Design and Simulation of Metasurfaces for High-Energy Physics Applications

Timur Abdilov[1 2], Nural Akchurin[1]

Department of Physics & Astronomy, Texas Tech University, Lubbock, TX 79409, USA

Department of Electrical & Computer Engineering, Texas Tech University, Lubbock TX 79409, USA

Background

High-energy jets in particle physics are detected using Cherenkov radiation, particularly in **Cherenkov fiber calorimeters**. A major challenge is controlling the emission direction, especially achieving flipped Cherenkov radiation to enhance signal collection. **Metasurfaces**—nanostructured materials that manipulate light at subwavelength scales—offer a promising solution. By integrating metasurfaces into Cherenkov fiber calorimeters, we aim to steer Cherenkov light more efficiently, improving detection accuracy and performance in high-energy experiments..

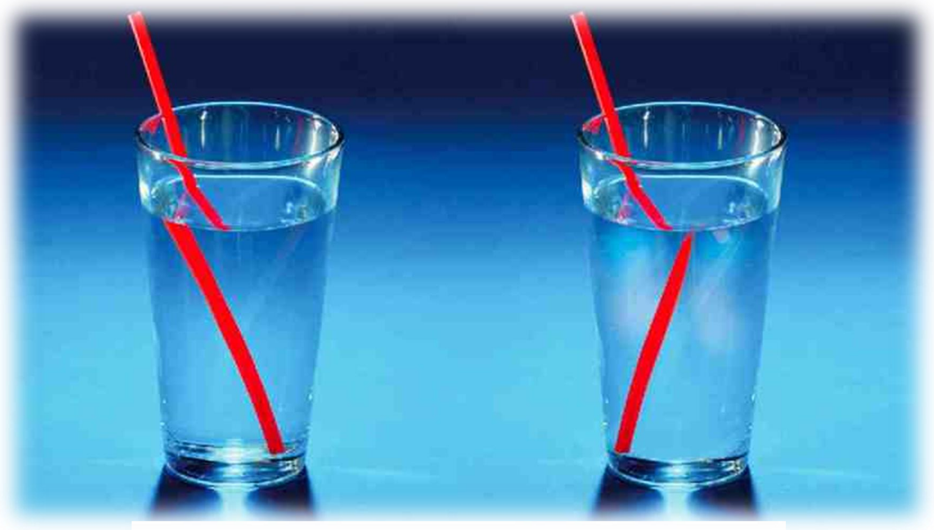
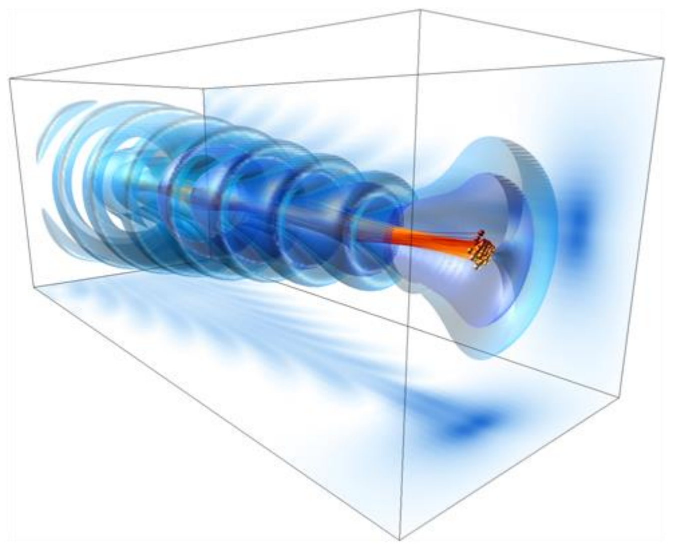


Figure 1. Visualization of Negative Index of Refraction



$$\cos\theta = \frac{c}{nv}$$

Figure 2. Visualization of Cherenkov Radiation

Negative Index of Refraction

Metamaterials with a negative refractive index ($n < 0$) bend light opposite to conventional materials, enabling precise control of Cherenkov radiation. In Cherenkov fiber calorimeters, this effect allows for flipped **Cherenkov radiation.**

