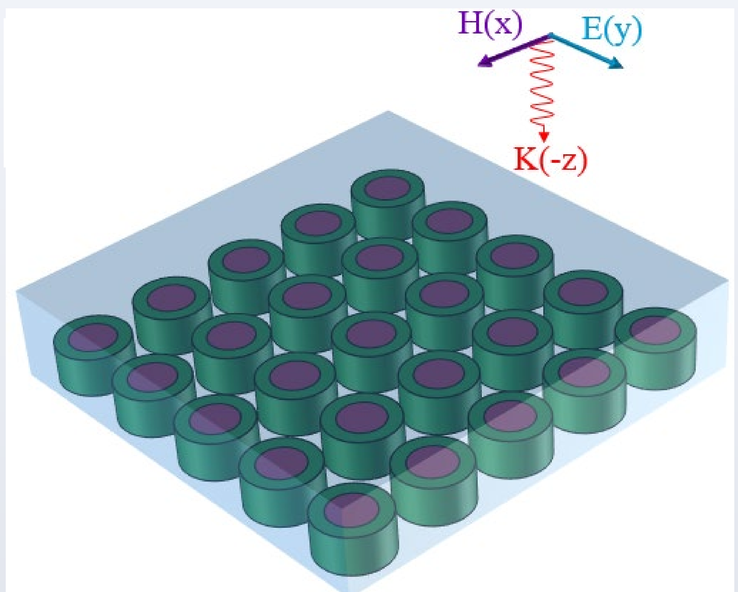
Cortex-Inspired Optical Computing Enabled by Photonic Metasurfaces

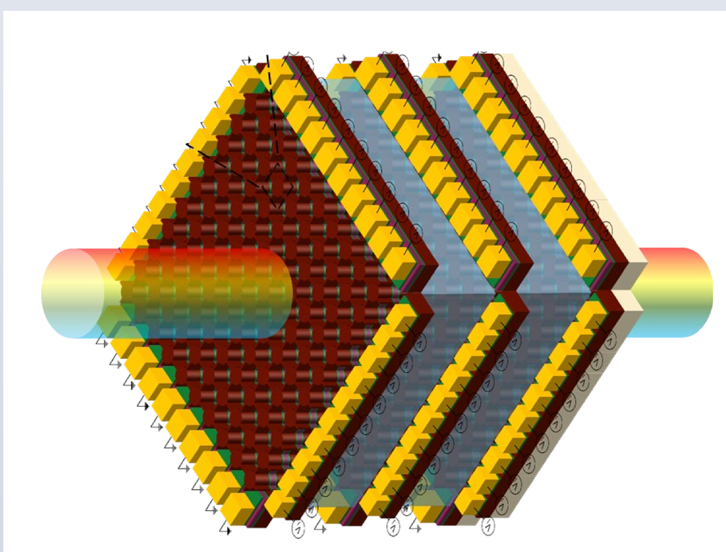
Muliang Zhu[1], Yashar Kiarashinejad[1], Sajjad Abdollahramezani[1], Tianren Fan[1], and Ali Adibi[1]

School of Electrical and Computer Engineering [1]

System Architechture



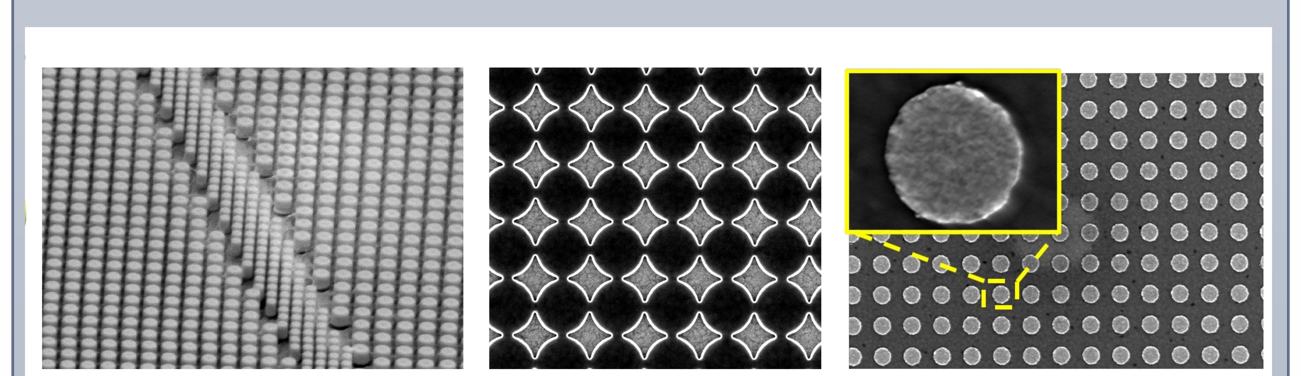
Schematic of a metasurface (MS) formed by an array of subwavelength meta-atoms, each formed by integration of different materials



