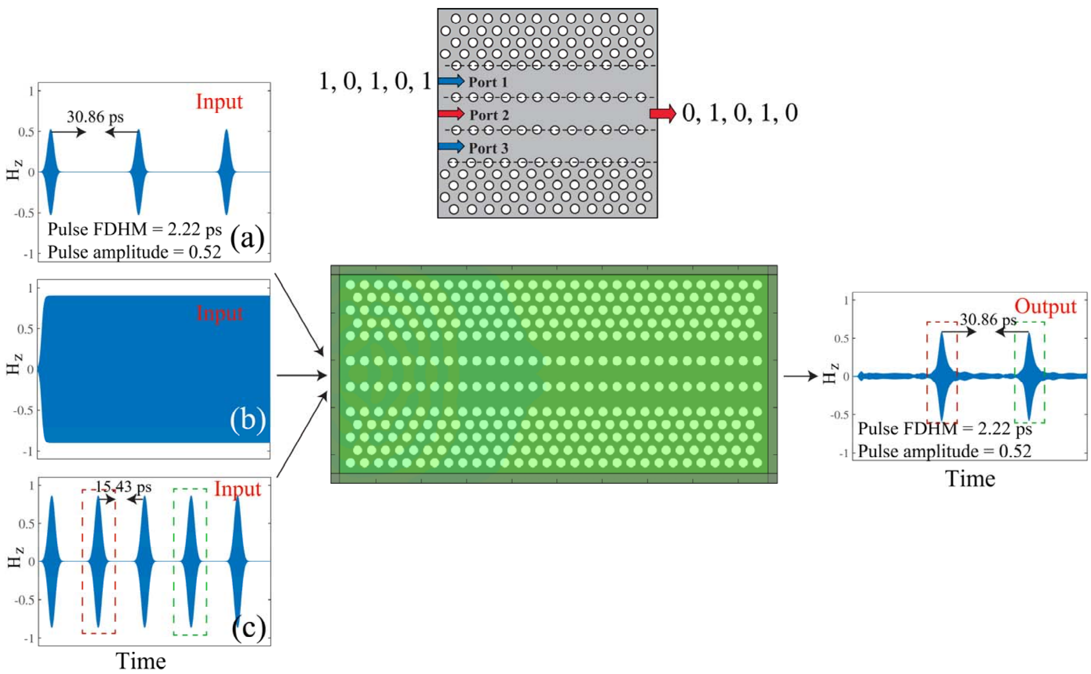
[1] V. Jandieri, R. Khomeriki and D. Erni, *Optics Express* , vol. 26, no. 16, 2018.

[2] V. Jandieri, T. Onoprishvili, R. Khomeriki, D. Erni and J. Pistora, *Optical and Quantum Electronics*, *Topical Collection on Optical Waveguide Theory and Numerical Modelling*, vol. 51, no. 4. paper no. 121, pp, 1-15, April, 2019.

Similar characteristics between I/O has been observed (key element for true all-optical logic gates). Relative error between the output and input signals (its amplitude and width) is about 7 % - 9 %.

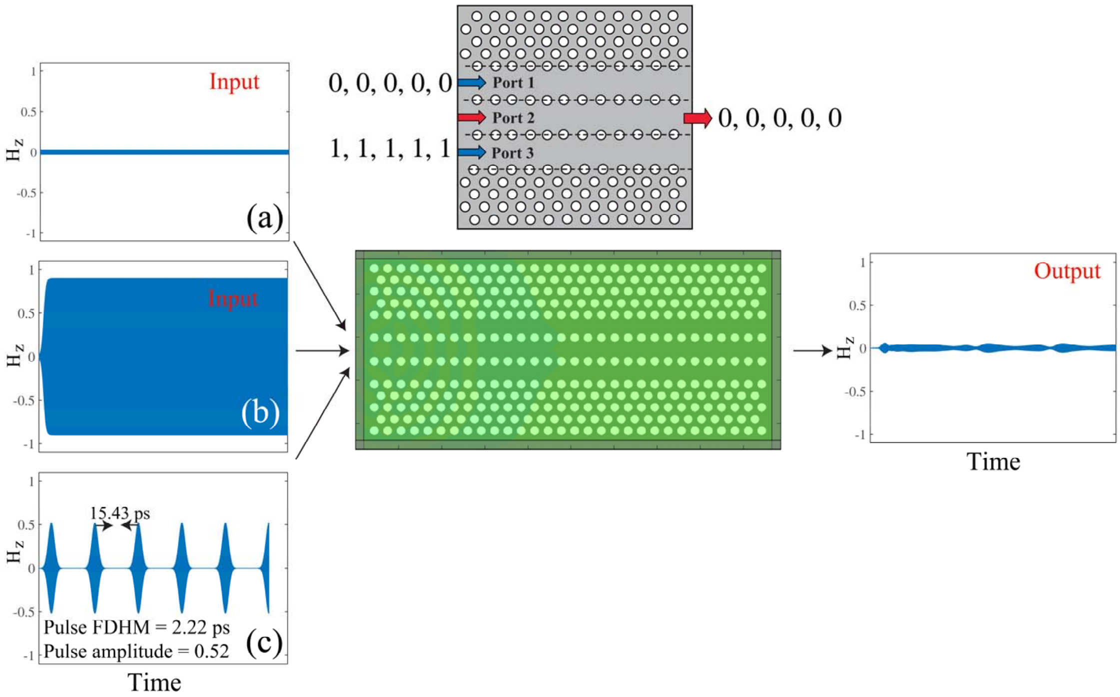
Numerical Results and Discussions (3)

