METAMATERIALS

Heat-assisted nonreciprocity

Transmitting light forward only in metasurfaces can be realized by embracing, rather than mitigating, thermal effects in carefully engineered metasurfaces.

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Making light travel one way only is not easy. The principle of Lorentz reciprocity stands in the way. Simply put, Lorentz reciprocity states that if light flows left to right, it must be able to flow right to left. Lorentz reciprocity makes it difficult to protect lasers from back reflections. Because of reciprocity, light emitted from a laser can be reflected to the laser itself, causing harm to the laser. To prevent that from happening, an element that breaks reciprocity is necessary. Nonreciprocal elements typically exploit magnetic effects which, unfortunately, are weak. As a result, those elements are bulky and difficult to integrate with other photonic technologies. Alternative methods have therefore received considerable interest in recent years.

Systems whose properties depend on the intensity of light, via so-called nonlinear effects, have long been recognized as an interesting route to nonreciprocity[1, 2]. However, nonlinear effects are usually also weak in thin films. Greater intensities can sometimes be used to compensate for weak nonlinearities, but that is not always possible. Wavelength- or sub-wavelength scale scatterers tend to heat up under laser irradiation and can even explode at modest intensities[3]. While light-induced temperature changes can in principle be harnessed to manipulate light at the nanoscale, most efforts in the photonics community have focused on mitigating thermal effects, such as added noise[4] or limited switching speeds[5].

Taking a different stance, two works reported in *Nature Photonics* demonstrate that thermal effects can be a powerful resource for manipulating light and achieving nonreciprocity in compact metasurfaces. Metasurfaces are thin films of scattering elements designed to manipulate waves, such as light, in unconventional ways. Jonathan King *et al.*[6] and Michele Cotrufo *et al.*[7] present innovative designs of nonlinear metasurfaces that can be switched between states with different transmission by varying the intensity of the incident radiation, contributing important experimental advances on the nonlinear route to nonreciprocity.

The two groups rely on the same three ingredients to make their metasurfaces nonreciprocal: a resonance, a structural asymmetry and a material nonlinearity. To see how this works, consider the situation depicted in Fig. 1. A metasurface can be illuminated from the front or the back. When the optical frequency is close to a resonance of the metasurface, energy is stored inside the metasurface. A small fraction of that stored energy is then absorbed and converted into heat. This heat modifies the refractive index of the material in an intensity-dependent way, thereby establishing a nonlinear process. The key point enabling nonreciprocity is that the stored energy and generated heat are different for front and back illumination (Fig. 1a, insets). This difference is due to the structural asymmetry in the metasurface, which couples light into the resonance more efficiently from one side than from the other. The net result is nonreciprocal transmission – more light flows one way than in the opposite way.

While both groups have achieved nonreciprocity following the same recipe explained above, the advances that they each present are complementary. Cotrufo *et al.* focus on the first two ingredients: engineering the resonance and the structural asymmetry[7]. They use silicon. Light-induced heating and nonlinear effects are well known to occur in silicon[8], but their use to achieve functional metasurfaces has not been demonstrated. By carefully tuning the geometry across multiple iterations of metasurfaces, Cotrufo *et al.* have shown that they can enhance the range over which the device is nonreciprocal (Fig. 1b). Specifically, they have experimentally demonstrated nonreciprocal transmission over a large range of intensities, with nonreciprocal ratios larger than 10 dB and insertion loss lower than 3 dB for average input intensities in the 1-5 KW cm^{-2} range. However, there is a catch: the stronger the nonreciprocity, the weaker the transmission in the preferred direction. In fact, there is a rigorous upper bound to the nonreciprocal intensity range for a given maximum transmission[9,10] (Fig. 1b). In this context, Cotrufo and coworkers have shown that their metasurfaces operate near this bound and thus perform in the most energy efficient way, meaning they lose as little of the input power as possible.

The main innovation of King *et al.* is in the third ingredient of the recipe – the material nonlinearity[6]. Instead of relying on silicon, the team use vanadium dioxide (VO_2). VO_2 is a phase-change material that switches from an insulating to a conducting phase near 68 degrees Celcius. This phase transition has dramatic consequences for the transmission of the metasurface. King *et al.* have realized that by applying heat to their metasurface, they could bias it close to the phase transition where a large change in transmission can occur. At that point, an incident light beam could provide the last bit of heating that pushes the material over the edge of the phase transition. Effectively, they have enhanced the strength of the nonlinear effects in their metasurface by combining the phase transition of VO_2 with external heating. However, purely nonlinear effects are not enough for nonreciprocity. Just like Cotrufo *et al.*, King *et al.* need to engineer a metasurface with a resonance that is excited more efficiently from one direction than from the opposite. To that end, they fabricated a resonant array of tiny square apertures in a metal film on top of the VO_2. They demonstrated an intensity regime in which infrared radiation transmits better one way than in the opposite way, while maintaining reasonable transmission levels. Furthermore, by adjusting the external heating (achieved by running current through the metal film, which thus conveniently performs a double role), the nonreciprocity threshold could be tuned (Fig. 1c). The reported experiment illustrates a powerful approach to achieve strong nonlinearities and hence nonreciprocity, based on the physics of phase transitions.