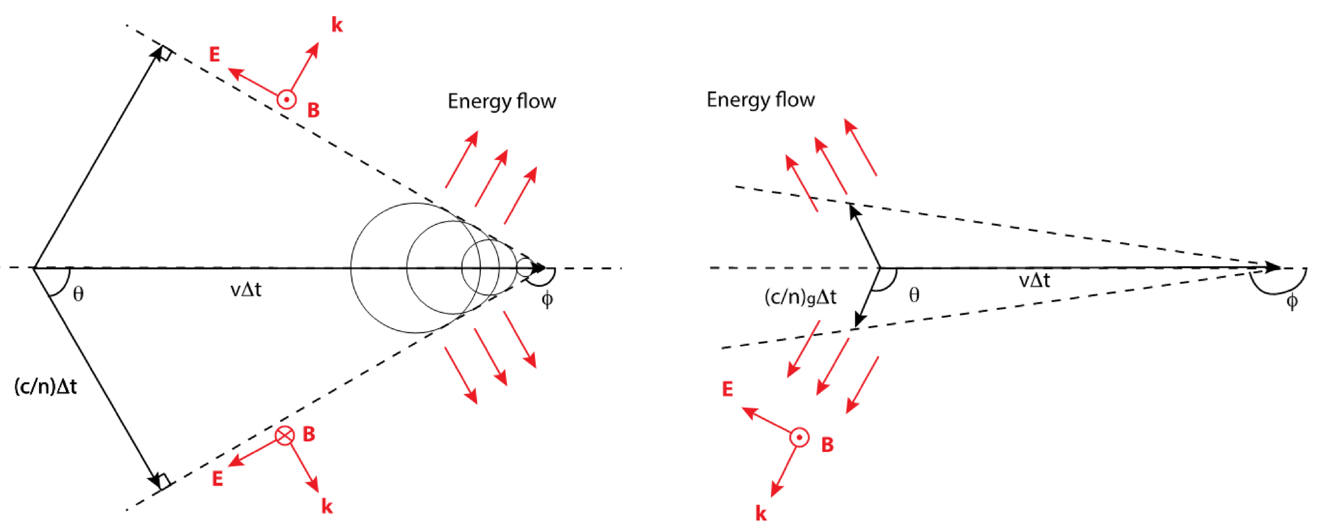


Figure 3. Propagation of Cherenkov Radiation vs Flipped Cherenkov Radiation

Metasurface Simulations

Metasurfaces are simulated using numerical methods in Rsoft Photonic Solutions Software by Synopsys, solving Maxwell's equations on a discrete space-time grid.

$$\nabla \cdot \mathbf{D} = \rho$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

$$\frac{1}{c_0^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} - \nabla^2 \mathbf{E} = \mathbf{0}$$
$$\frac{1}{c_0^2}\frac{\partial^2 \mathbf{B}}{\partial t^2} - \nabla^2 \mathbf{B} = \mathbf{0}$$