The schematic of the proposed multi-MS platform for optical computing

- Optical MSs offer a nature strategy for natural wide networks for image processing and computing.
- The resonance nature of the meta-atoms provides a large range of control over the spatial (e.g., amplitude, phase, and polarization), spectral, and temporal properties of an incident wavefront.
- A subset of these meta-atoms can be considered as a neuron with the MS acting as a layer of a neural network (NN).
- Furthermore, it is possible to combine linear and nonlinear MSs to implement a NN-like architecture.
- Using 1) active reconfigurable materials (such as germanium antimony telluride (GST) with strong tunability of refractive index) to construct linear MS layers, and 2) passive nonlinear materials (such as lithium niobate ($LiNbO_3$) with second-order nonlinearity) to construct nonlinear MS layers, it is possible to reconfigure the functionality of the neuron.

Sample Fabricated Nanostructures



Examples of MSs formed by arrays of nano-antennas (or meta-atoms) fabricated at our group

Design Principles of the Nonlinear MS Layers

- The nonlinear process is optimized by using a pulsed pump at wavelength λ/2 for input/output signal at wavelength λ.
- The nonlinear MS is designed to have resonances at both (pump and signal) wavelengths to enhance nonlinear interactions and allow low-power operation.
- The proposed platform will be the first real implementation of NN-type computing using photonics.
- Second harmonic polarization matrix for LiNbO3 with crystal axis along the z-direction:

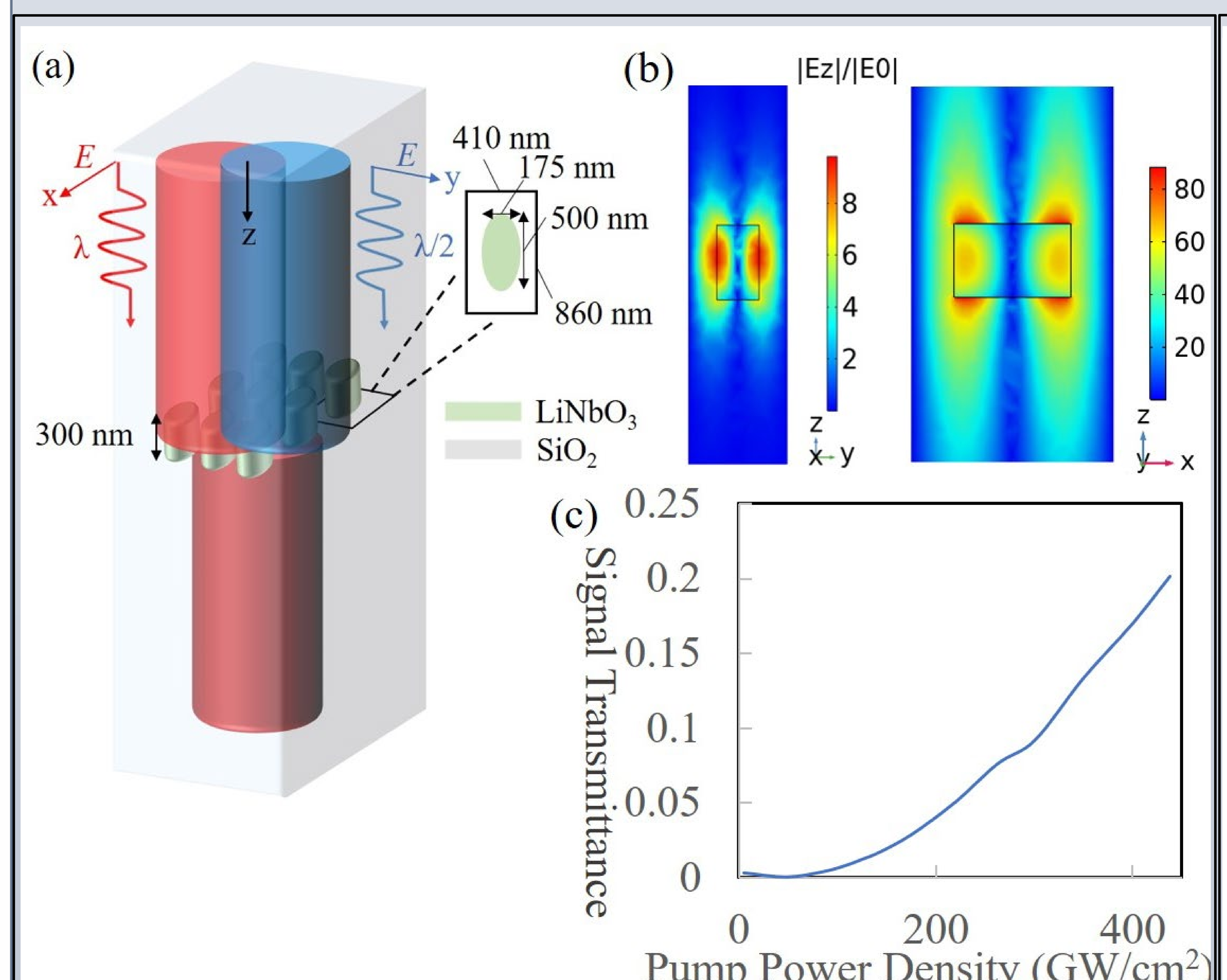
$$\begin{pmatrix}P_X\\P_Y\\P_Z\end{pmatrix}=\begin{pmatrix}0&0&0&0&d_{31}&-d_{22}\\-d_{22}&d_{22}&0&d_{31}&0&0\\d_{31}&d_{31}&d_{33}&0&0&0\end{pmatrix}\begin{pmatrix}E_X^2\\E_Y^2\\E_Z^2\\2E_YE_Z\\2E_ZE_X\\2E_XE_Y\end{pmatrix}$$

