Tunable Electro-Optic Resonant Metasurfaces

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ABSTRACT

We investigate the tunability of metasurface resonances through an electro-optic mechanism based on the Pockels effect. By integrating an electro-optic material with a designed multi-resonant nanoantenna array, we demonstrate control and wide-range tunability of the metasurface resonances. The applied electric field enables dynamic modulation of the optical properties, allowing for the adjustment of the metasurface response. This approach offers a versatile platform for developing tunable photonic devices, with potential applications in optical communication and sensing.

Keywords: Pockels Effect, Chalcophosphate, Lithium Niobate, Barium Titanate, Nanoantenna, Optoelectronics, Modulator, Switch

1. INTRODUCTION

Metasurfaces, composed of subwavelength nanostructures, have attracted significant attention for their ability to manipulate light in unconventional ways.[1, 2] Traditional metasurfaces often exhibit fixed optical properties, which limits their applicability in dynamic environments. Recent advances in electro-optic materials provide a promising pathway to achieve tunable metasurface resonances, enabling adaptable and reconfigurable photonic devices.[3–6] In this study, we explore the integration of electro-optic mechanisms into metasurface design, aiming to achieve precise and real-time control over their resonant behavior, which is crucial for next-generation optical technologies.

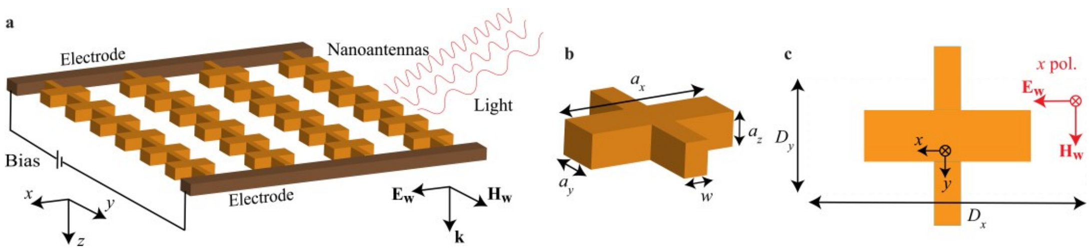

Figure 1. Schematic of the metasurface with bridged nanocuboids made of an electro-optic crystal with refractive index n. Nanocuboids are positioned on a silica substrate and are overlaid with an index-matching superstrate (not depicted here as the refractive index of the surrounding medium n_s matches that of the substrate, making it uniform). a) Schematic of the nanoantenna array with electrodes connected to the nanocuboids at both ends along the y direction. b) Single nanocuboid of lateral dimensions a_i (i = x, y, z) with the bridge. The width of the latter is fixed to w = 80 nm. c) Top view of the unit cell (of periods D_x and D_y), showing the orientation of the electromagnetic fields of the incident light wave with respect to the nanocuboid.

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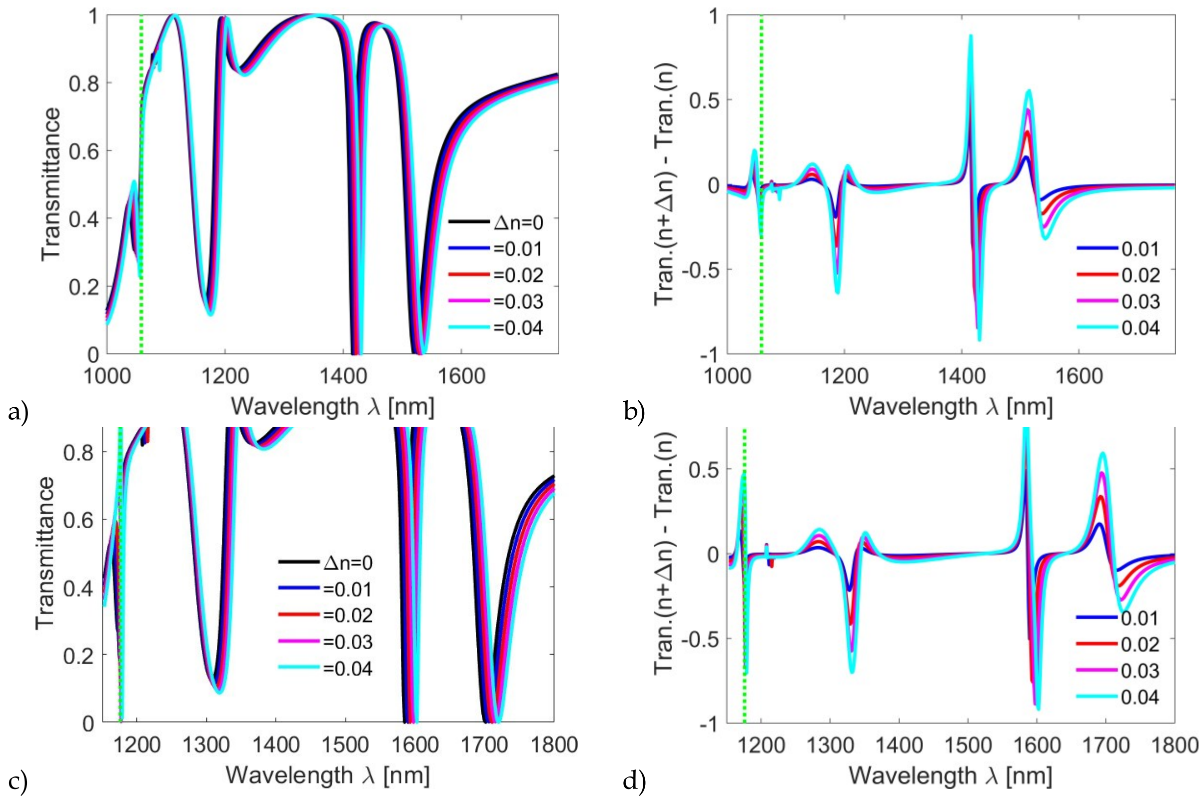

