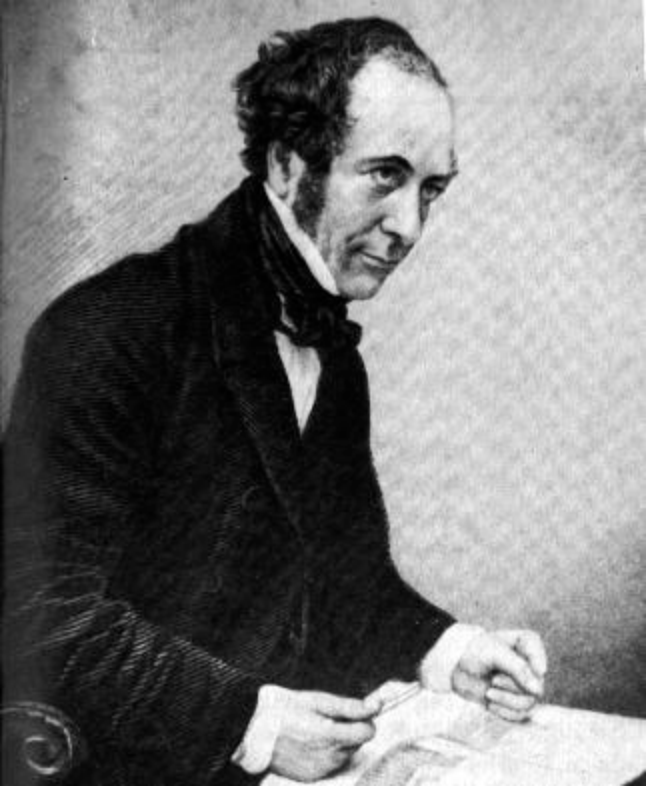
Tbilisi State University

All-optical Logic Gate Signal Processing in Photonic Crystals with Bandgap Solitons

Ramaz Khomeriki



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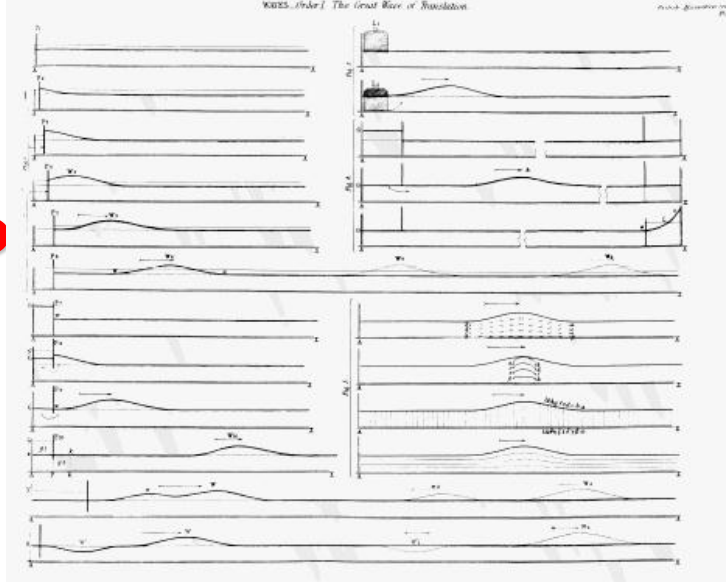

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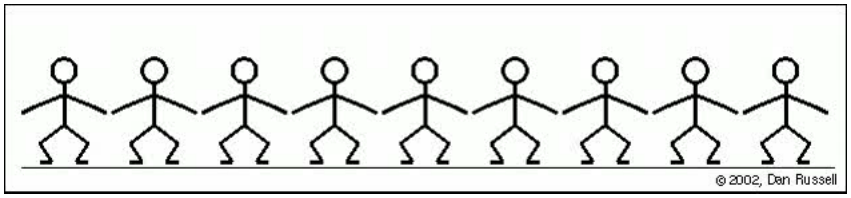
Solitons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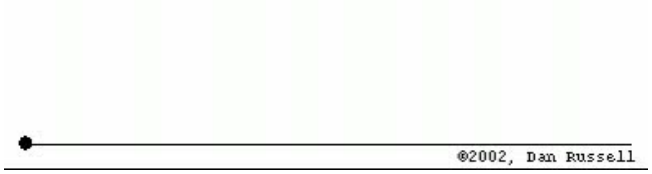
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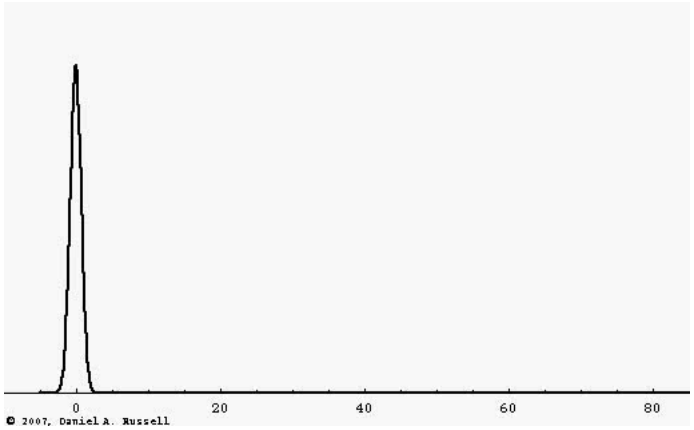
0
20
40
60
80
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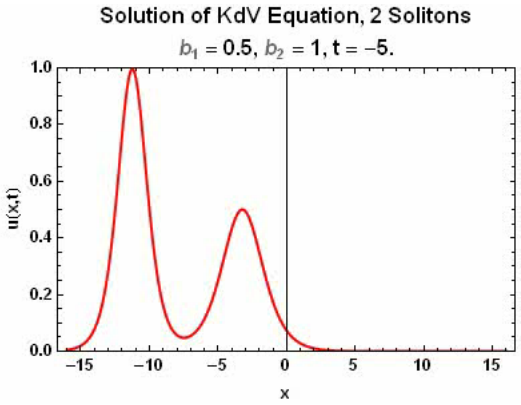
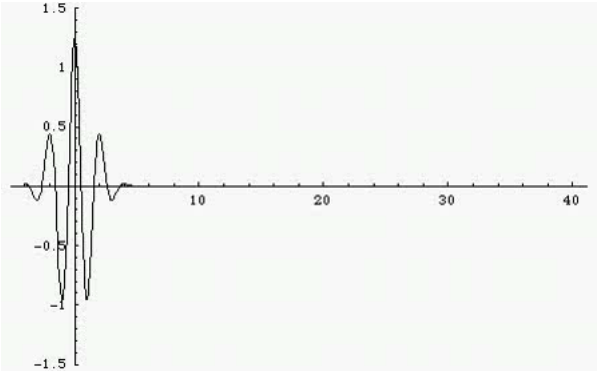
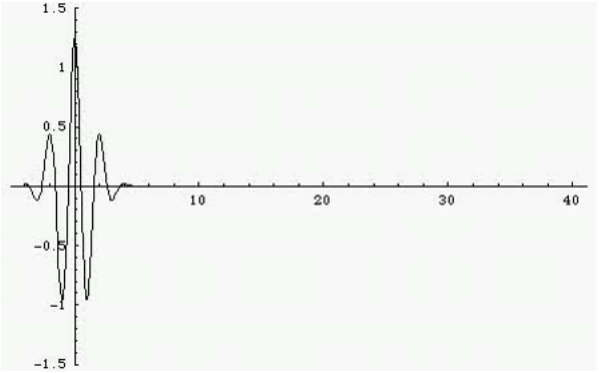
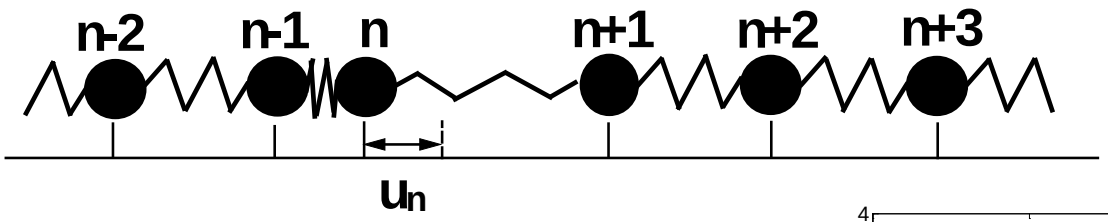

Solution of KdV Equation, 2 Solitons
$b_1 = 0.5, b_2 = 1, t = -5.$
u(x,t)
x
1.0
0.8
0.6
0.4
0.2
0.0
−15
−10
−5
0
5
10
15


1.5
1
0.5
−0.5
−1
−1.5
10
20
30
40


1.5
1
0.5
−0.5
−1
−1.5
10
20
30
40

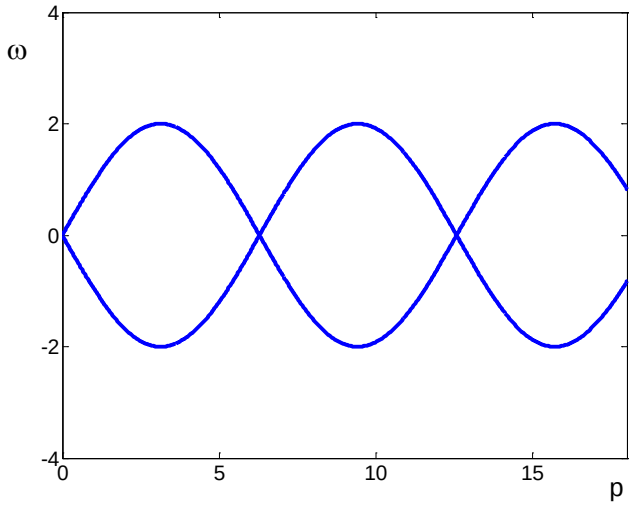
Anharmonic Lattices.



