Asymmetric control of light at the nanoscale

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Metamaterials

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Abstract
Breaking reciprocity at the nanoscale can produce directional formation of images due to the asymmetric nonlinear optical response of subwavelength anisotropic resonators. The self-induced passive non-reciprocity has advantages compared to magnet or time modulation approaches and may impact both classical and quantum photonics.

The breaking of symmetry in physical systems can have fundamental implications in their response and alter their operation in a profound and fundamental way. Interestingly, the tantalizing task of asymmetric control of light due to nonlinear light–matter interactions at the nanoscale can lead to the design of novel nanophotonic components, such as asymmetric imaging devices and non-reciprocal directional optical filters. These appealing optical functionalities are mainly hindered by the weak non-reciprocal response of nanophotonic systems and the difficulty in designing asymmetric subwavelength resonators with enhanced optical nonlinear response.

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Recent progress in electromagnetics has demonstrated the ability to break reciprocity in a variety of ways, such as material nonlinearities, external magnetic fields and time-modulated media.[1,2] Although the use of magnetism is the most widely used technique to break reciprocity, magnets are bulky, lossy and expensive, making this approach impossible to implement on chip-integrated nanophotonic circuits. Hence, we need to resort to dynamically modulated systems to enable nanoscale non-reciprocity. However, the use of time modulation to break reciprocity is challenging in optical frequencies mainly due to its weak response, power inefficiency and increased complexity of electro-optical modulators.[2] Interestingly, non-reciprocity by exciting optical nonlinear effects in asymmetric configurations is a more appealing passive technique that benefits from the absence of any kind of external bias.[3,4] Although self-induced non-reciprocal structures cannot be used as isolators under two or more co-existing excitations,[5] they are ideal to realize non-reciprocal routing of pulsed signals for LiDAR applications,[3] non-reciprocal directional filters and optically controlled transmission switches, and ultrathin protective layers for sensitive optical components, for example, asymmetric limiters to protect a pulsed laser source from damage due to the detrimental back reflection of light.[4] The nonlinear non-reciprocal system is self-biased by the signal itself travelling through its structure, making this modulation technique more attractive to implement due to its relative simple design and reduced power requirements.

Now, writing in *Nature Photonics*, Kruk et al. propose a sophisticated ultrathin nonlinear dielectric metasurface design composed of engineered subwavelength anisotropic resonators to achieve non-reciprocal asymmetric generation of visible images with extremely high contrast range.[6] The demonstrated nanophotonic design can substantially enhance nonlinear light–matter interactions at the nanoscale leading to asymmetric control of the generated light with important implications for both classical and quantum photonics. Although asymmetric imaging is mainly presented,[6] the proposed nanophotonic system can go beyond light parametric generation and may find applications in asymmetric generation of entangled photon pairs as well as in asymmetric self-action effects leading to efficient non-reciprocity at the excitation frequency.[3,4]

The inventive anisotropic subwavelength cylindrical resonator designs can achieve magneto-electric coupling at the nanoscale. When this functionality is combined with the inherent geometrical asymmetry of the nonlinear nanostructure, it can lead to the breaking of reciprocity in a self-induced fashion without any additional external bias or modulation. The ability to engineer optical interactions beyond the electric dipole mode by utilizing a strong optically induced magnetic response combined with robust magneto-electric coupling can pave the way towards novel functionalities of nonlinear nanoscale optical metadevices beyond the limitations of the current linear optics.

The demonstrated asymmetric nonlinear nanoresonators are assembled into large-scale translucent metasurfaces, leading to substantially asymmetric transmission of nonlinearly generated light with respect to reversals in the positions of the infrared emitters and the visible light receivers. Moreover, Kruk et al. move beyond uniform metasurface designs consisting of identical nanoresonators to non-uniform metasurface clusters assembled from a set of dissimilar resonators.[6] Nonlinear metasurfaces can generate, in principle, light through harmonic-generation processes with different parameters, including intensity, phase and polarization.[7] In the study by Kruk et al., the metasurface is optimized to produce only different intensity harmonic-generated waves,[6] a functionality reminiscent of conventional spatial light modulators but achieved at the nanoscale. This effect leads to different images produced by forward or backward excitations that are limited to binary intensity, that is, either ON or OFF, for the generated light. Finally, the nonlinear imaging metasurfaces are placed on a substrate that introduces additional asymmetry to an already highly asymmetric system. The shape of the cylindrical resonators is also changed to an elliptical cross-section to allow for an extra geometrical parameter in the optimization process of the asymmetric image brightness. The resulting imaging pixels can generate different images depending on the direction of sample illumination, as depicted in **Fig. 1.**

While the idea of the presented concept is original and the implementation is state of the art in terms of optical design and nanofabrication, various limitations still exist that, if alleviated, promise to further improve the impact of the confirmed asymmetric control of light. The image generation in the third-harmonic response of the