Realization of fully optical NOT logic gate



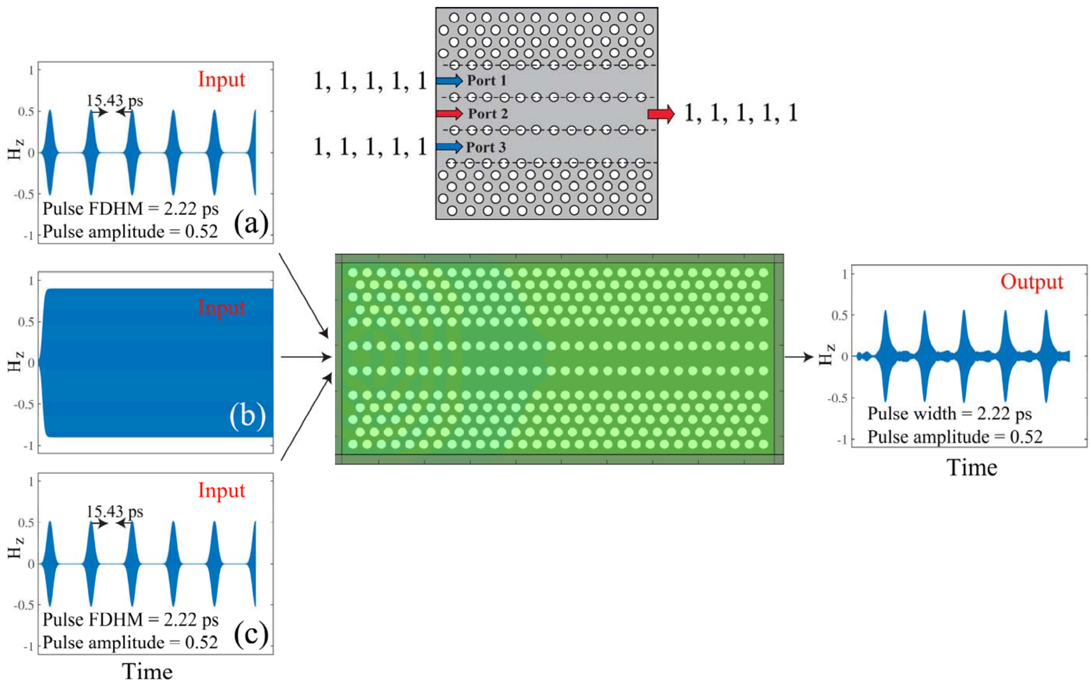
Numerical Results and Discussions (4)