β–FPU

$$V = \sum_n \frac{1}{2}(u_n - u_{n-1})^2 + \frac{1}{4}(u_n - u_{n-1})^4$$

$$\ddot{u}_n = u_{n+1} + u_{n-1} - 2u_n + (u_{n+1} - u_n)^3$$



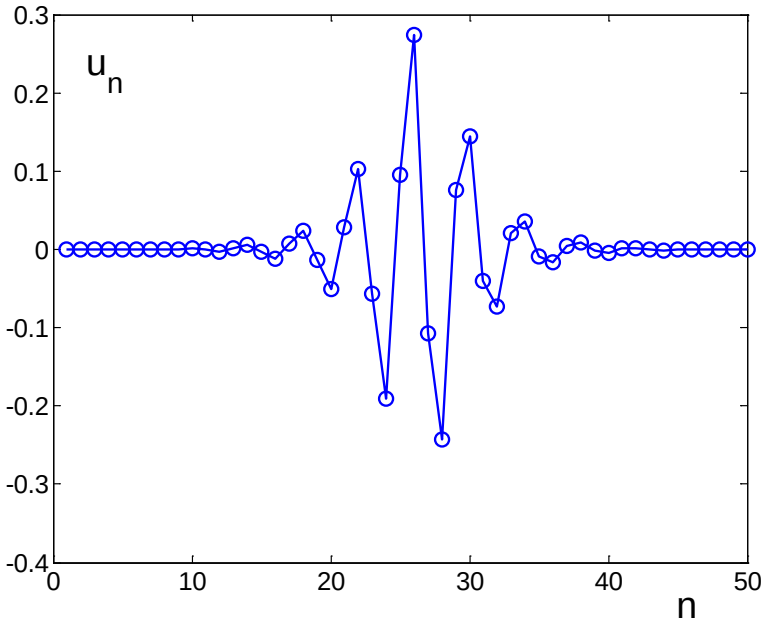
Nonlinear Extended waves: $u_n = A\cos(kn - \omega t)$

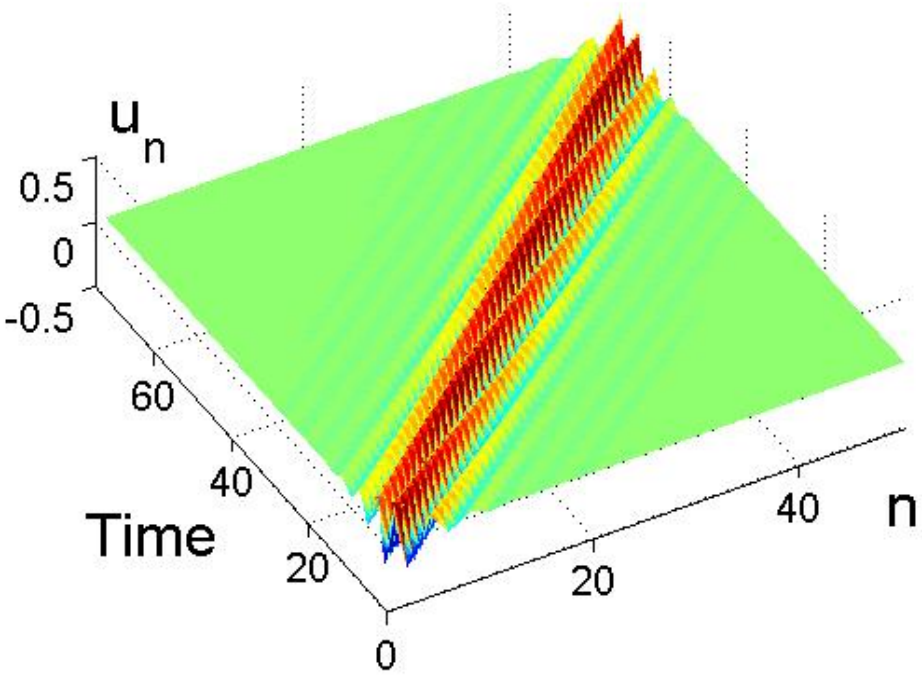
$$\omega^2 = 2(1\text{-}\cos k) + 3(1\text{-}\cos k)^2 A^2$$

Harmonic Band $\omega_B^2 = 2(1\text{-}\cos k) \quad 0 < \omega_B < 2$

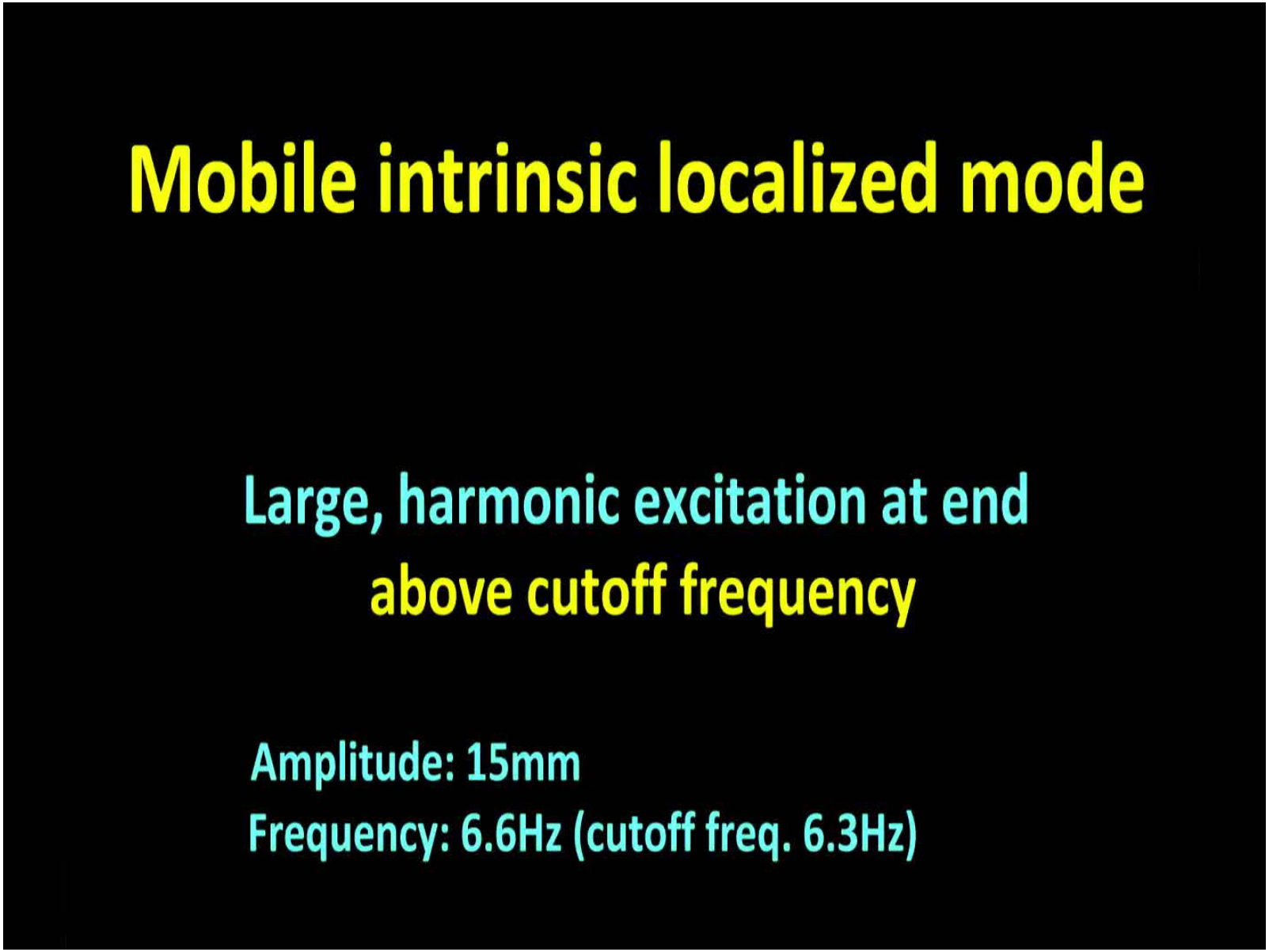
Out of Band driving $u_0 = A_0\cos(\omega_0 t); \quad \omega_0 > 2$

$$u_n = A\cos\left[\omega t - pn + A^2\,\frac{3\omega^3}{16}t\right] \Big/ \cosh\left[A\omega\sqrt{\frac{3}{2}}(n - \mathrm{v}t)\right]$$