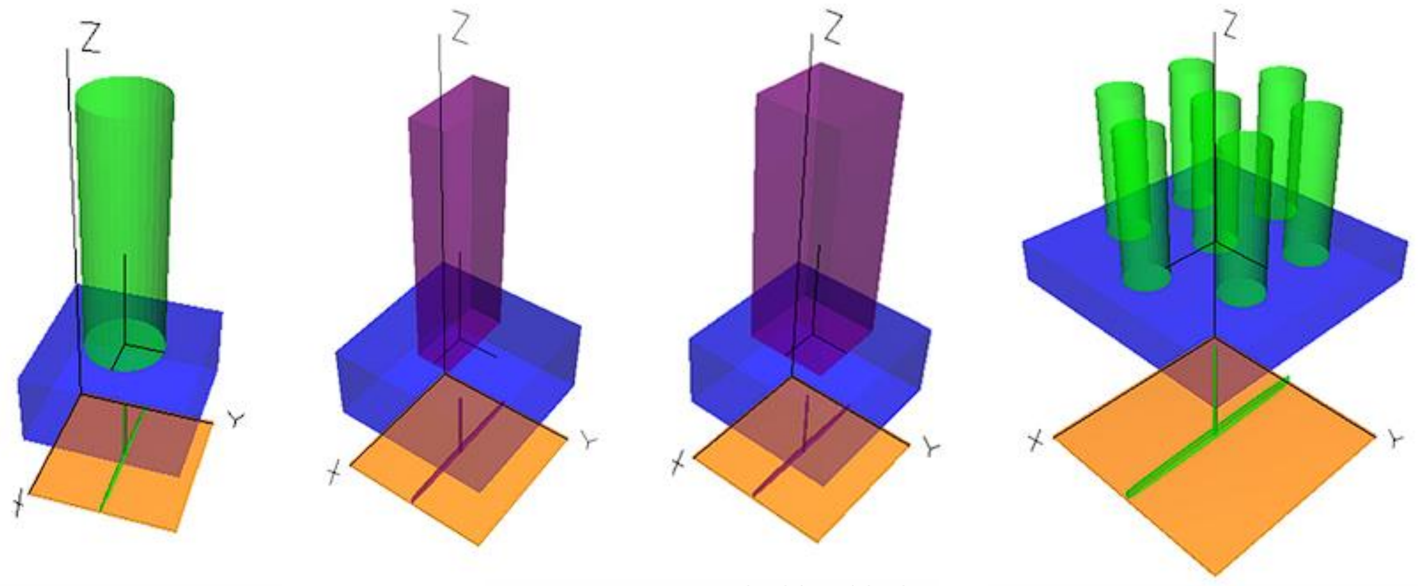


Figure 4. Meta-Atoms building blocks

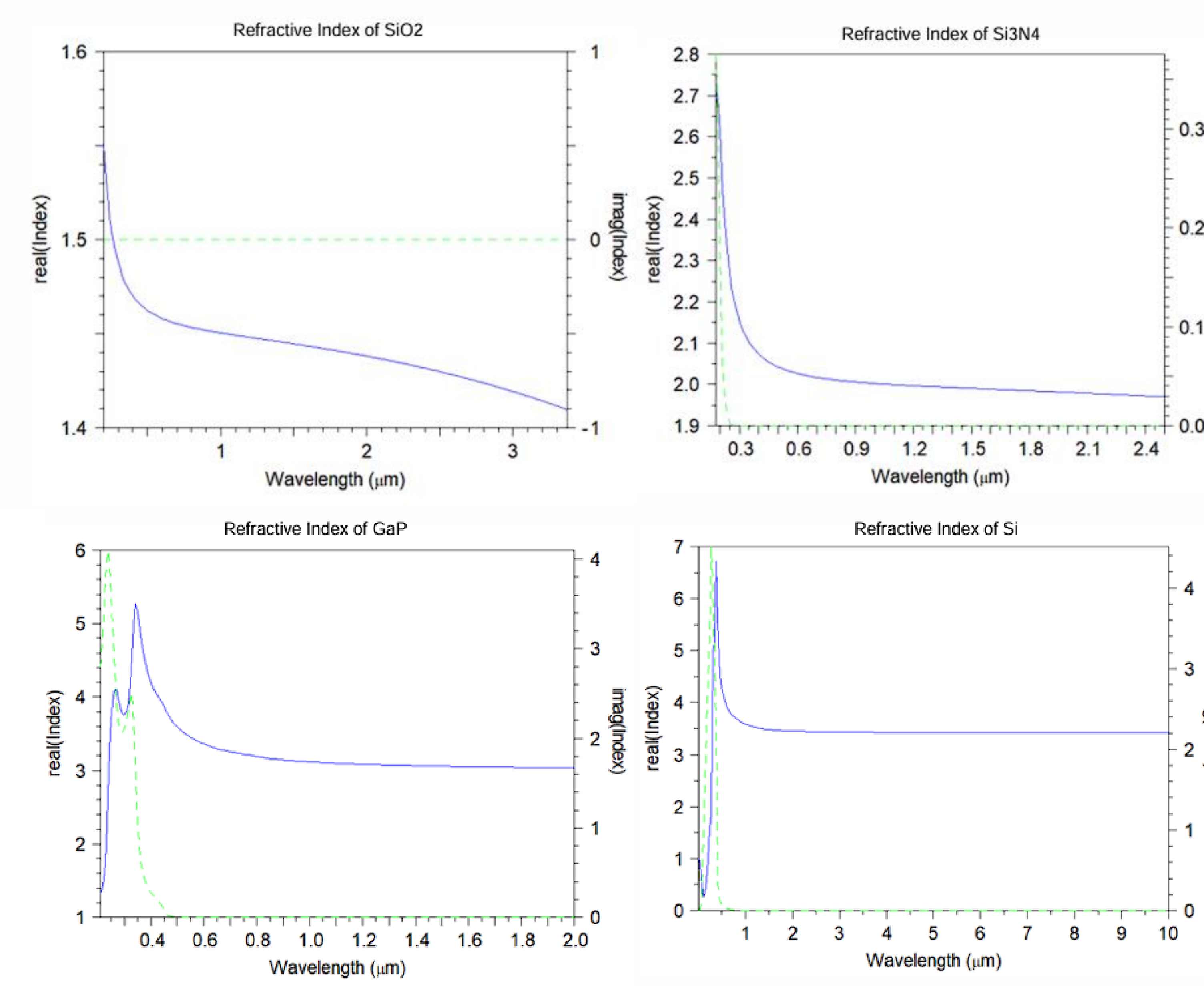


Figure 5. Refractive index of materials suitable for metamaterial design

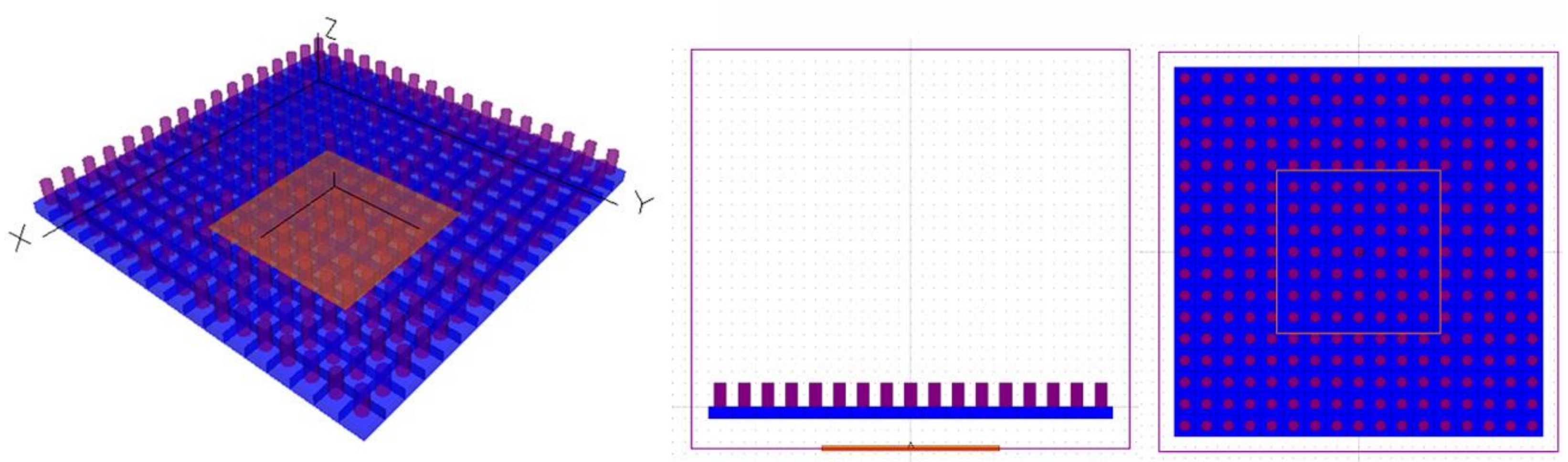


Figure 6. Circular Nanopillar Metasurface and simulation coordinate grid

Metalens Simulations

Metalenses also use nanostructured fins to manipulate light at subwavelength scales, enabling ultra-thin, flat lenses with custom focal distances. By precisely arranging these fins, engineers can design flat lenses. Additionally, Metalenses can be tuned for specific polarizations.