Advances on nonreciprocity akin to those reported by King *et al.* and Cotrufo *et al.* have largely been motivated by the need to make compact, broadband and energy-efficient optical isolators. These are nonreciprocal devices that are widely used to protect lasers from destabilizing back reflections. The devices by these two groups are compact and attractive for free-space applications, but they also suffer from important limitations. First and foremost, the slowness of thermal effects. When changing the intensity, it takes about a microsecond for the temperature profile, and hence the refractive index, to stabilize. This limits the maximum rate at which pulses, or information, can be transmitted nonreciprocally to about a MHz. In addition, nonreciprocal devices relying on nonlinear effects are well known to protect against a limited class of signals. In particular, the nonreciprocity can be compromised when signals are incident on the metasurface from both directions simultaneously[11]. Finally, both systems suffer from a fundamental trade-off between the power range over which they behave non-reciprocally and the amount of reflected light. These issues and trade-offs make up for a grand challenge that will likely continue to stimulate innovations and many technological developments, yet whether an all-encompassing solution exists remains unclear.

Some of the limitations of current metasurfaces can be readily addressed using recently developed concepts in the field. For example, the trade-off between reflection and isolation range can be improved by involving additional resonances[10,12]. In addition, thermal engineering can also improve the operation speed, with recent work suggesting sub-ns cooling times for thermal nonlinearities[13]. Finally, engineered materials with stronger and/or faster nonlinearities[14] may be employed, or even new materials with phase transitions near room temperature. Exploiting phase transitions seems particularly promising for reducing the power needed for nonlinear effects. However, at the transition point, systems usually become extremely slow. As a result, there is a trade-off between energy efficiency and speed. Whether and how the phase-change materials can be properly integrated with photonic devices remains to be seen. For now, the works of Cotrufo *et al.* and King *et al.* illustrate that the conversion of light into heat offers more than just absorption or losses. It can be a powerful route to realize nonlinear effects and enable unprecedented functionalities of metasurfaces.

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Competing Interests

The authors declare no competing interest.

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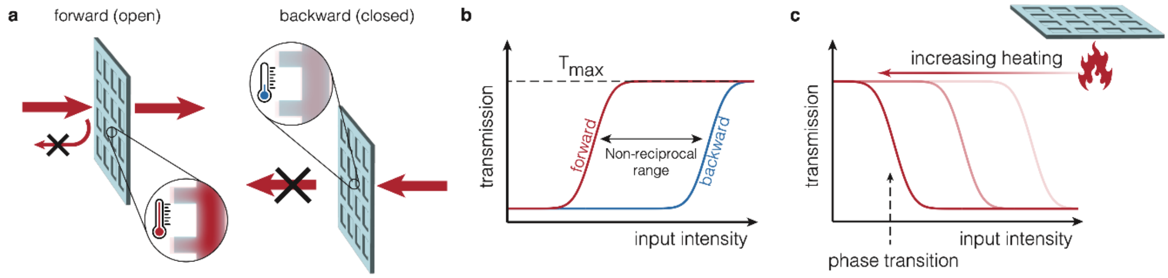

Fig. 1. Nonreciprocity in metasurfaces through heat. a, Schematic of an ideal nonreciprocal metasurface. It transmits fully in the forward direction, but nothing in the backward direction. This nonreciprocity emerges from the combination of a resonance, a structural asymmetry, and a nonlinear response associated with heating. Essentially, the metasurface has a resonance that is excited more efficiently from one side than from the other, resulting in different metasurface temperatures (see insets). As a result, due to the thermal nonlinearity, the transmission of the metasurface is direction dependent. **b,** The transmission of these metasurfaces is a nonlinear function of the incident intensity, which can be very different for opposite directions of incidence. Consequently, an intensity range opens up over which the device is strongly nonreciprocal. Cotrufo *et al.* demonstrate that a trade-off exists between the intensity range and the maximum transmission[7]. **c.** By tuning the steady-state temperature of their nonreciprocal device, King *et al.* show that the threshold power for nonreciprocity can be tuned by roughly an order of magnitude[6].