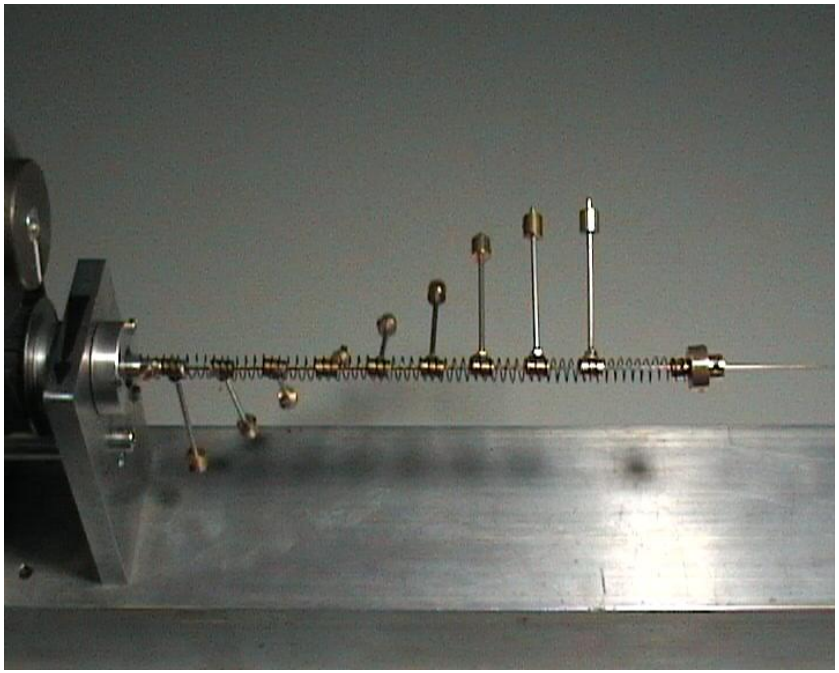


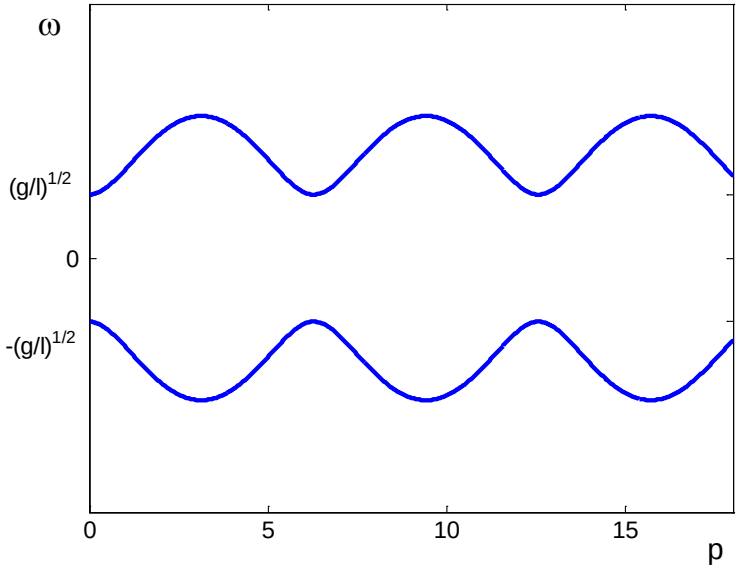


YosukeWatanabe, et.al. Phys. Lett. A, 382, 1957 (2018)



Pendula Chain

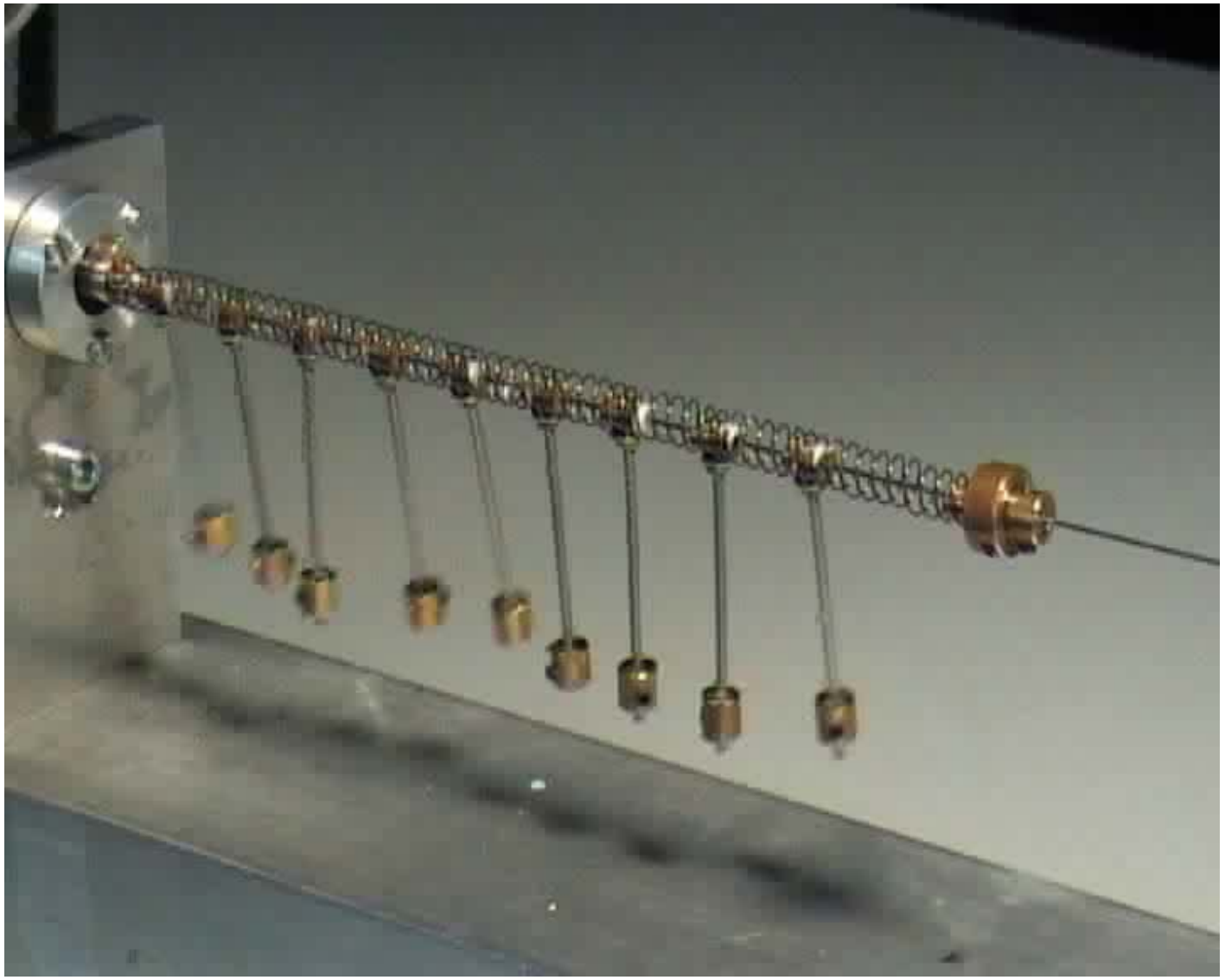




$$l^2 \frac{d^2\alpha_n}{dt^2} = k(\alpha_{n+1} - \alpha_n) + k(\alpha_{n-1} - \alpha_n) - gl\sin(\alpha_n)$$

$$\omega^2 = 2(k/l^2)(1-\cos p) + (g/l)$$

Short Pendula Chain Harmonically Driven by One end There is a Free end Pendulum at the Other Side

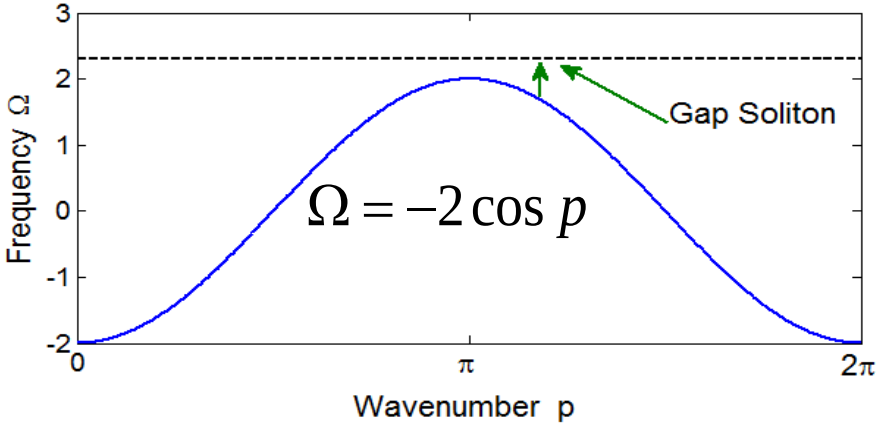


Discrete Boundary Driven Nonlinear Schroedinger Equation

R. Khomeriki, Phys. Rev. Lett. 92, 063905 (2004)

$$i\frac{\partial \psi_n}{\partial t} + \psi_{n+1} + \psi_{n-1} - |\psi_n|^2 \psi_n = 0$$