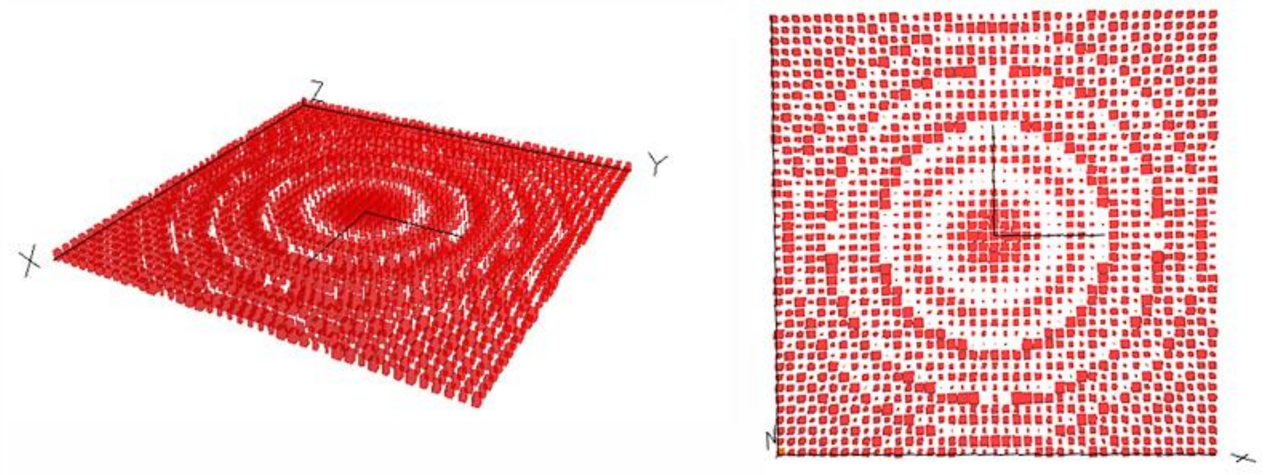


Figure 7. Si Metalens based on rectangular pillars

Methods

- BeamPROP - Beam Propagation Method (BPM) for simulation of optical wave propagation

$$\frac{\partial u}{\partial z} = \frac{i}{2\bar{k}}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \left(k^2 - \bar{k}^2\right)u\right)$$

- FullWAVE - Finite-Difference Time-Domain (FDTD) method for simulation of electromagnetic wave propagation.

$$H^{n+1/2}_{x(i,j,k)} = H^{n-1/2}_{x(i,j,k)} + \frac{\Delta t}{\mu\Delta z}\left(E^{n}_{y(i,j,k)} - E^{n}_{y(i,j,k-1)}\right) - \frac{\Delta t}{\mu\Delta y}\left(E^{n}_{z(i,j,k)} - E^{n}_{z(i,j-1,k)}\right)$$

$$E^{n+1}_{x(i,j,k)} = E^{n}_{x(i,j,k)} + \frac{\Delta t}{\varepsilon\Delta y}\left(H^{n+1/2}_{z(i,j+1,k)} - H^{n+1/2}_{z(i,j,k)}\right) - \frac{\Delta t}{\varepsilon\Delta z}\left(H^{n+1/2}_{y(i,j,k+1)} - H^{n+1/2}_{y(i,j,k)}\right)$$

- BandSolve - Plane-Wave Expansion (PWE) method for calculation of photonic band structures

$$\hat{\mathbf{L}}\mathbf{u}_{\mathbf{k}} = (i\mathbf{k}+\nabla)\times\left[\frac{1}{\varepsilon(\mathbf{x})}(i\mathbf{k}+\nabla)\right]\times\mathbf{u}_{\mathbf{k}} = \omega'^2\mathbf{u}_{\mathbf{k}}$$

Acknowledgements

I would like to thank the TrUE Scholars Program for funding this research project. Additionally, APD lab work is supported by the US Department of Energy, Office of Science grants DE-SC001559 and DE-SC0023690.

