METAMATERIALS

Designing disorder

Metasurfaces can in principle provide a versatile platform for optical functionalities, but in practice designing and fabricating them to specifications can be difficult. Now, the realization of metasurfaces with engineered disorder allows for versatile optical components that combine the best features of periodic and random systems.

Jacopo Bertolotti

It might come as a surprise to some, but it is now well understood that a completely disordered and scattering optical medium can sometimes outperform the most carefully designed and engineered photonic device[1]. Disordered structures completely scramble any incident light, producing high transverse wavevectors that can be used to generate a very sharp focus[2], or multiple foci[3], whose position can be freely moved[4]. The scrambling also mixes spatial and temporal degrees of freedom, allowing the manipulation of the temporal response of the system[5,6]. Recent results even showed that a scattering material can be used as a tunable interferometer for the control of quantum states of light[7,8]. The price to pay when using disordered media is that the response function of the system is complex and unknown. Therefore, before a scattering material can be of any use, it has to be carefully characterized — a lengthy and often difficult task[9].

Now, writing in *Nature Photonics*, Jang et al. demonstrate wavefront shaping with disorder-engineered metasurfaces, reaping the advantages of disordered systems and keeping disadvantages to a minimum[10]. In particular, they show that a disordered metasurface can be used to obtain high resolution and a large field of view at the same time, well beyond what is possible with conventional optics.

When designing an optical device, it is often useful to do it modularly. A properly designed lens will have a predictable and repeatable effect on a collimated beam, and so will a diffraction grating, a beam splitter or a polarizer. By chaining such elementary building blocks, one can reliably construct more complex systems like a Mach–Zehnder interferometer, which can, in turn, be used as a building block for an even more complex device. This approach has the advantage of being dependable and easy to engineer for optimal performance, but it also suffers from a lack of flexibility. The ability to change even just the focal length of a single lens requires a complex design, which often translates into higher costs. In many cases, it is much simpler (and cheaper) to just swap optical components when different functionality is required, rather than design a tunable system.

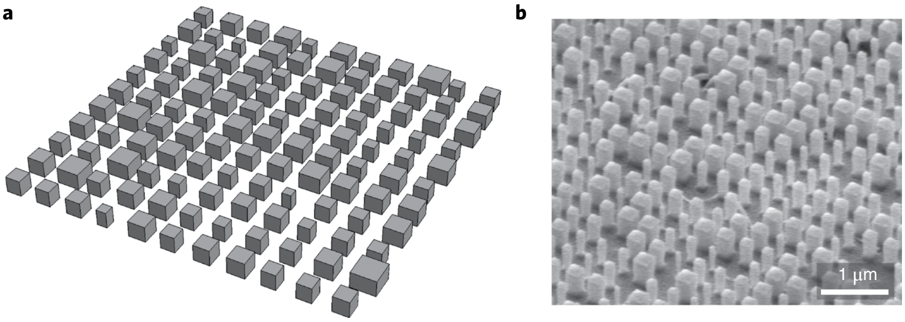

Fig. 1 | Engineered disordered metasurfaces. a, Using a subwavelength array of nanopillars of variable width, a disordered metasurface with a known scattering matrix can be designed. **b**, After it is fabricated, such a structure can be immediately used as an optical device without requiring any lengthy characterization. Panel **b** reproduced from ref. [10], Macmillan Publishers Ltd.

At first sight, disordered media do not seem a likely candidate to compete with highly engineered optical systems. In fact, when light interacts with a disordered material it is scattered multiple times and completely scrambled, resulting in a seemingly unpredictable and chaotic output. On the other hand, scattering from a disordered material is actually still a completely deterministic process; it might look complicated, but there is nothing truly random in it. If the input intensity is doubled in the same random medium, twice the very same output intensity will be achieved. It is therefore possible to characterize the system response to every possible input, and summarize it as a scattering matrix S. The elements of this matrix are each given by the combination of a very large number of uncorrelated contributions (the individual scattering events), and thus S can be described to a very good approximation as a random matrix[11]. As a large enough set of random vectors can be used as a complete basis, the knowledge of S allows the generation of practically any output one might desire[12].