$$\psi_0 = \exp\left[-i\omega t\right]$$

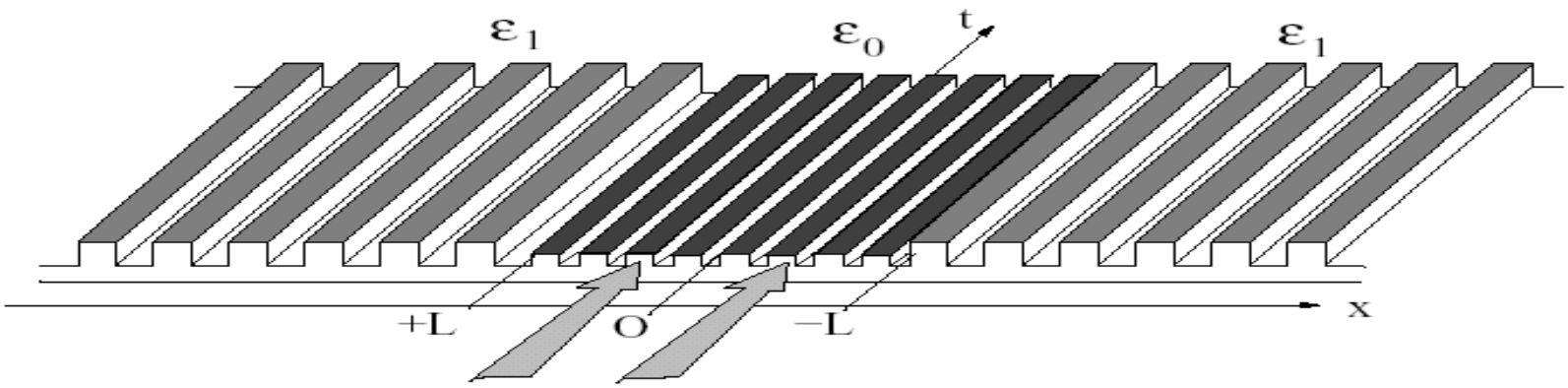


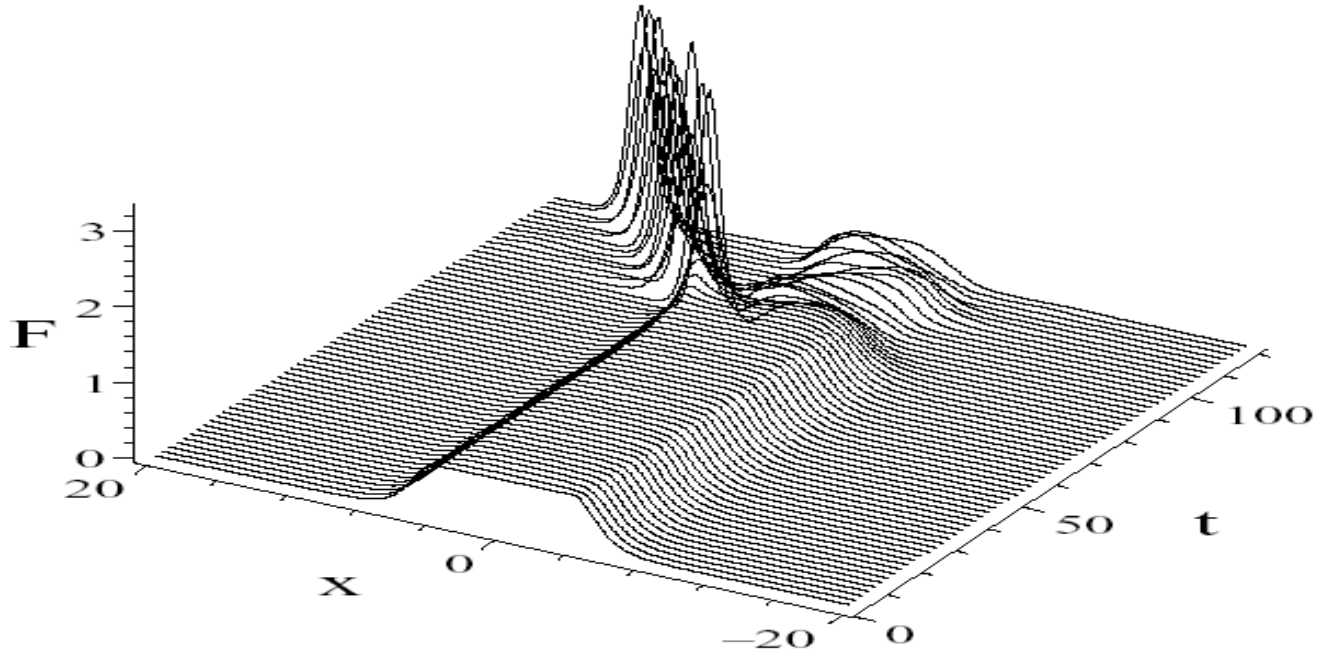
$$\Psi_n = A\frac{\exp\left[-i(\Omega+\delta\Omega)t + ipn\right]}{\cosh\left[(n-\mathrm{v}t)/\Lambda\right]} \qquad \mathrm{v} = \frac{\partial\Omega}{\partial p}, \quad \delta\Omega = \frac{1}{2}A^2,$$

$$\Lambda_j = \frac{1}{A}\sqrt{2\Omega''}, \qquad \Omega'' = \frac{\partial^2\Omega}{\partial p^2}$$

$$\omega = -2\cos p + \frac{A^2}{2} \quad \Rightarrow \quad A_{th}^2 = 2(\omega - 2)$$

Optical Supratransmission (Jerome Leon)





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.

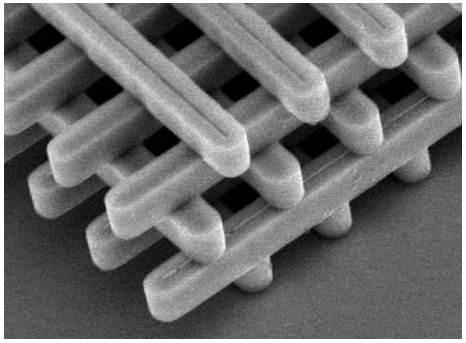
- **We, actually for the first time, demonstrate the realization of true all-optical NOT, AND and NAND logic gates using bandgap solitons in photonic crystal waveguides composed of an experimentally feasible planar air-hole type hexagonal structure.**

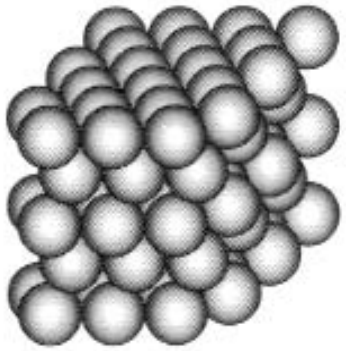
- **A key element in the working concept of the proposed all-optical logic gates is the virtually "perfect digitalization" of the involved time-domain signals inherent to the process of bandgap transmission.**

- 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





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

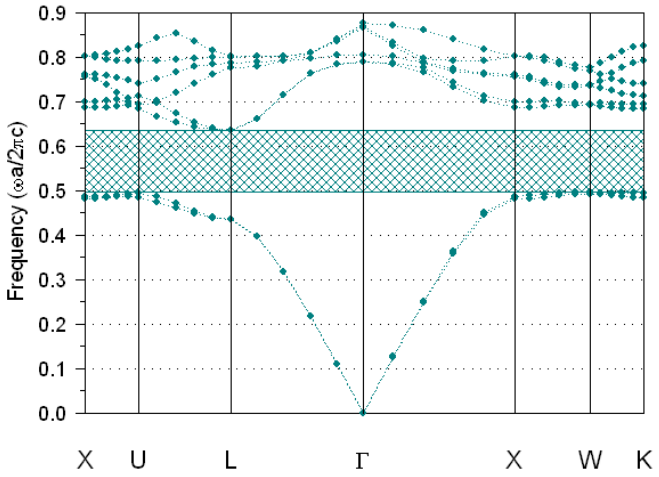
1. K. Yasumoto, H. Toyama and T. Kushta, *IEEE Transaction on Antennas and Propagation*, vol.52, pp. 2603-2611, 2004.

2. K. Yasumoto, V. Jandieri and Y. Liu, *JOSA A*, vol.30, no.1, pp. 96-101, 2013.

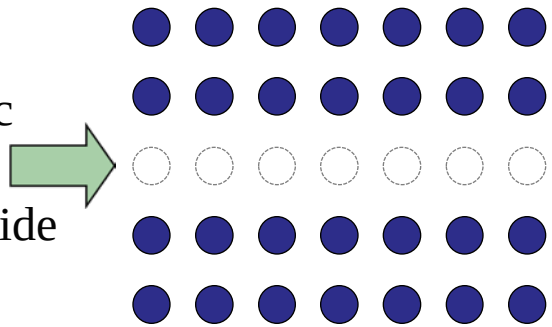
3. V. Jandieri, K. Yasumoto and J. Pistora, *JOSA A*, vol.31, no.3, pp. 518-523, 2014.

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.



Photonic Crystal Waveguide



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

Reduction to Nonlinear Schroedinger Equation

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 $\chi^{(3)}$.

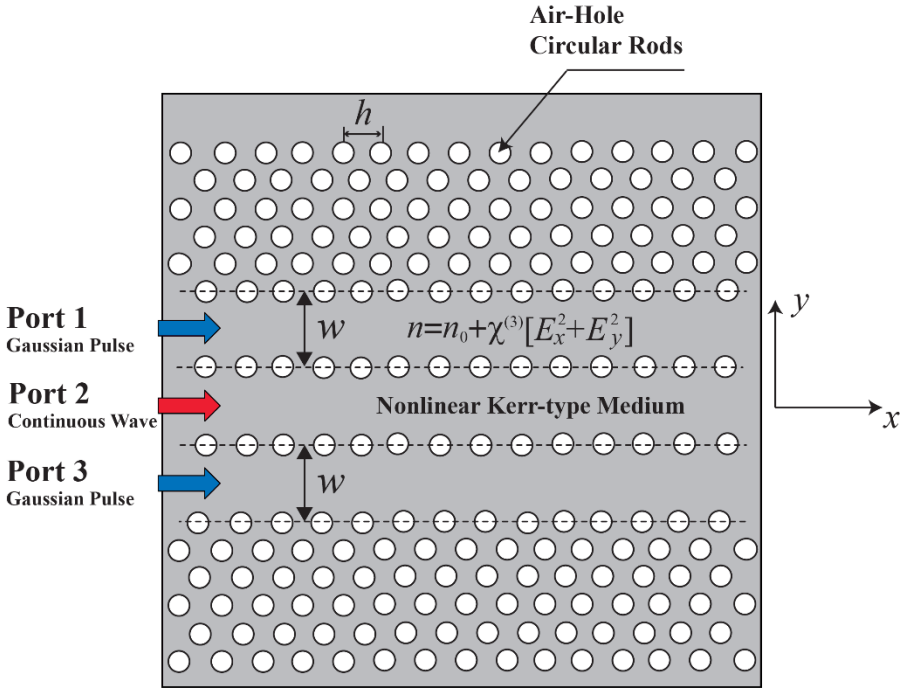
Group velocity of soliton.

