Chapter 6

CONCLUSIONS

In this thesis, we explored and developed new pathways toward realizing an electrically programmable, universal active metasurface for dynamic, independent, and comprehensive control over the properties of light. The work outlined here encompasses multiple facets, including the investigation of system-level metasurface operation modes, optimized array configurations, unit cell design, and integration of novel materials. The findings presented here establish a comprehensive framework for next-generation nanophotonic platforms with enhanced information processing capabilities.

We first leveraged plasmonic, field-effect tunable metasurfaces using indium tin oxide (ITO) as a platform to develop an array-level inverse design approach which co-optimizes the array phase and amplitude profiles for a desired objective function. Through iterative optimization methods, we demonstrated that nonintuitive array configurations could enhance the directivity of beam steering metasurfaces by up to 84% compared to conventional forward designs, despite nonideal amplitude and phase response from the antenna components of a previously realized ITO-based metasurface [42]. Experimental validation for a metasurface with approximately 220° phase modulation further confirmed that inverse-designed metasurfaces yield improved beam steering performance. We extended this optimization framework to alternative objective functions, including the design of metasurface arrays for flat top beams, tunable full-width at half-maximum, and multi-beam steering configurations. These results establish array-level inverse design as a powerful tool for overcoming antenna-level nonidealities in practical metasurface applications.

While array-level inverse design enhances the capability of active metasurfaces to perform a variety of functions with improved performance, optimization becomes increasingly challenging as the complexity of the target function increases, particularly when simultaneous optimization of multiple tasks is required. To address this challenge, we extended the operational regime of optical metasurfaces to space-time modulation using the previously introduced ITO-based metasurface. In this regime, a near-infrared metasurface is modulated with tailored waveforms at MHz frequencies to generate frequency harmonics offset from the incident laser frequency by integer multiples of the modulation frequency. By introducing phase offsets between the waveforms applied to adjacent electrodes, we experimentally demonstrated tunable diffraction of desired frequency harmonics up to an angle of 14°. We then extended this concept theoretically, demonstrating spatiotemporal wavefront configurations that enable multi-frequency, multi-beam steering, realizing an example of active multitasking metasurfaces with increased channel capacity. While challenges remain in experimentally enhancing the modulation bandwidth and efficiency of the generated frequency harmonics, our results highlight the potential of space-time modulated metasurfaces in enhancing the channel capacity in next-generation active metasurfaces and enabling advanced components such as nonreciprocal optical elements.

To enhance device efficiency and extend the operation wavelength range, we shifted our focus to electro-optically tunable metasurfaces based on the Pockels effect in barium titanate (BTO). Convential bottom-up growth techniques typically result in BTO thin films with reduced electro-optic coefficients. To overcome this limitation, we developed a scalable and cost-effective fabrication method that relies on spalling single-crystal thin films from bulk substrates using a metal stressor layer. Using this approach, we successfully obtained mm-scale a-axis and c-axis thin films with thicknesses ranging from 100 nm to 15 μm. While stress-induced domain switching during spalling introduces surface roughness, we verified that the spalled thin films retain their bulk electro-optic properties. Ellipsometric Teng-Man measurements revealed a Pockels coefficient of $r_{33} = 55 \pm 5$ pm/V in multi-domain regions and $r_{33} = 160 \pm 40$ pm/V in smaller, likely single-domain regions, exceeding the performance of commercially available thin film lithium niobate.

Buidling on these material advancements, we then designed transmissive metasurfaces leveraging the bulk electro-optic properties of BTO. Our calculations indicate that, with an optimal crystal orientation and applied field configuration, index changes of up to 0.3 are attainable with applied fields around 0.3 MV/cm at visible wavelengths. Using this response, we simulated a transmissive metasurface operating at $\lambda = 628.7$ nm, achieving a phase modulation of 272.7° with an associated transmittance modulation from $50 - 97\%$. Using this design, we simulated beam steering up to ±58° with diffracted transmission efficiencies between $17 - 24\%$. Finally, leveraging the broad transparency window of BTO, we adapted this design for beam steering in transmission at RGB wavelengths.

To conclude, we outlined pathways toward the realization of a universal active metasurface, highlighting the need for advancements in materials, design methodologies, and scalable control architectures for two-dimensional wavefront shaping. We envision key research directions that include the discovery of low-loss, high-speed tunable materials, the development of unit cell designs that enable independent control over multiple properties of light, and the miniaturization of electrical control networks for large-scale metasurfaces. Addressing these challenges will require a multidisciplinary approach integrating nanophotonics, materials science, and computational design. Ultimately, the results presented in this thesis provide a foundation for realizing reprogrammable, intelligent optical systems that dynamically adapt to diverse technological demands in transformative applications.