Design of Tunable Nanophotonic Devices

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Abstract: This tutorial addresses design of tunable nanophotonic arrays, enabling dynamic, active control of the properties of light – amplitude, phase, wavevector, wavelength and polarization – opening new applications such as optical beam steering, focusing and wavefront engineering.

1. Introduction

Achieving versatile dynamical control of the key constitutive properties of light at the nanoscale is a grand challenge for nanophotonics. In the last several years, metasurfaces have shown extraordinary promise to achieve such comprehensive control over the characteristics of scattered light. Metasurfaces can be viewed as artificially designed arrays of subwavelength optical scatterers, where each scatterer introduces abrupt changes to the phase, amplitude or polarization of the reflected or transmitted electromagnetic waves[1-3]. Thus, metasurfaces offer the ability to control the wavefront of the scattered light, thereby creating new flat optics and ultrathin optoelectronic components[4, 5]. To date, metasurfaces have been used to demonstrate a number of low-profile optical components with important capabilities including focusing[6-9], polarization control and detection[10-12], holograms[13-15], and quantum light control[16, 17].

Among the large volume of experimental reports about metasurfaces, most demonstrated so far are passive. For passive metasurfaces, the light scattering characteristics are defined by the geometry and arrangement of subwavelength scatterers, fixed at the time of fabrication. In contrast to passive metasurfaces, actively-tunable metasurfaces can realize multiple functions[18-20], serving as low-profile nanophotonic devices capable of beam steering, active polarization switching, and formation of reconfigurable metalenses.

So far, a number of different methods have been used to realize tunable metasurfaces, commonly by incorporating an active material into the metasurface structure. The dielectric permittivity of the active material is then dynamically controlled via application of an external stimulus such as an electrical bias[21, 22], laser pulse[23], or heat input[24]. Reconfigurable metasurfaces, which are based on incorporating active materials into otherwise passive antenna arrays, are hereafter referred to as hybrid metasurfaces. For example, incorporation of monolayer graphene into a plasmonic metasurface can enable active tuning of the spectral response by electrically tuning the Fermi level of the graphene sheet[25-27]. Electrical tuning of the coupling between metasurface resonances and intersubband transitions in multiple-quantum-wells (MQWs) has also been explored for applications such as tunable filters[28] and optical modulators at mid-infrared wavelengths[29]. To achieve active metasurface performance at visible and near-infrared (NIR) wavelengths, the integration of metasurfaces with phase-change materials or liquid crystals has enabled the demonstration of phase modulation and active beam switching. Modulation of the dielectric permittivity near the epsilon-near-zero (ENZ) transition in doped transparent conducting materials can yield large optical modulation of the scattered light, and to date the ENZ transition in indium tin oxide and titanium nitride has been exploited to electrically tune the properties of scattered/emitted light. These hybrid metasurfaces operate by spectrally overlapping the geometrical antenna resonance and the ENZ permittivity regime, and also spatially overlapping the metasurface element mode profile with the tunable permittivity transparent conducting material. To enable a widely tunable optical response, strong local field confinement and enhancement in the active material is required. Prior research has also combined tunable metasurface optics with microelectromechanical systems (MEMS) technology to demonstrate varifocal lenses. Moreover, previous work has shown that fabricating metasurfaces on elastomeric substrates may yield adaptive metalenses, strain-multiplexed meta-holograms, and an active control of the structural color. However, in MEMS-based and mechanically stretchable substrate modulation approaches, control of the optical response is achieved by changing the distance between either adjacent metasurface elements or entire element arrays, and requires a mechanical transducer, which limits the frequency bandwidth. While interesting, these approaches are not able to yield versatile active control over the scattered light wavefront over a wide frequency range. This condition can only be realized by electronic tuning the optical response of each metasurface element.

Fabricating metasurface elements directly in an active material could substantially simplify the metasurface design and facilitate the fabrication process. For example, prior research has used phase-change materials as metasurface building blocks to achieve actively tunable optical responses. The ability to rewrite metasurface patterns incorporating phase-change materials with a pump laser has enabled the demonstration of multiple functions when using a single sheet of either GST or VO_2. However, the tuning speed of the phase-change-material-based tunable metasurfaces is usually slow because the phase transition speed is typically limited by the thermal response time in material heating.