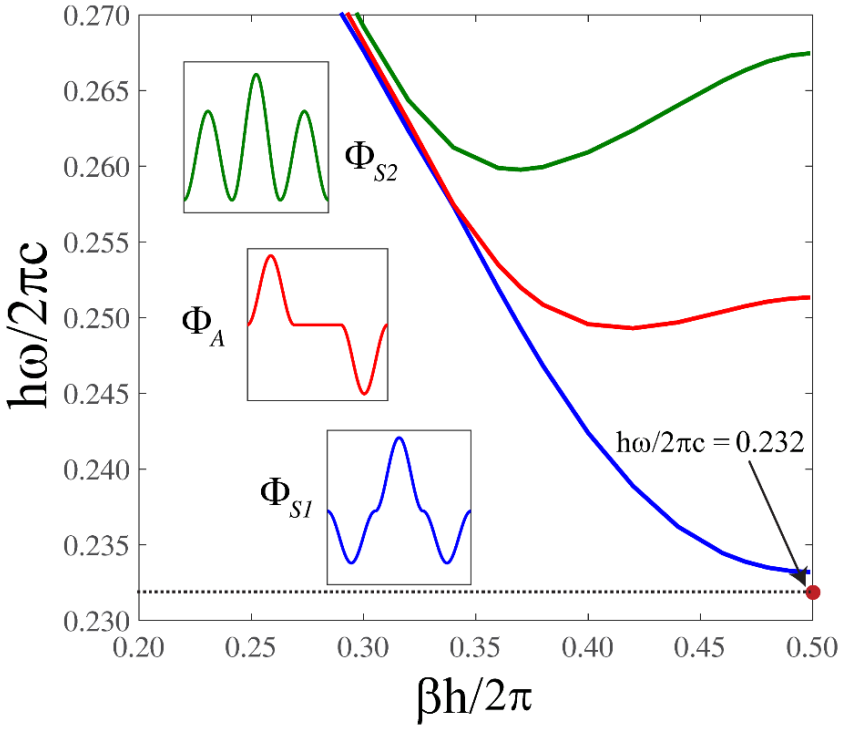
$$\delta\omega_{S,A}=\frac{1}{4}\gamma\left(F_{S,A}^0\right)^2$$

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 (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 30*h*.

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

Frequency shift due to the Kerr effect.

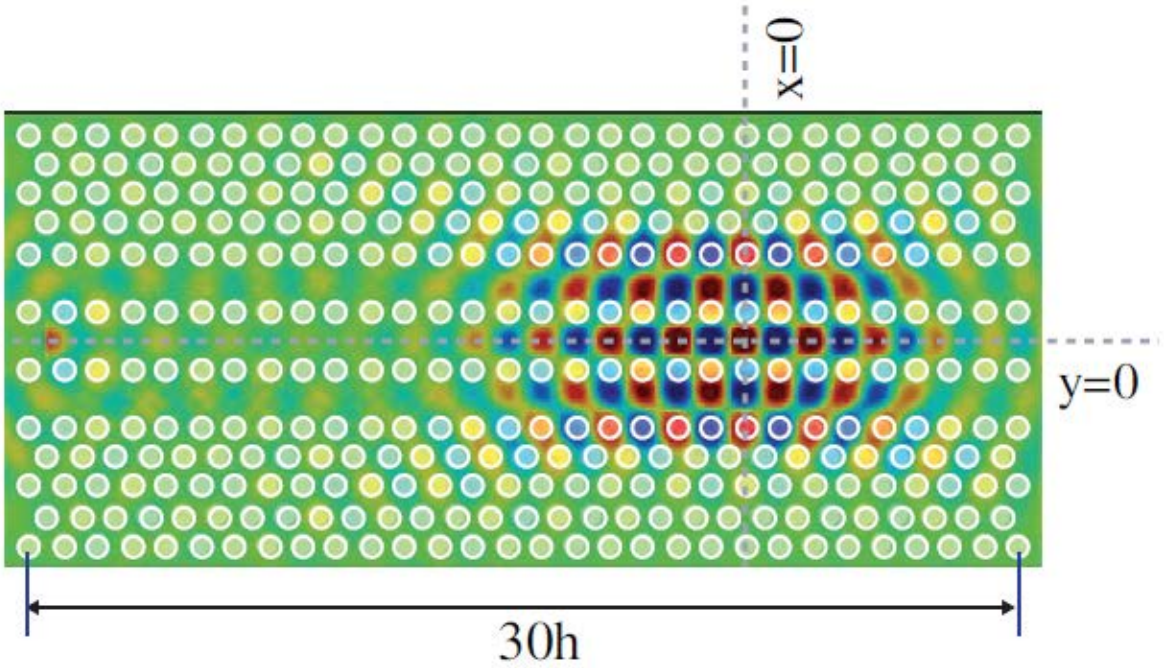
$$H_z^{S1} = \Phi_{S1}(x,y)\frac{F_{S1}^{0}\exp[i(\beta_{S1}x-\omega t)]}{\cosh\left[F_{S1}^{0}(x-v_{S1}t)\sqrt{\gamma/2\omega''}\right]}$$

Propagating Symmetric.

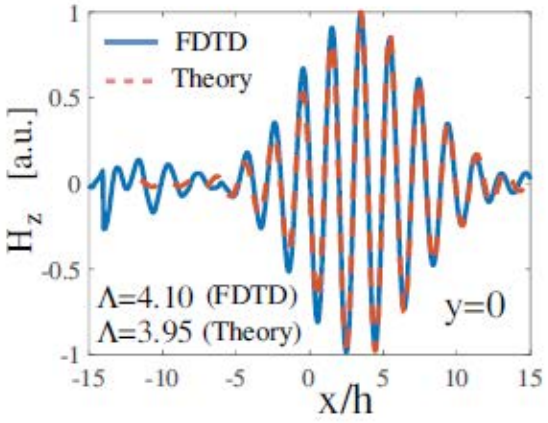
$$H_z^{A} = \Phi_A(x,y)F_A^{0}\exp(-i\omega t-|\beta_A|x)$$

Evanescent Anti-Symmetric.

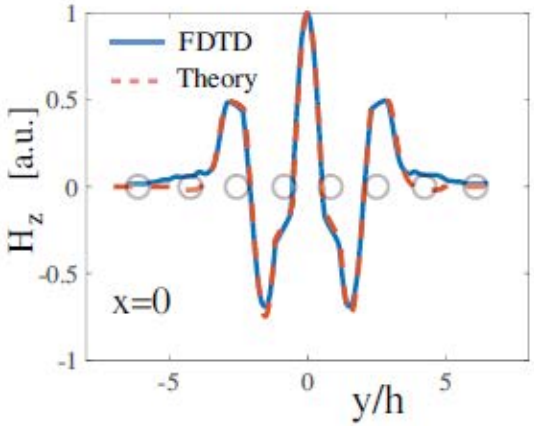
Envelope Soliton Profies



(a)

