Wavefront shaping

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Deep focusing with broadband light

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Broadband energy can be delivered to extended targets deep inside a multiple-scattering system, paving ways for using broadband, partially incoherent light in a wide range of applications, such as deep-tissue imaging, laser therapy and optogenetics.

Light scattering is something that we routinely observe in our everyday lives. For example, when you hold a flashlight up to your hand, the resulting diffuse glow is created by light scattering in a myriad of directions. Many researchers who design microscopes, fabricate random lasers, perform laser surgery, or develop new phototherapy treatments endeavour to better understand this fundamental optical process. In many areas of research like those listed above, gaining better control over how and where light scatters could unlock a variety of exciting capabilities. For example, what if it were possible to guide the flashlight's incident beam towards a specific area deep within the body?

The work of Rohin McIntosh and colleagues, reporting in *Nature Photonics*, takes a key step towards addressing this core challenge[1]. Using new theoretical and experimental insights, the team have successfully demonstrated a robust method to enhance the total amount of energy delivered to deep targeted areas within scattering media using broadband light (Fig. 1).

Over the past decade, researchers have developed a variety of new 'wavefront-shaping' methods to focus and control light within the presence of significant scattering[2]. Most wavefront-shaping methods precisely control the amplitude and phase of a beam across space, which in turn can account for the impact of scattering and thus enhance focusing capabilities. To understand wavefront shaping, it is helpful to imagine a tiny source of light at the location of an intended focus deep within a scattering sample. This small, imagined source will emit radiation that scatters outward, which will eventually form a particular randomized wavefront that emerges at the scattering sample's surface. If one has an ability to capture this randomized wavefront, reshape it, and then 'send it backwards' to retrace its scattered trajectory back through the tissue, it will achieve a tight focus back at its original location. The ability to capture and reshape wavefronts is now enabled by modern digital image sensors and spatial light modulators, which are routinely used in multiple laboratories around the world to measure and subsequently sculpt light into any variety of shapes to enhance deep-tissue focusing[3].

Unfortunately, several key challenges have limited the efficacy of today's wavefront-shaping methods. First, most techniques rely on monochromatic light from a laser, which is sensitive both to small variations within the scattering sample, for example, minute movements, and to the set-up, for example, slight changes in position, angle and illumination wavelength. Second, while there are multiple techniques that can focus monochromatic light efficiently to a very narrow diffraction-limited spot within scattering media, it turns out that it is not so simple to evenly focus it to larger targeted areas, which are areas within the tissue that are significantly larger than the optical wavelength, in part because of the effects of interference.

McIntosh and colleagues address both of these challenges through the development of a theoretical and experimental toolbox that supports effective focusing of polychromatic light into large target areas[1]. Their exciting work builds on the recently published mathematical formulation of the deposition matrix[4], a measurement set that establishes a mapping between an incident wavefront's shape and its resulting deposition of energy at different locations within a scattering sample. By establishing this mapping through experimental measurements and algorithmic computation, it is subsequently possible to establish optimal wavefront shapes to direct polychromatic light into desired target areas at maximum optical energy.

When verifying this concept, it is quite challenging to directly observe how light is behaving inside a scattering sample without perturbing the scattering process itself. To overcome this hurdle, McIntosh and colleagues cleverly limited their observations to just a single two-dimensional (2D) plane of scattering. Specifically, they guided light via a digitally controlled spatial light modulator into

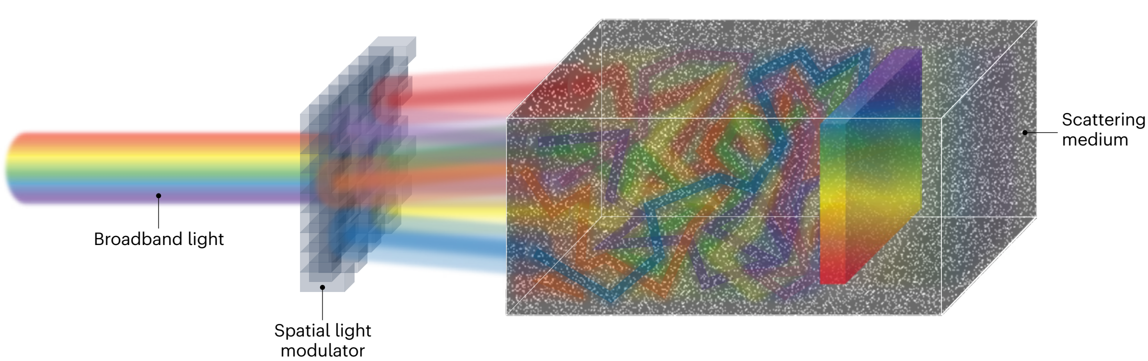

Fig. 1 | Deep focusing to targeted areas within a scattering medium using broadband light. A spatial light modulator shapes a beam of broadband light to focus energy deep within a scattering medium.

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custom-fabricated disordered 2D waveguides. The waveguides contained randomly centred sub-wavelength scattering centers formed by etching holes into the silicon-on-insulator wafer. By capturing light that scattered out-of-plane from the 2D waveguide with a camera, the team was able to directly observe the process of optical scattering as a function of depth to carefully assess their targeted energy delivery efforts.

Surprisingly, the team found that the ability to enhance energy delivered to deep target areas increased as a function of the depth within the scattering material. This new finding — that it is possible to focus more energy the deeper you go inside a disordered material — is of course quite a head-scratcher. Building on prior work[4,5], the team argue that this unexpected trend is caused by what are commonly known as 'long-range' correlations within the scattered light across the target area — a topic originally explored within the context of electron transport through mesocopic structures[6]. These long-range scattering correlations are a bit of an experimental oddity and can be considered as a weaker counterpart to the well-known 'memory effect' correlation that is often used to form images with scattered coherent light[7,8]. A key finding of the work by McIntosh and colleagues is that long-range correlations can also significantly enhance the focusing power of broadband light within scattering media. This result connects an otherwise subtle and difficult-to-observe physical effect to a very clear practical application.

Although it represents a critical first step towards tightly focusing broadband light with wavefront shaping, the method by the team must still undergo further exploration and assessment of its fascinating physical findings. For example, the experimental investigations of their work operated within a waveguide, which does not allow light to escape. In applications like focusing light within biological tissue, light can scatter out and away, where there can be optical loss. Additional experiments may be required to explore polychromatic energy delivery trends in such open systems. Furthermore, it would be fascinating to see if future research can replicate these findings completely non-invasively in 3D materials, instead of within 2D waveguides where one can readily observe what is occurring deep inside.

As an early and somewhat surprising demonstration of the importance of long-range scattering correlations for polychromatic focusing, however, this effort will most definitely inspire follow-on research. For example, new techniques may be developed that enhance optical absorption with long-range correlation effects, which might help improve solar panel efficiencies. This work may also lead to new insights into some other mysteries surrounding long-range correlations, such as their relationship with the memory effect correlation across both local and global scales. As common and widespread as light scattering is, it is amazing to see how new and surprising phenomena continue to emerge that might pave the way for the ability to carefully direct and target light to specific areas within scattering media, such as our bodies, solar panels, waveguides and many more.

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Competing interests

The authors declare no competing interests.