2. References:

1.Hsiao H.-H., Chu C. H., Tsai D. P. Fundamentals and applications of metasurfaces. *Small Methods* **1**, 1600064 (2017).
2.Yu N., Capasso F. Flat optics with designer metasurfaces. *Nat. Mater.* **13**, 139-150 (2014).
3.Minovich A. E., Miroshnichenko A. E., Bykov A. Y., Murzina T. V., Neshev D. N., Kivshar Y. S. Functional and nonlinear optical metasurfaces. *Laser Photonics Rev.* **9**, 195-213 (2015).
4.Haffner C., Heni C., Fedoryshyn Y., Niegemann J., Melikyan A., Elder D. L., et al. All-plasmonic Mach–Zehnder modulator enabling optical high-speed communication at the microscale. *Nat. Photon.* **9**, 525-528 (2015).
5.Lee H. W., Papadakis G., Burgos S. P., Chander K., Kriesch A., Pala R., *et al.* Nanoscale conducting oxide PlasMOStor. *Nano Lett.* **14**, 6463-6468 (2014).
6.Wang S., Wu P. C., Su V.-C., Lai Y.-C., Chen M.-K., Kuo H. Y., *et al.* A broadband achromatic metalens in the visible. *Nat. Nanotechnol.* **13**, 227-232 (2018).
7.Chen B. H., Wu P. C., Su V.-C., Lai Y.-C., Chu C. H., Lee I. C., *et al.* GaN metalens for pixel-level full-color routing at visible light. *Nano Lett.* **17**, 6345-6352 (2017).
8.Aieta F., Genevet P., Kats M. A., Yu N., Blanchard R., Gaburro Z., *et al.* Aberration-free ultrathin flat lenses and axicons at telecom wavelengths based on plasmonic metasurfaces. *Nano Lett.* **12**, 4932-4936 (2012).
9.Chen W. T., Zhu A. Y., Sanjeev V., Khorasaninejad M., Shi Z., Lee E., *et al.* A broadband achromatic metalens for focusing and imaging in the visible. *Nat. Nanotechnol.* **13**, 220-226 (2018).
10.Wu P. C., Chen J.-W., Yin C.-W., Lai Y.-C., Chung T. L., Liao C. Y., *et al.* Visible metasurfaces for on-chip polarimetry. *ACS Photonics* **5**, 2568-2573 (2018).
11.Rubin N. A., Zaidi A., Juhl M., Li R. P., Mueller J. P. B., Devlin R. C., *et al.* Polarization state generation and measurement with a single metasurface. *Opt. Express* **26**, 21455-21478 (2018).
12.Chen W. T., Török P., Foreman M. R., Liao C. Y., Tsai W.-Y., Wu P. R., *et al.* Integrated plasmonic metasurfaces for spectropolarimetry. *Nanotechnology* **27**, 224002 (2016).
13.Lin J., Genevet P., Kats M. A., Antoniou N., Capasso F. Nanostructured holograms for broadband manipulation of vector beams. *Nano Lett.* **13**, 4269-4274 (2013).
14.Huang Y.-W., Chen W. T., Tsai W.-Y., Wu P. C., Wang C.-M., Sun G., *et al.* Aluminum plasmonic multicolor meta-hologram. *Nano Lett.* **15**, 3122-3127 (2015).
15.Kamali S. M., Arbabi E., Arbabi A., Horie Y., Faraji-Dana M., Faraon A. Angle-multiplexed metasurfaces: encoding independent wavefronts in a single metasurface under different illumination angles. *Phys. Rev. X* **7**, 041056 (2017).
16.Jha P. K., Ni X., Wu C., Wang Y., Zhang X. Metasurface-enabled remote quantum interference. *Phys. Rev. Lett.* **115**, 025501 (2015).
17.Stav T., Faerman A., Maguid E., Oren D., Kleiner V., Hasman E., *et al.* Quantum entanglement of the spin and orbital angular momentum of photons using metamaterials. *Science* **361**, 1101-1104 (2018).
18.Wu P. C., Zhu W., Shen Z. X., Chong P. H. J., Ser W., Tsai D. P., *et al.* Broadband wide-angle multifunctional polarization converter via liquid-metal-based metasurface. *Adv. Opt. Mater.* **5**, 1600938 (2017).
19.Dong K., Hong S., Deng Y., Ma H., Li J., Wang X., *et al.* A Lithography-free and field-programmable photonic metacanvas. *Adv. Mater.* **30**, 1703878 (2017).
20.Arash N., Qian W., Minghui H., Jinghua T. Tunable and reconfigurable metasurfaces and metadevices. *Opto-Electronic Advances* **1**, 180009 (2018).
21.Thyagarajan K., Sokhoyan R., Zornberg L., Atwater H. A. Metasurfaces: millivolt modulation of plasmonic metasurface optical response via ionic conductance. *Adv. Mater.* **29**, 1701044 (2017).
22.Yao Y., Shankar R., Kats M. A., Song Y., Kong J., Loncar M., *et al.* Electrically tunable metasurface perfect absorbers for ultrathin mid-Infrared optical modulators. *Nano Lett.* **14**, 6526-6532 (2014).
23.Shcherbakov M. R., Liu S., Zubyuk V. V., Vaskin A., Vabishchevich P. P., Keeler G., *et al.* Ultrafast all-optical tuning of direct-gap semiconductor metasurfaces. *Nat. Commun.* **8**, 17 (2017).
24.Dicken M. J., Aydin K., Pryce I. M., Sweatlock L. A., Boyd E. M., Walavalkar S., *et al.* Frequency tunable near-infrared metamaterials based on VO_2 phase transition. *Opt. Express* **17**, 18330-18339 (2009).
25.Miao Z., Wu Q., Li X., He Q., Ding K., An Z., *et al.* Widely tunable terahertz phase modulation with gate-controlled graphene metasurfaces. *Phys. Rev. X* **5**, 041027 (2015).
26.Mousavi S. H., Kholmanov I., Alici K. B., Purtseladze D., Arju N., Tatar K., *et al.* Inductive tuning of Fano-resonant metasurfaces using plasmonic response of graphene in the mid-infrared. *Nano Lett.* **13**, 1111-1117 (2013).
27.Sherrott M. C., Hon P. W. C., Fountaine K. T., Garcia J. C., Ponti S. M., Brar V. W., *et al.* Experimental demonstration of >230° phase modulation in gate-tunable graphene–gold reconfigurable mid-infrared metasurfaces. *Nano Lett.* **17**, 3027-3034 (2017).
28.Benz A., Montaño I., Klem J. F., Brener I. Tunable metamaterials based on voltage controlled strong coupling. *Appl. Phys. Lett.* **103**, 263116 (2013).
29.Sarma R., Campione S., Goldflam M., Shank J., Noh J., Le L. T., *et al.* A metasurface optical modulator using voltage-controlled population of quantum well states. *Appl. Phys. Lett.* **113**, 201101 (2018).