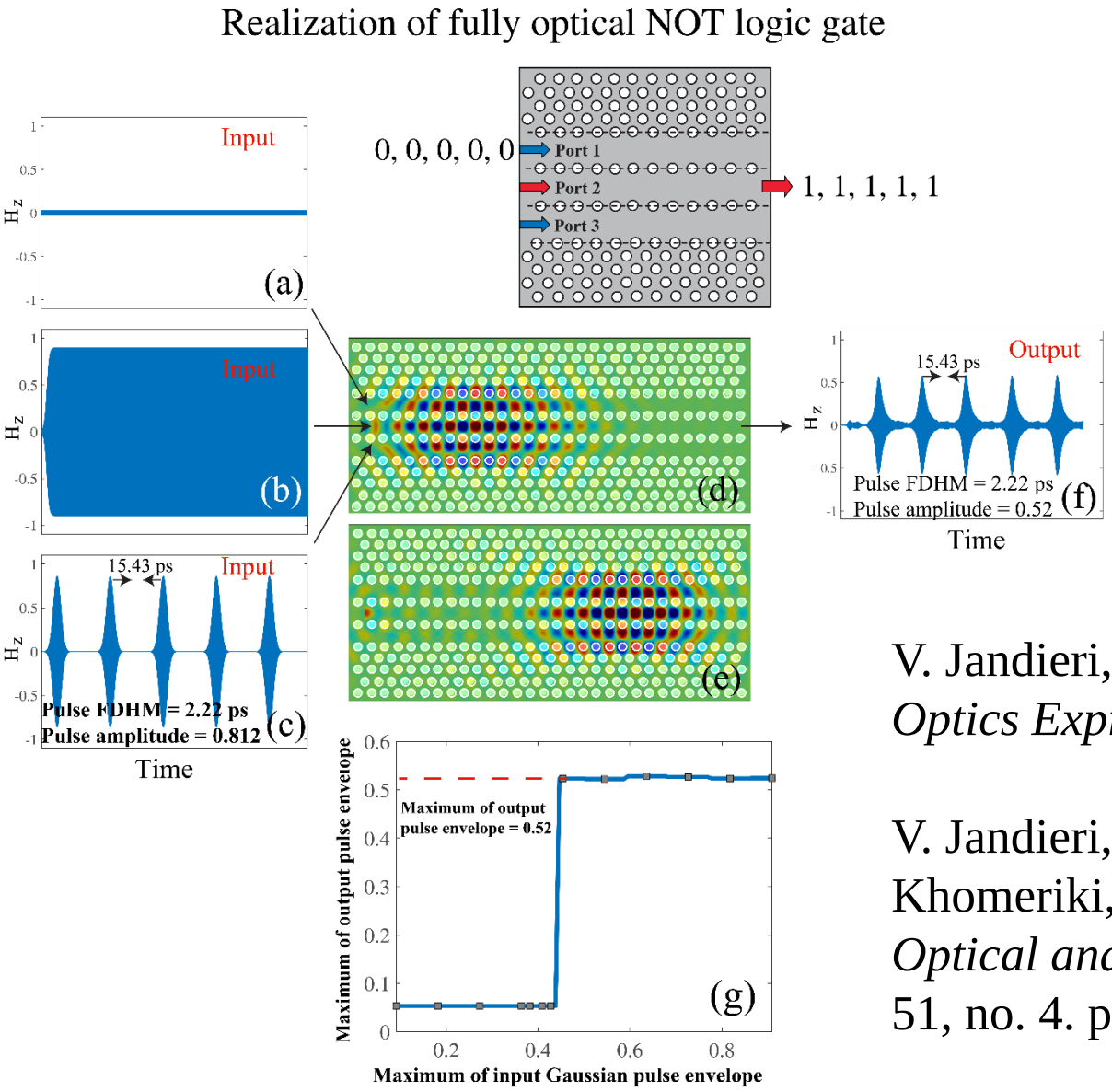


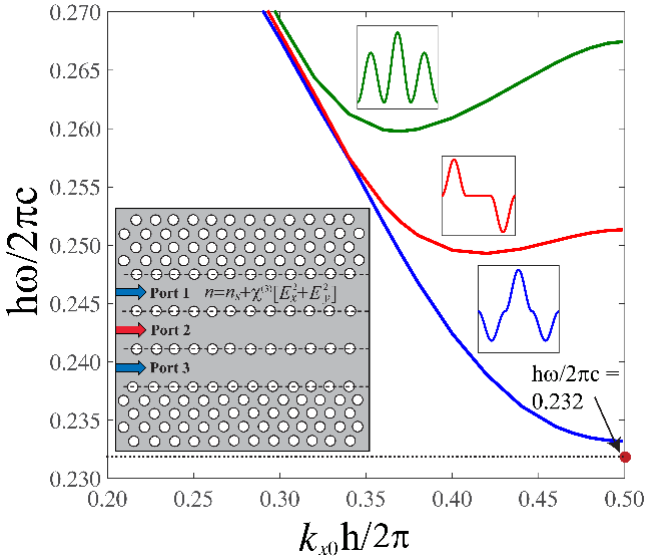
(b)



(c)

Numerical Results and Discussions



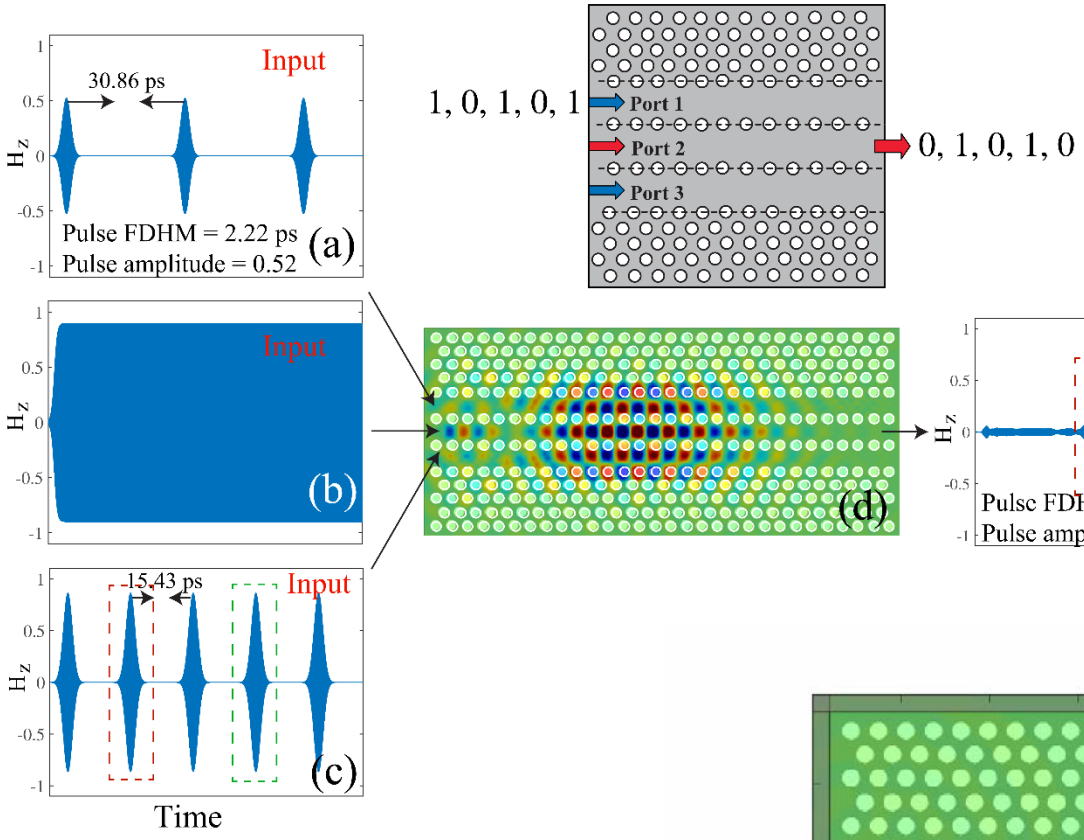


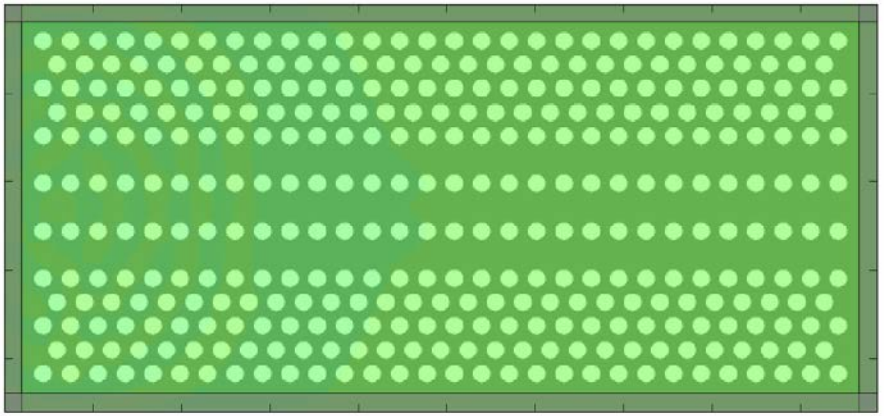
V. Jandieri, R. Khomeriki and D. Erni, *Optics Express* , vol. 26, no. 16, 2018.

V. Jandieri, T. Onoprishvili, R. Khomeriki, D. Erni and J. Pistora, *Optical and Quantum Electronics*,, vol. 51, no. 4. pp, 1-15, 2019.