Usually, the full characterization of S requires an interferometric measurement for every possible input. However, if the microscopic structure of the scattering system is known, Maxwell's equations can be numerically solved and S can be obtained without any measurement. Thus, the logical solution would be to fabricate a known disordered system. After all, if the exact position of each scatterer is known, as well as its scattering cross section, S can be computed. The problem with this approach is that light diffusion in a multiple scattering medium is a fully developed chaotic process[13], where any change in the boundary condition (for example, the exact position of a scatterer) can modify the final output in an unpredictable way. Jang et al. show that this problem can be overcome for a particularly interesting case: a disordered metasurface. Since a metasurface is extremely thin, light is scattered only once when passing through it, thus avoiding any problem with chaos. Despite not being a fully fledged 3D scattering medium, there is still a lot one can do with a disordered metasurface, especially because an engineered metasurface can be made to approximate very well the idealized disorder case that is often used (Fig. 1). In fact, the structure fabricated by Jang et al. is very thin and consists of a subwavelength array of nanopillars with random widths, which results in very high transverse wavevectors together with a wide memory effect range (that is, adding a phase gradient to the input adds the same phase gradient to the output), a combination that is difficult to achieve with natural or self-assembled systems. While the engineered disordered metasurface doesn't do anything that a conventional thin scattering medium can't do, its strength lies in its simplicity of use and reliability. As the scattering matrix is known a priori, such a metasurface can be used as a wide-field and high-magnification optical component without any characterization (once it is properly aligned). Furthermore, contrary to many self-assembled systems that tend to drift with time, the engineered metasurface is extremely durable and stable, making it realistic for use as an everyday component, such as in a microscope.

It is still unclear whether it will ever be possible to reliably design and fabricate the full 3D multiply scattering media necessary to control quantum states or the time evolution of laser pulses, but 2D disordered metasurfaces offer many optical functionalities and the freedom to tune them at will. It would be no surprise if such devices became commonplace in tomorrow's microscopes. ❐

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OPTICAL PHYSICS

Broadband optomechanical non-reciprocity

Implementing non-reciprocal elements with a bandwidth comparable to optical frequencies is a challenge in integrated photonics. Now, a phonon pump has been used to achieve optical non-reciprocity over a large bandwidth.

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Non-reciprocal elements play an important role in photonic circuits. Two hallmark examples are optical isolators and circulators, where the input–output relations are not symmetric. Specifically, an isolator allows for transport in one direction and suppresses it in the other, and a circulator is essentially a multiport generalization of an isolator. Developing such devices at the microscale is crucial for routing photons and reducing backscattering and parasitic interference effects in integrated photonic circuits.

Non-reciprocity can be achieved by locally breaking time-reversal symmetry. For example, time-reversal symmetry can be broken by applying a magnetic field in materials with strong magneto-optical responses. A Faraday rotator is an example of such a device that rotates the polarization of light in a non-reciprocal fashion. However, due to the weakness of the magneto-optical effect in materials used in nanophotonics as well as the difficulties in controlling large magnetic fields at small length scales, this approach may not be suitable for engineering on-chip non-reciprocity.

In recent years, there has been an active search for alternatives to magneto-optical non-reciprocity. In a seminal work published in 2009, Yu and Fan proposed that isolation in a nanophotonic system can be achieved by modulating the refractive index of the material[1]. The modulation provides the momentum and energy required for an interband photonic transition. Specifically, because of the phase-matching condition, the transition is only allowed for photons travelling in one direction and is non-reciprocal. This proposal was implemented in 2012 in an electrically driven silicon chip[2]. In the same year, it was proposed that non-reciprocity can also be achieved in optomechanical systems[3]. In this scheme, non-reciprocal interactions are realized by selective enhancement of the optomechanical coupling in one direction by optical pumping.

Recently, this proposal was implemented in a whispering gallery microresonator[4] and later generalized to other optomechanical systems[5]. Previous optomechanical implementations have relied on optical modulation with a laser to achieve non-reciprocity[4–6]. In these approaches, the bandwidth of the non-reciprocal behaviour is limited to the kHz–MHz range by the width of the mechanical oscillator resonance.

As reported in *Nature Photonics*, Donggyu Sohn and colleagues from the University of Illinois at Urbana-Champaign have now successfully used mechanical modulations to achieve non-reciprocity over a large GHz bandwidth[7]. Reversing the role of mechanical and optical modes allows the bandwidth to be dictated by the optical loss, which is orders of magnitude larger than its mechanical counterpart.

Sohn et al. used an optomechanical resonator that supports two optical modes (Fig. 1a). Because of the photoelastic effect, these optical modes couple to acoustic waves that are pumped into the structure. The strength of this three-way interaction depends on the overlap of the optical modes and the mechanical displacements. Therefore, when the acoustic mode is modulated, this interaction can lead to a simultaneous absorption of an optical excitation in one of the modes and a mechanical excitation and an optical