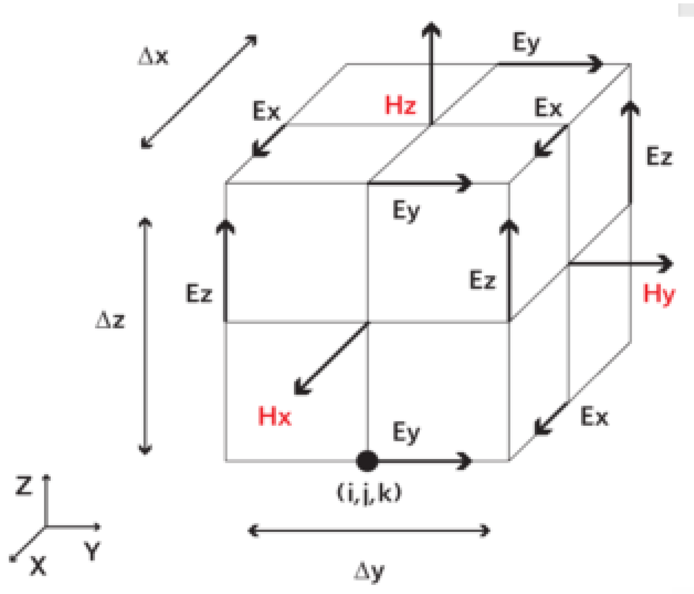
References

A. Arbabi, Y. Horie, M. Bagheri, and A. Faraon, "Dielectric metasurfaces for complete control of phase and polarization with subwavelength spatial resolution and high transmission," Nature Nanotechnology, vol. 10, pp. 937–943, 2015. https://doi.org/10.1038/nnano.2015.186

A. M. Urbas, Z. Jacob, L. Dal Negro, et al., "Roadmap on optical metamaterials," Journal of Optics, vol. 18, no. 9, p. 093005, Aug. 2016. DOI: 10.1088/2040-8978/18/9/093005.

V. G. Veselago, "The electrodynamics of substances with simultaneously negative values of ε and μ," Soviet Physics Uspekhi, vol. 10, p. 509, 1968. Z. Duan, X. Tang, Z. Wang, et al., "Observation of the reversed Cherenkov radiation," Nature Communications, vol. 8, p. 14901, 2017. https://doi.org/10.1038/ncomms14901

Z. Su, B. Xiong, Y. Xu, Z. Cai, J. Yin, R. Peng, and Y. Liu, "Manipulating Cherenkov Radiation and Smith–Purcell Radiation by Artificial Structures," Advanced Optical Materials, vol. 7, p. 1801666, 2019. https://doi.org/10.1002/adom.201801666.



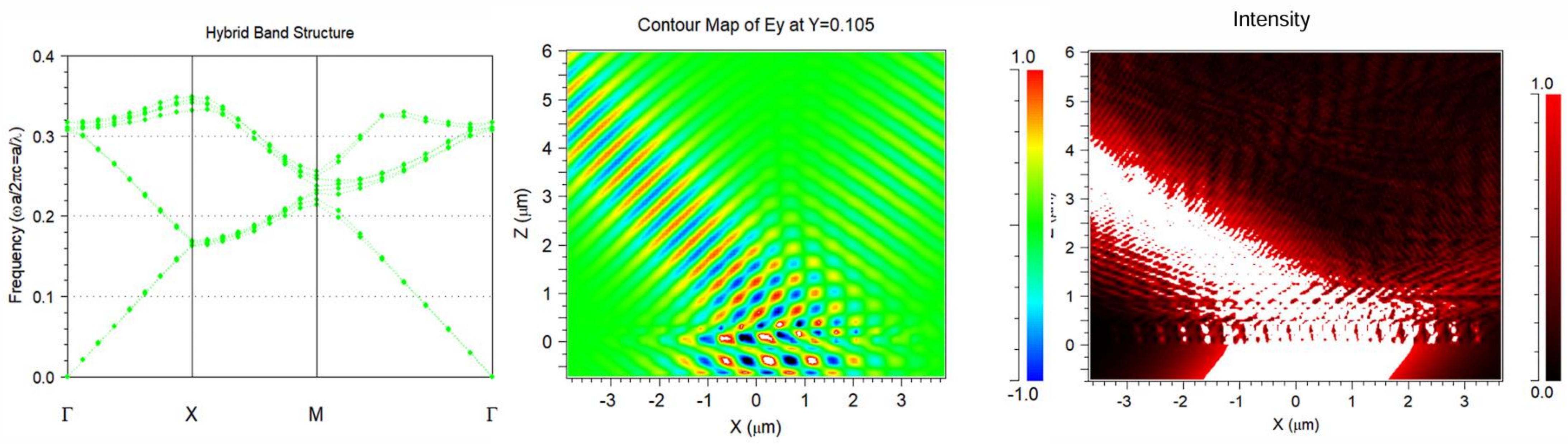


Figure 7. Simulation Results of a Metasurface with GaP circular pillars on SiO2 substrate