where d_{22} = 2.1 pm/V, d_{31} = -4.3 pm/V, and d_{33} = -27 pm/V. under the circumstance that both pump and signal waves exhibit large resonant nearfield enhancement for the z-component at the MS, a relatively large z-nonlinear polarization can be generated at the signal wavelength for mixing the pump wave and the conjugate of signal wave.

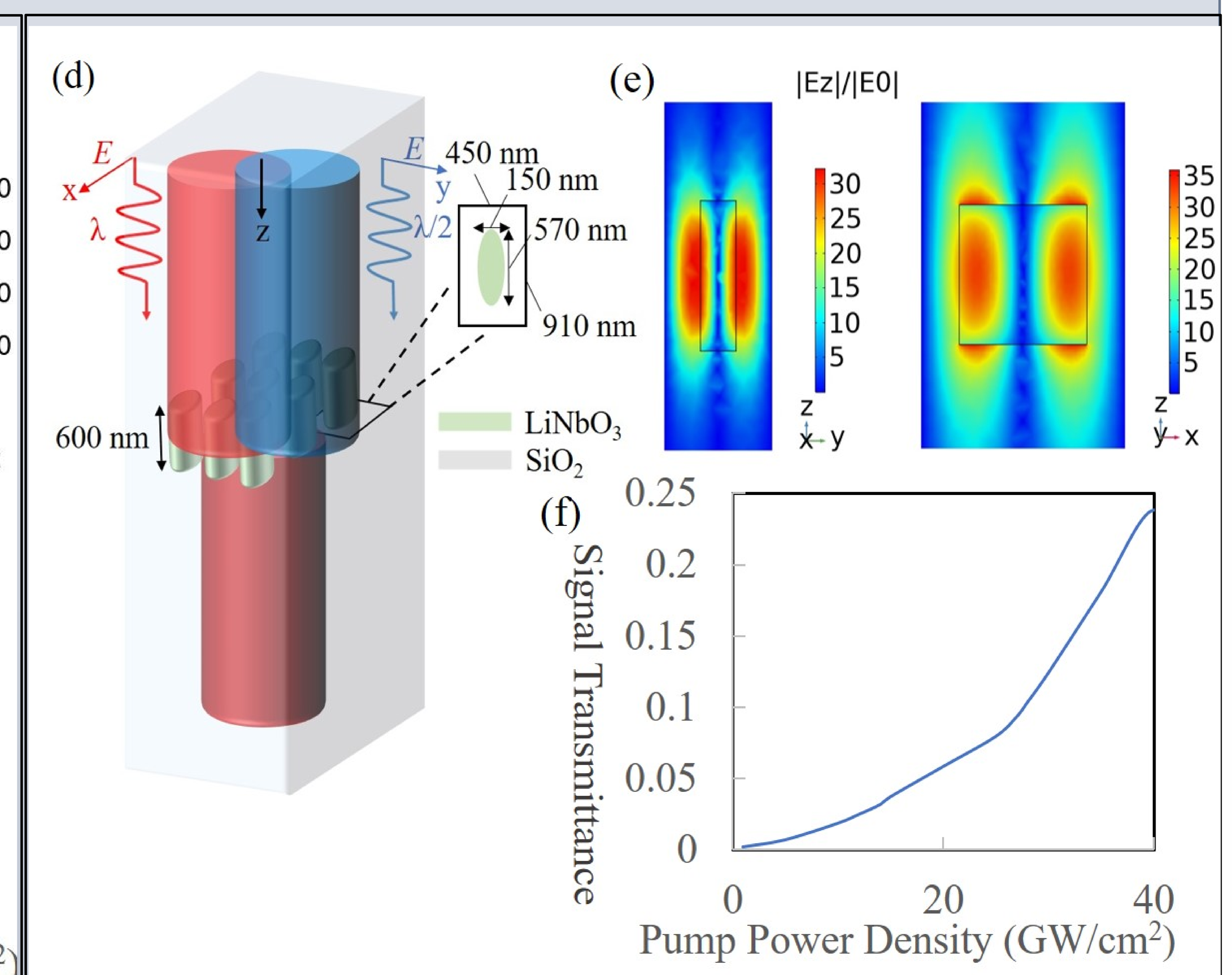
D. A. Roberts, IEEE J. Quantum Electron. **28**, 2057 (1992)