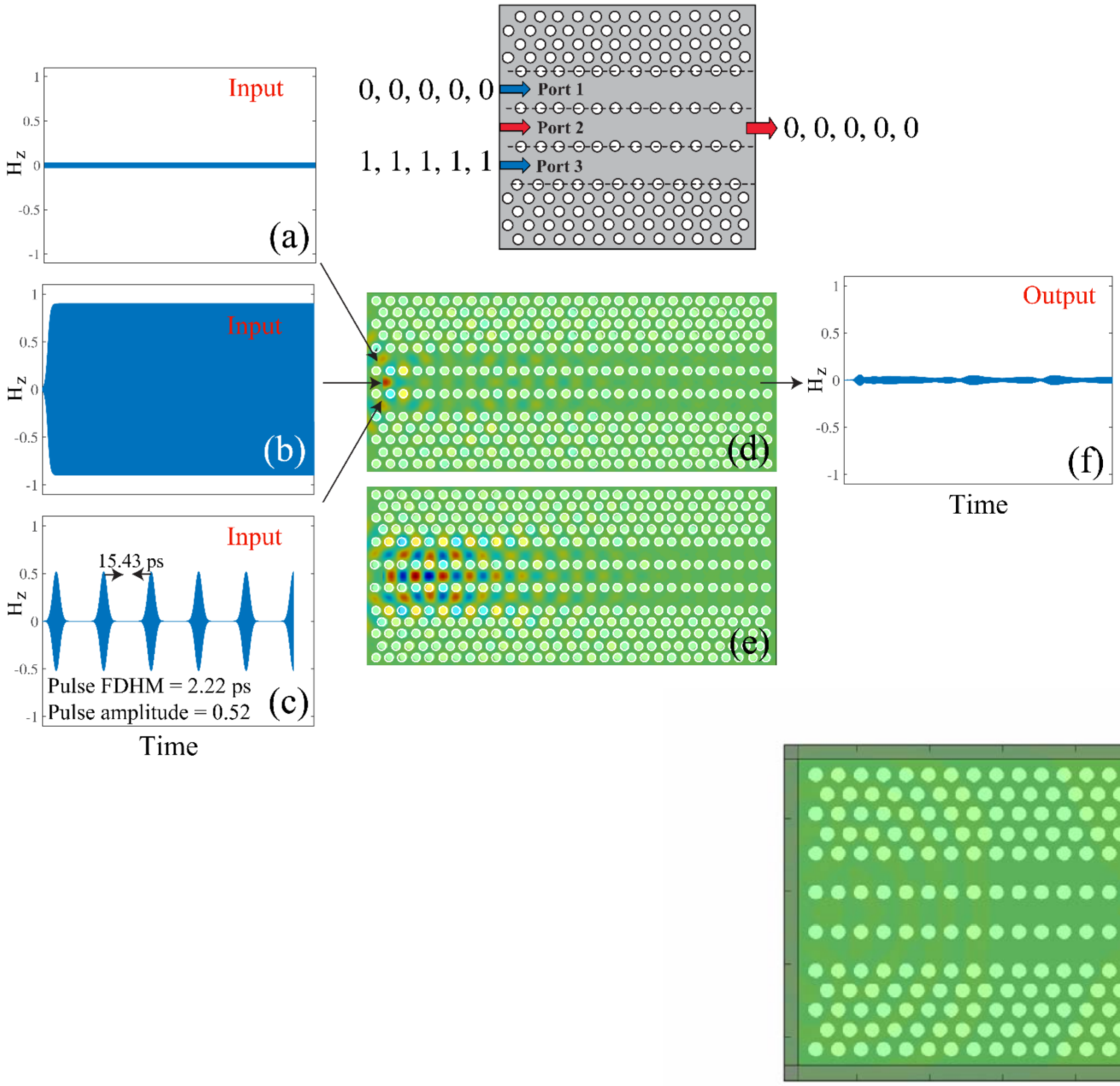
Numerical Results and Discussions

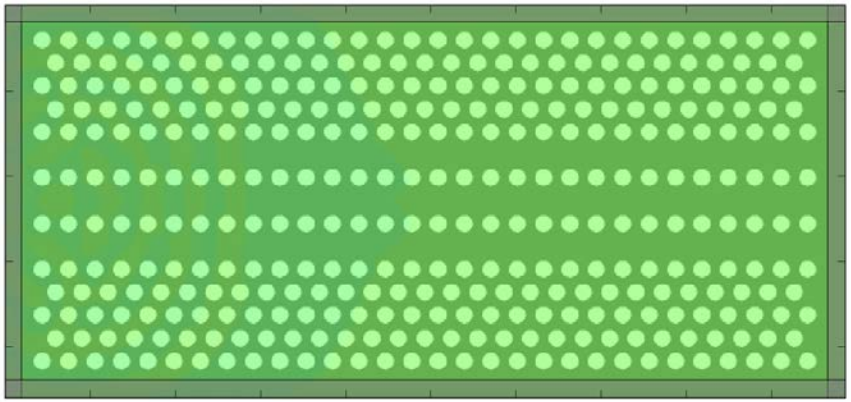
Realization of fully optical NOT logic gate



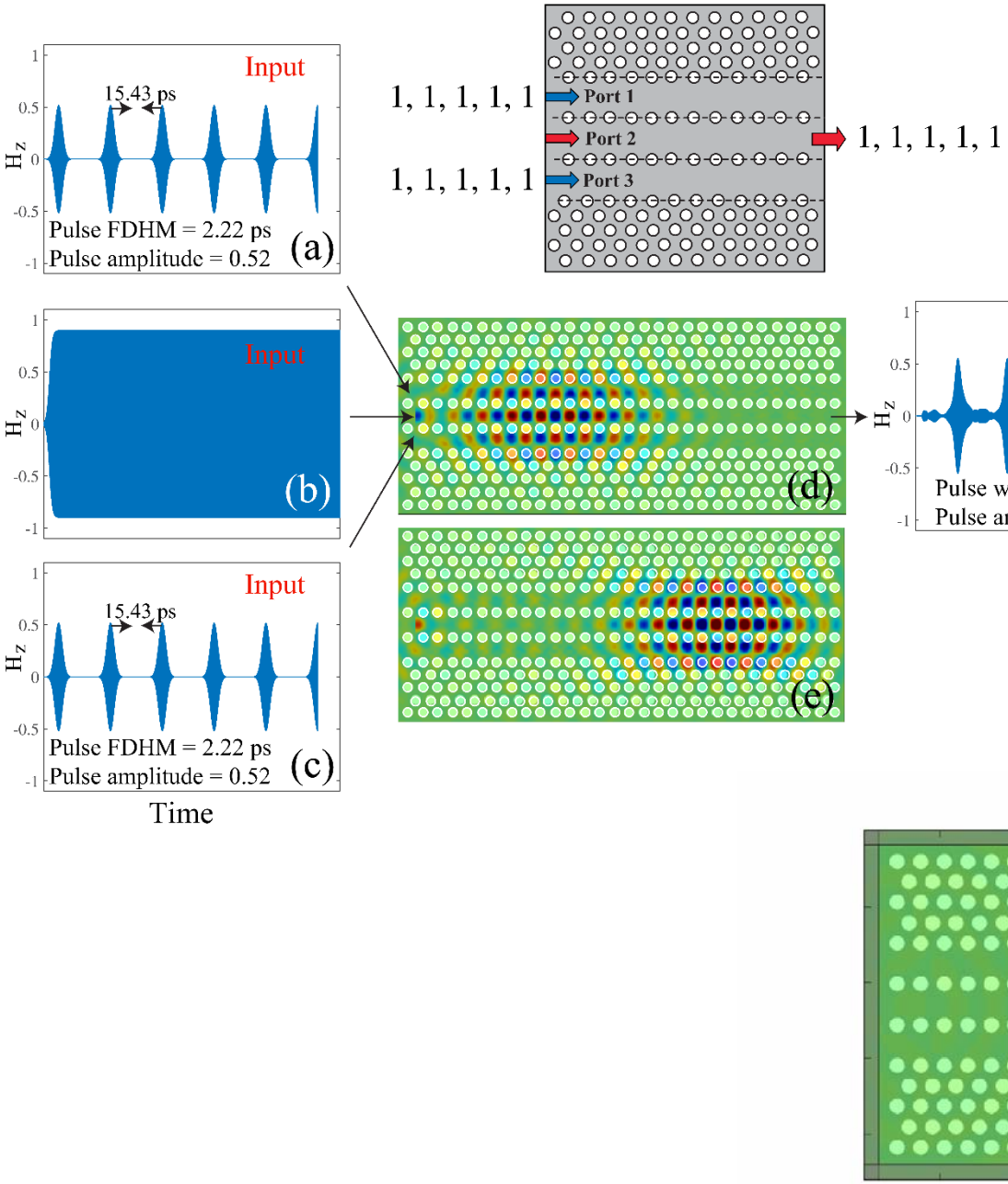


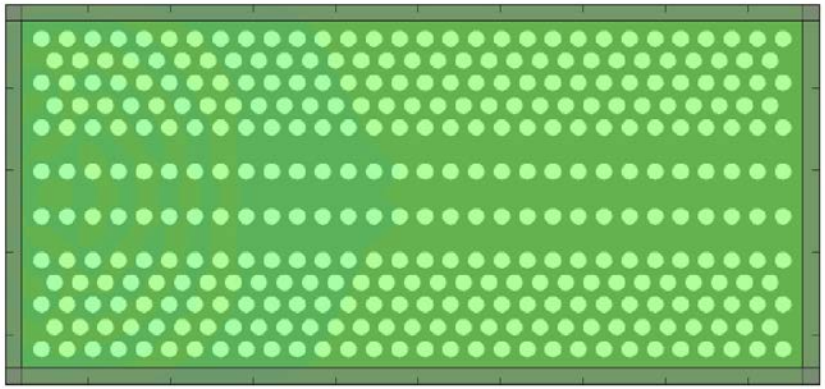
Realization of fully optical AND logic gate