Realization of fully optical AND logic gate



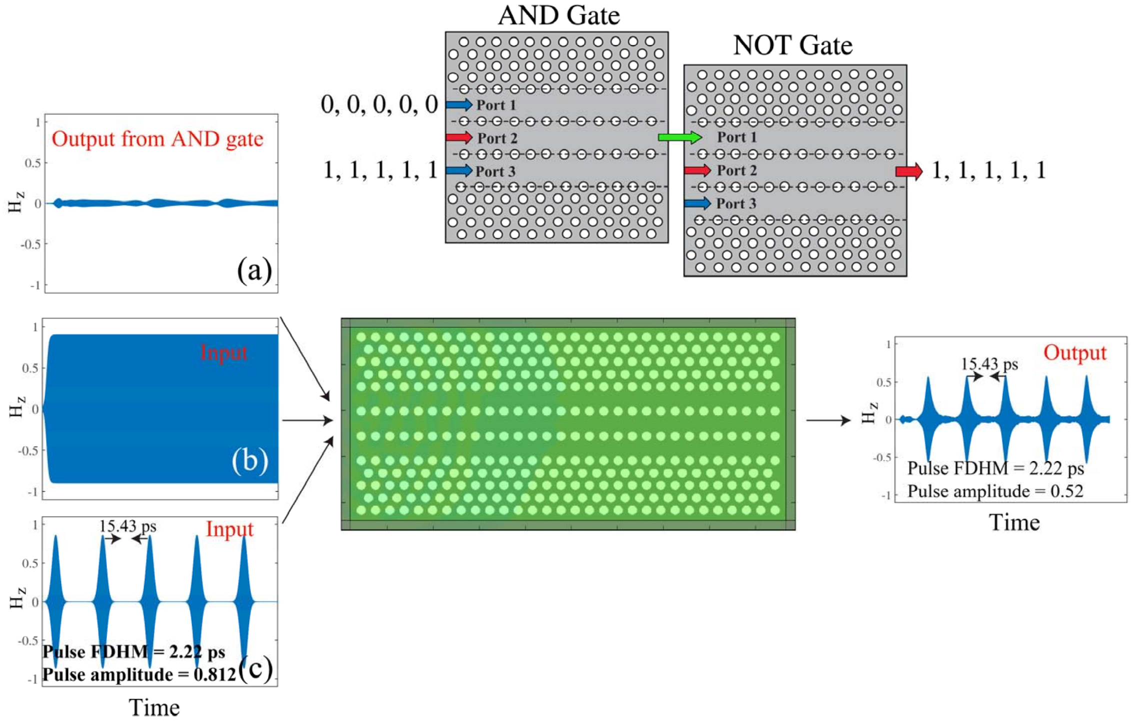
Numerical Results and Discussions (5)

Realization of fully optical AND logic gate



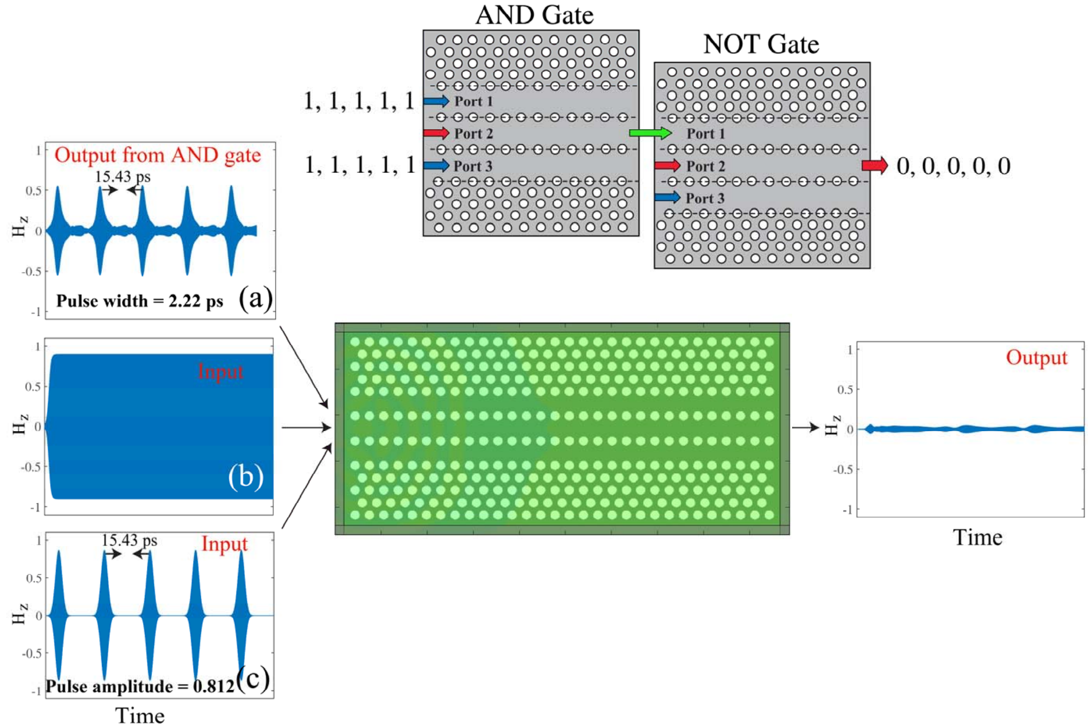
Numerical Results and Discussions (6)

Realization of fully optical NAND logic gate



Numerical Results and Discussions (7)

Realization of fully optical NAND logic gate



Thank You!

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