Design and Simulations of the Nonlinear MSs

- SiO_2-sealed x-cut $LiNbO_3$ MSs composed of nano-cylindroid building blocks are designed for an initial numerical study with COMSOL Multiphysics.
- The periodic nano-cylindroids are seated in a rectangular lattice, with the short semi-axis aligned in the short period direction and long semi-axis aligned in the long period direction.



A design resulting in relatively high pump power threshold for λ_{signal} = 1280.72 nm
(a) The schematic of the $LiNbO_3$ MS design resulting in high pump power threshold
(b) Normalized nearfield plots of the MS at pump (left) and signal (right) wave incidence for correspondent high pump power threshold design
(c) The signal transmittance plot to pump power density, which showcases the relatively high pump power threshold

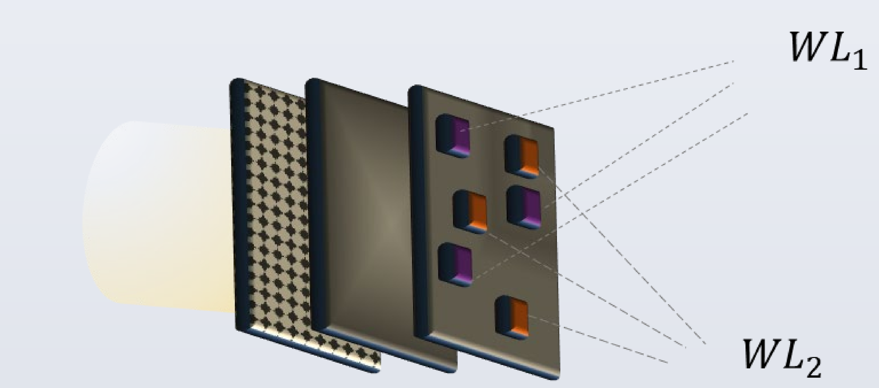


A design resulting in relatively low pump power threshold for λ_{signal} = 1382 nm
(d) The schematic of the $LiNbO_3$ MS design resulting in low pump power threshold
(e) Normalized nearfield plots of the MS at pump (left) and signal (right) wave incidence for correspondent low pump power threshold design
(f) The signal transmittance plot to pump power density, which showcases the relatively low pump power threshold

- Observation: Under equivalent resonant nonlinear polarization enhancement at the signal wavelength, a stronger resonance at the pump wavelength can substantially lower the pump power threshold of the nonlinear MS..