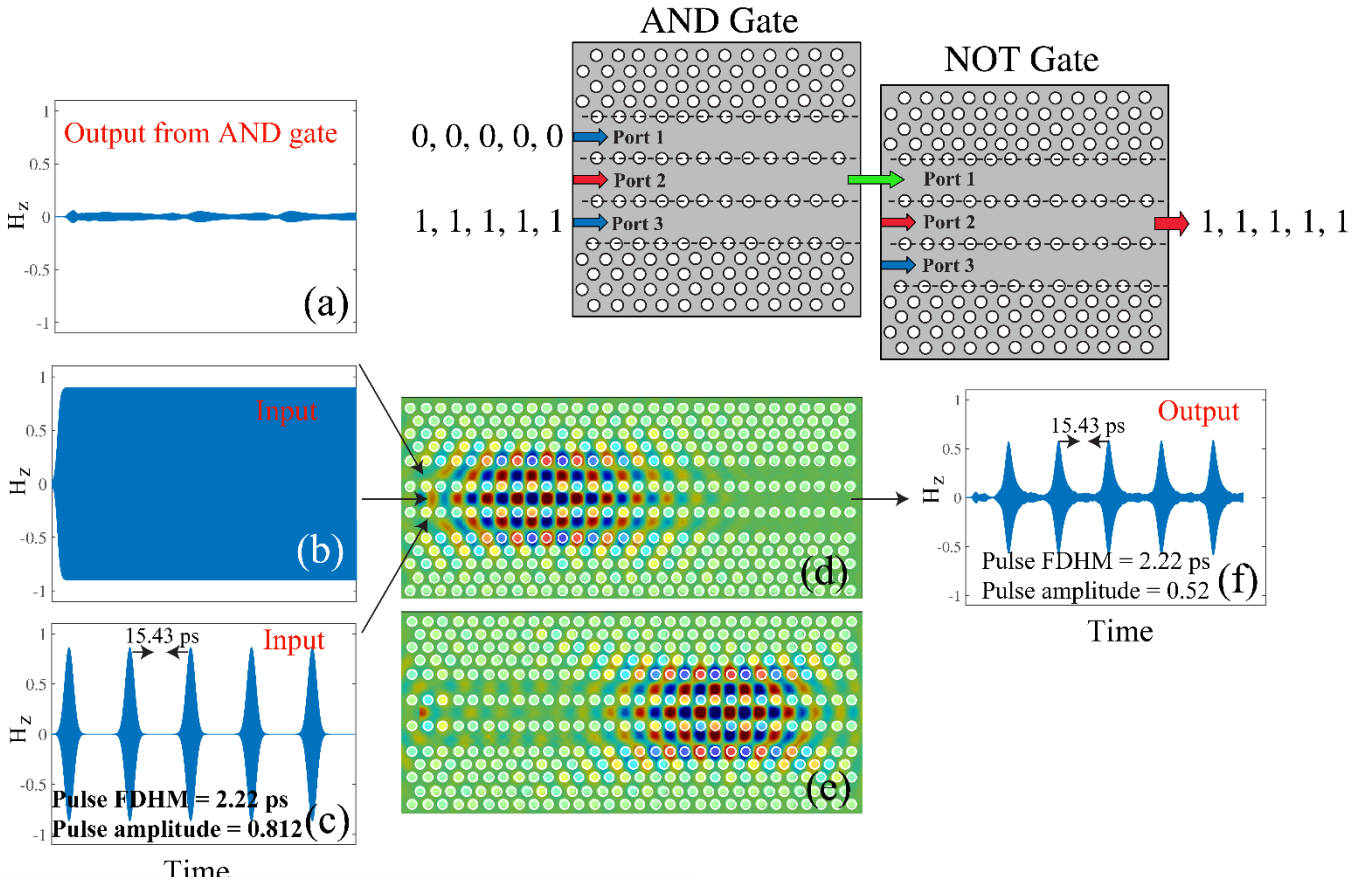


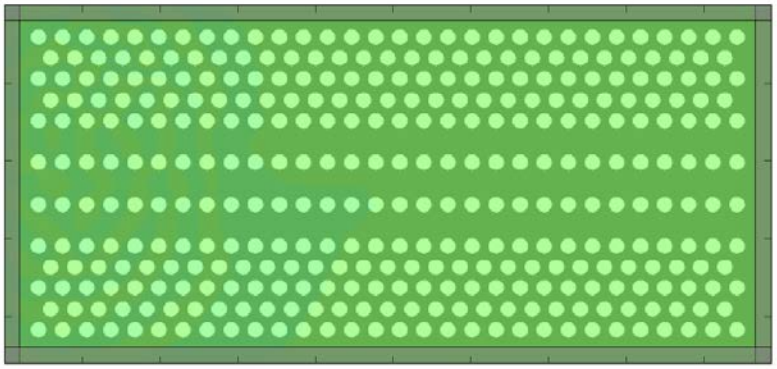
Realization of fully optical AND logic gate

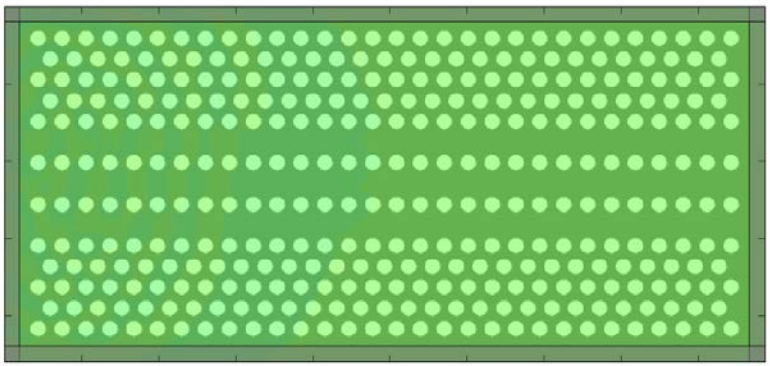




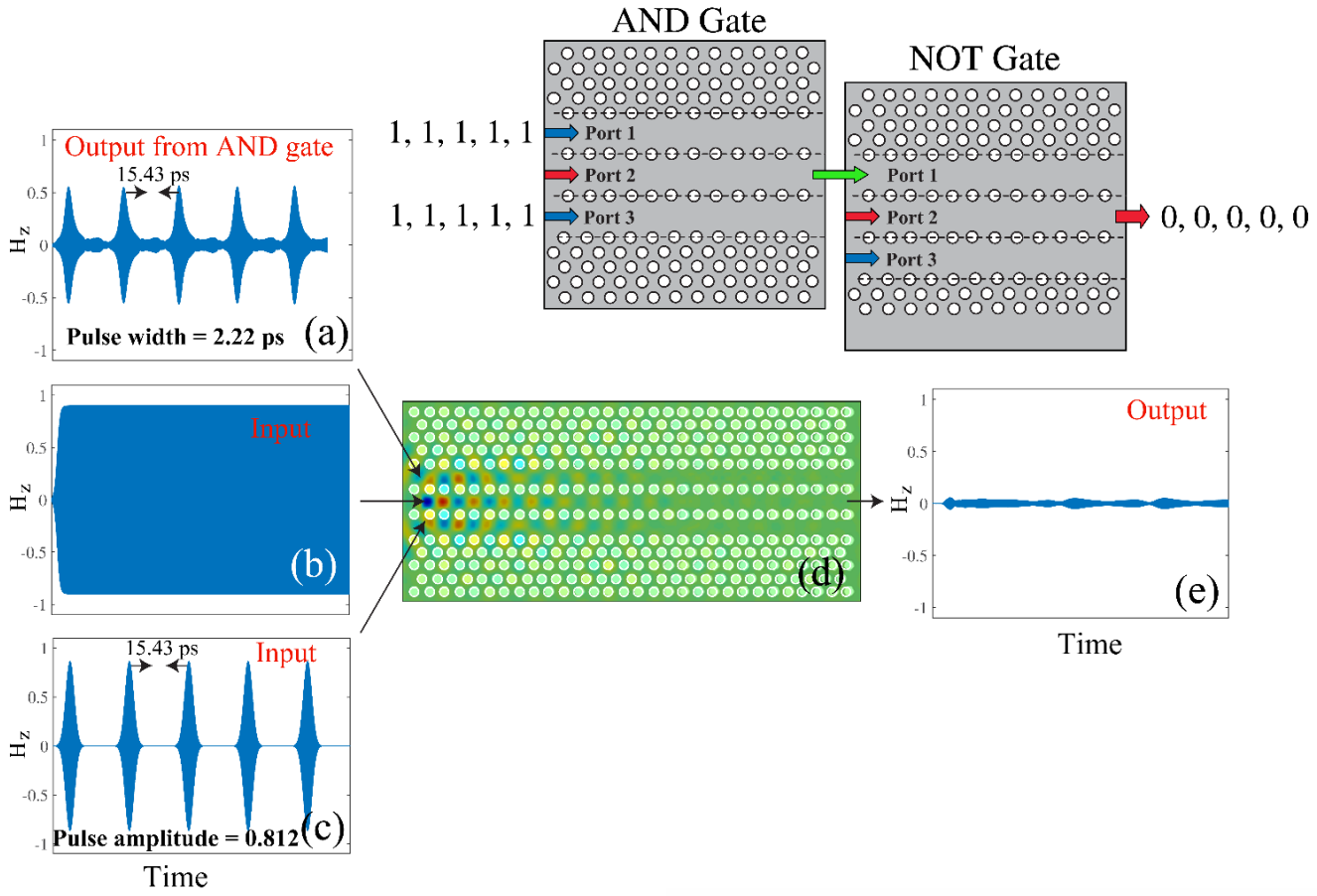
Realization of fully optical NAND logic gate

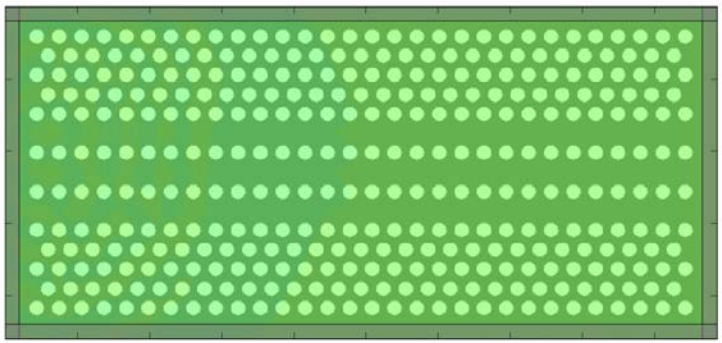


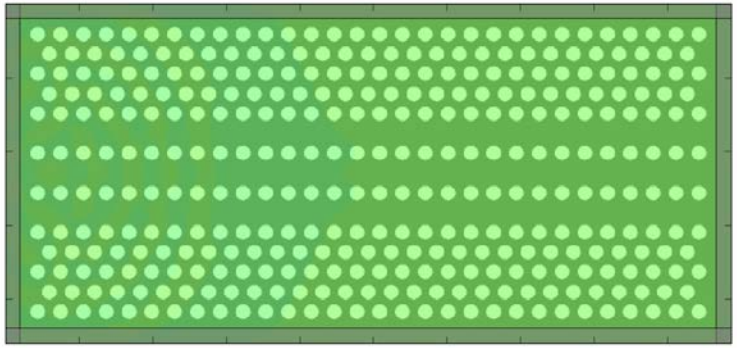




Realization of fully optical NAND logic gate







THANK YOU