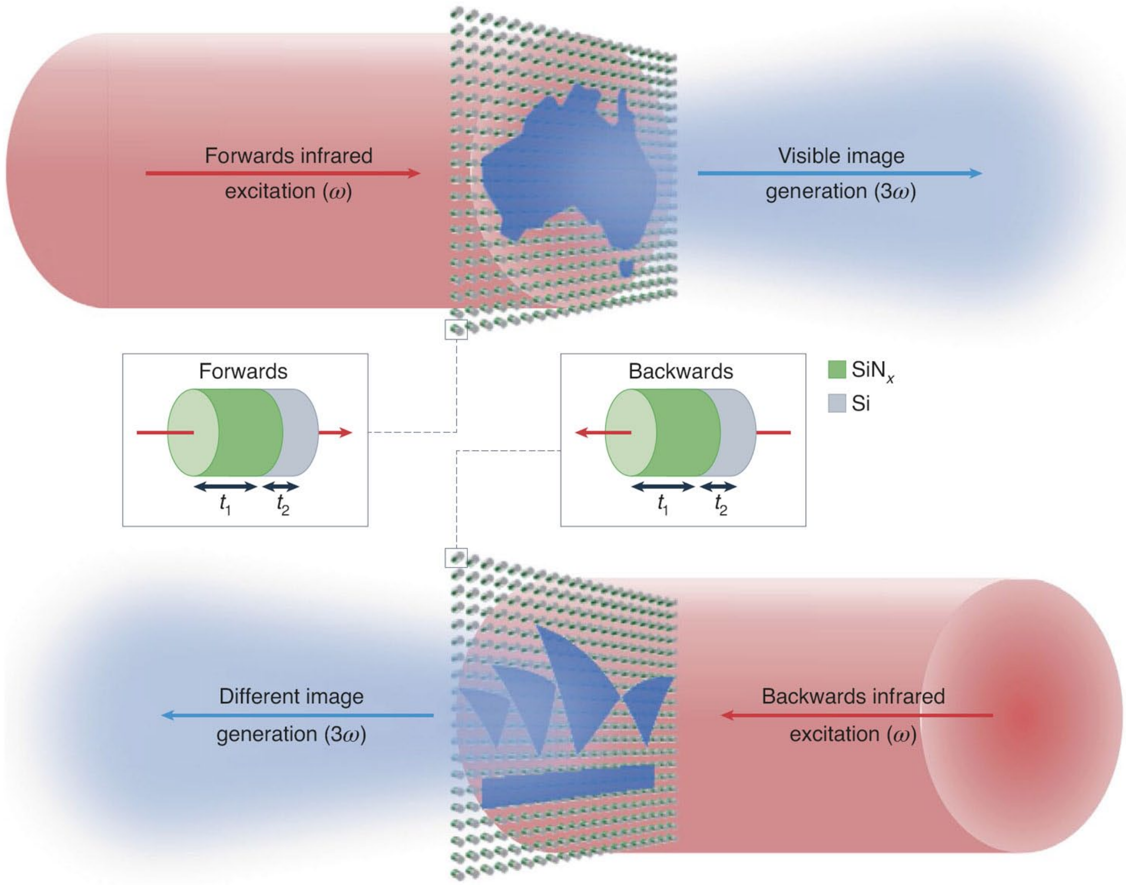

Fig. 1 Asymmetric imaging generation with nonlinear anisotropic dielectric metasurfaces. Directional formation of images is achieved at the third-harmonic-generation frequency by using nonlinear anisotropic dielectric metasurfaces with asymmetric geometry and strong magneto-optical coupling. The unit cell is composed of subwavelength nanoresonators based on silicon nitride (SiN_x) and amorphous silicon (Si) with different thicknesses that are equal to t_1 = 400 nm and t_2 = 220 nm, respectively. ω is the fundamental frequency. Figure adapted from ref. 6, Springer Nature Ltd.

demonstrated ingenious metasurface designs is limited to pixel sizes that are much larger than the wavelength. In addition, the produced images are restricted to binary intensity resolution. The image quality can be further improved and enhanced if geometrical phase control is achieved by each nonlinear metasurface. This will lead to asymmetric anomalous beam steering, directional hologram generation and several other intriguing nonlinear optical functionalities.[7] The harmonic-generation efficiency of the presented metasurfaces is also relatively low (~10^{-5} range) and needs to be substantially enhanced to realize energy-efficient practical imaging applications. The increase in power efficiency can potentially lead to asymmetric control of quantum light at the ultimate low-power limit, that is, the single-photon level. This quantum functionality may be possible with metasurfaces supporting more exotic resonances than the current magneto-optical coupling, such as bound states in the continuum.[8] In addition, active asymmetric systems based on the co-existence of nonlinearity and parity–time symmetry can further improve the power-efficiency performance.[9,10] Finally, the breaking of reciprocity at the excitation frequency based on the Kerr effect,[3,4] which is a different optical nonlinear process than the presented harmonic generation, is a major challenge to be implemented at the nanoscale and can be addressed in the future. However, the currently demonstrated ingenious nonlinear metasurface designs and their asymmetric imaging properties point to the correct direction towards realizing self-induced non-reciprocity that is expected to lead to numerous practical devices exploiting the intriguing physics of asymmetric nanophotonic systems.

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Competing interests The author declares no competing interests.

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