Figure 2. Transmittance of the metasurface for different values of the refractive index (n = 2.7 and Δn = 0 - 0.04) and its variation relative to the initial value. a) Transmittance T for an array with periods $D_x = D_y$ = 720 nm and nanocuboid side $a_x = a_y = a_z$ = 550 nm. b) Difference in transmittance $\Delta T(\Delta n) = T(n + \Delta n) - T(n)$ for the same array as in panel a). c) and d) Transmittance T and transmittance difference $\Delta T\,(\Delta n)$, respectively, for an array with periods $D_x = D_y$ = 800 nm and nanocuboid side $a_x = a_y = a_z$ = 620 nm. The green dotted vertical line in all panels corresponds to the Rayleigh anomaly wavelength $\lambda_{\mathrm{RA}} = n_s D_x$, which is 1058 nm for a) & b) and 1176 nm for c) & d).

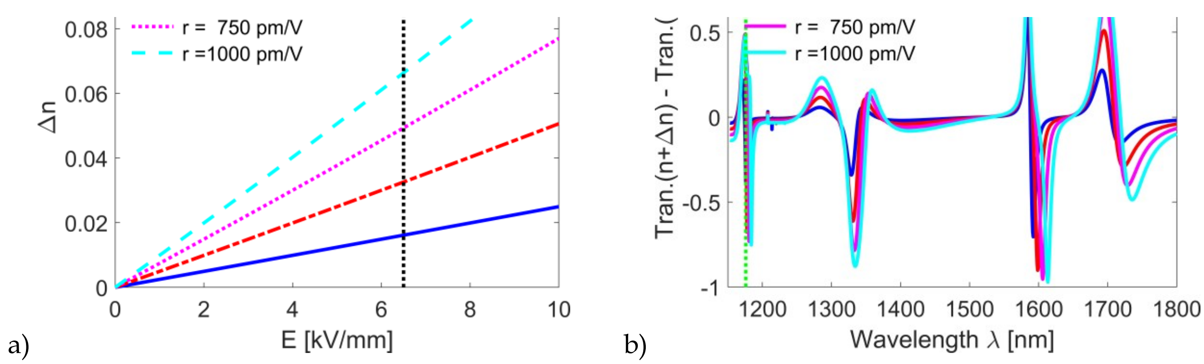

Figure 3. a) Change in refractive index Δn for different electric field strength E and electro-optic coefficient r. The black dotted vertical line corresponds to E = 6.5 kV/mm, which is selected for the simulations shown in panel b). b) Difference in metasurface transmittance $\Delta T\,(\Delta n) = T\,(n + \Delta n) - T\,(n)$ corresponding to E = 6.5 kV/mm for four values of r. The array has periods $D_x = D_y$ = 800 nm, and the nanocuboid sides are $a_x = a_y = a_z$ = 620 nm. The green dotted vertical line corresponds to the Rayleigh anomaly wavelength $\lambda_{\mathrm{RA}} = n_s D_x$ = 1176 nm.

2. RESULTS

We perform numerical simulations of a metasurface (Figure 1) composed of nanocuboids with a refractive index of $n = 2.7$, which is considered moderate (compared to the high values of silicon or III-V compounds) and close in value to typical electro-optic materials. In order to leverage the electro-optic properties of the metasurface material and impart tunability to the structure, the structure needs to be biased. As such, the nanocuboids are connected by bridges in one direction (y), and electrodes are built on two opposite sides of the array. Figure 2 illustrates the transmittance of the metasurface of Figure 1a as a function of the refractive index ($n = 2.7 + \Delta n$) and the resulting shifts in the spectral profile with Δn. Two different nanocuboids and array periods are considered. The simulations reveal multiple resonances in the spectrum, and their position changes slightly with increasing Δn. However, even if these shifts are small, changes in transmittance for wavelengths near the resonance can be significant because of the steep spectral features. The largest changes are observed for the second transmittance dip (counting from the red side). Additionally, we observe that larger nanocuboids induce a more pronounced resonance shift, further enhancing the tunability of the metasurface.