MS Application to Weak-Learners (WLs)

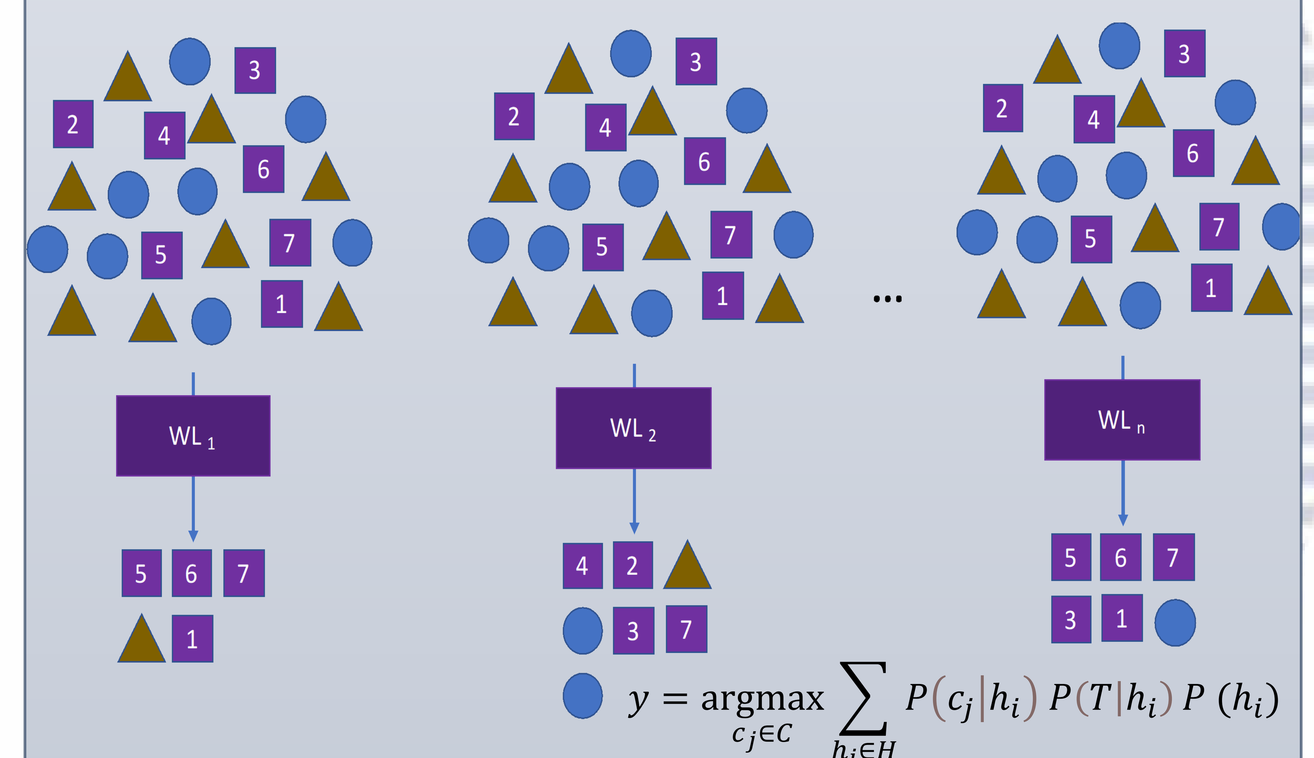
- Formation of detected pixels with reconfigurable, linear, and nonlinear MSs
- Utilization of large array of weak-learners (WLs) composed of small subsets of detected pixels to form an ensembled classifier
- Through training, several WLs can be simultaneously defined for different computing tasks (or feature selection).



WLs in a multi-MS structure with reconfigurable, linear, and nonlinear layers

- Independent MS-based WLs that can each identify the desired feature with a relatively low probability (e.g., 55-65%), which is restricted by fabrication and characterization imperfections of nanophotonic devices
- However, large degree of parallelism in the multi-MS-based WL architecture can potentially provide an overall accuracy close to 100%

J. J. Rodriguez, *et al*., IEEE Trans. Pattern Anal. Mach. Intell. **28**, 1619 (2006)



Ensemble Classifier

Illustration of the ensemble classifier for classifying blue squares. The system consists of n WLs and each of them has more than 50% accuracy in finding the desired shape (i.e. purple squares)

Future Work

- Further lowering the pump power threshold of the nonlinear MS
- Figuring out an activation function for the nonlinear transmission characteristic of the $LiNbO_3$ MSs
- Simulating the joint structure of proposed nonlinear MSs and the GST-based linear MSs
- Demonstration of a nanophotonic NN with multi-layer linear and nonlinear MSs leveraging WL-based technique to develop a robust computing platform against fabrication imperfection