Next, we calculate the change in the refractive index $\Delta n = (1/2)n^3 rE$ due to the Pockels effect for various strengths of the electric field, E, and the electro-optic coefficient, r (Figure 3a), and simulate the corresponding transmittance changes for $E = 6.5$ kV/mm (Figure 3b). Consistent with the previous results, the most significant changes occur at the second transmittance dip (counting from the red side of the spectrum). In particular, the transmittance change can be positive or negative, depending on the specific parameters.

Many chalcophosphates are known to have ferroelectric phases and are promising in electro-optic applications.[7–10] In particular, $Sn_2P_2S_6$ has an electro-optic coefficient on the order of 100 pm/V at room temperature and a Curie temperature of only 64-66°C,[7–9] making this material an ideal candidate for tunable photonic applications. The results presented in this study could be directly applicable to chalcophosphate metasurfaces, enabling enhanced tunability in the metasurface properties as a result of the electro-optic effect.

3. CONCLUSION

We demonstrated the tunability of metasurface resonances using an electro-optic mechanism in metasurfaces made of nanocuboids with moderate refractive index and connected with bridges. The integration of electro-optic materials with metasurfaces allows for dynamic control of optical properties, offering significant potential for optoelectronics and nanophotonics. Our results highlight the effectiveness of this approach in achieving precise modulation of resonant frequencies, paving the way for innovative devices and optical components. Future directions can include optimizing the electro-optic response and exploring broader applications in areas such as optical communication, sensing, and adaptive optics.

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REFERENCES

[1] Babicheva, V. E. and Evlyukhin, A. B., "Mie-resonant metaphotonics," *Advances in Optics and Photonics* **16**(3), 539–658 (2024).

[2] Han, A., Moloney, J. V., and Babicheva, V. E., "Applicability of multipole decomposition to plasmonic- and dielectric-lattice resonances," *The Journal of Chemical Physics* **156**(11), 114104 (2022).

[3] Weigand, H., Vogler-Neuling, V. V., Escale, M. R., Pohl, D., Richter, F. U., Karvounis, A., Timpu, F., and Grange, R., "Enhanced electro-optic modulation in resonant metasurfaces of lithium niobate," *ACS Photonics* **8**(10), 3004–3009 (2021).

[4] Weiss, A., Frydendahl, C., Bar-David, J., Zektzer, R., Edrei, E., Engelberg, J., Mazurski, N., Desiatov, B., and Levy, U., "Tunable metasurface using thin-film lithium niobate in the telecom regime," *ACS Photonics* **9**(2), 605–612 (2022).

[5] Fedotova, A., Carletti, L., Zilli, A., Setzpfandt, F., Staude, I., Toma, A., Finazzi, M., De Angelis, C., Pertsch, T., Neshev, D. N., and Celebrano, M., "Lithium niobate meta-optics," *ACS Photonics* **9**(12), 3745–3763 (2022).

[6] Babicheva, V. E. and Rumi, M., "Chalcophosphate metasurfaces with multipolar resonances and electro-optic tuning," *RSC Advances, under review* (2024).

[7] Carpentier, C. and Nitsche, R., "Ferroelectricity in $Sn_2P_2S_6$," *Materials Research Bulletin* **9**(8), 1097–1100 (1974).

[8] Haertle, D., Caimi, G., Haldi, A., Montemezzani, G., Günter, P., Grabar, A. A., Stoika, I. M., and Vysochanskii, Y. M., "Electro-optical properties of $Sn_2P_2S_6$," *Optics Communications* **215**(4), 333–343 (2003).

[9] Moriya, K., Iwauchi, K., Ushida, M., Nakagawa, A., Watanabe, K., Yano, S., Motojima, S., and Akagi, Y., "Dielectric studies of ferroelectric phase transitions in $Pb_{2x}Sn_{2(1-x)}P_2S_6$ single crystals," *Journal of the Physical Society of Japan* **64**, 1775–1784 (1995).

[10] Sevison, G. A., Halasyamani, P. S., Slagle, J., and Rumi, M., "Temperature dependence of the second harmonic generation efficiency in $Sn_2P_2(S_{1-x}Se_x)_6$ powders," in [*CLEO 2024*], *CLEO 2024* , JTh2A.3, Optica Publishing Group (2024).