interview

Volume optics

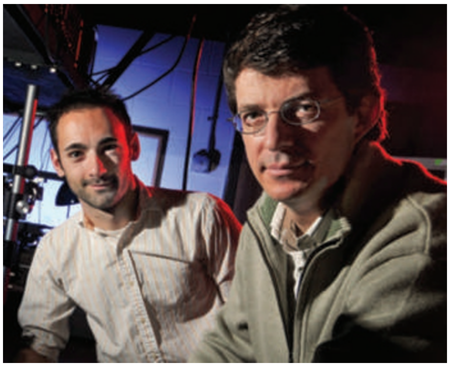
A new method for designing aperiodic volume optical elements will offer researchers more degrees of freedom in the design of optical devices. Rafael Piestun explained to *Nature Photonics* how this method may lead to a myriad of applications in beam-shaping and imaging.

What is volume optics?

Volume optics is a concept for creating optical functionality within a 3D device or system, as opposed to traditional optical design, which involves the plane-to-plane transformation of objects to images. These devices are numerically generated and present 3D structures that control light in multiple dimensions including wavelength, time, 3D space and coherence function. This flexibility is significant because controlling light is a quintessential optical task for researchers, and using all the available degrees of freedom is necessary for higher-dimensional operations. For example, volume optics could perform input-selective beam-shaping, implement multiplexed point-spread functions, shape a pulse in space and time, or encode multispectral information.

What have you achieved?

Our work focuses on the domain of volumetric aperiodic structures. We set out to explore what could be achieved within a given volume by shaping the refractive index according to a computer-generated design. The physical phenomenon is described by a scattering potential, which is quite general and essentially equivalent to imposing Maxwell's equations within a volume. Furthermore, during the design process, we introduced constraints that mathematically express the computation and fabrication limitations. For instance, we set 3D sampling conditions, available space–bandwidth products and achievable index contrasts. We then came up with a way of optimizing the design using a 'projection onto constraints set' algorithm, which is a more general version of the well-known phase-retrieval and iterative Fourier transform methods. The algorithm finds an approximate design solution that matches — as much as possible — all the conditions required from the volume optics. Finally, we fabricated these devices by scanning tightly focused femtosecond laser pulses in the bulk of glass. This 3D micromachining technique proved to be suitable for rapid prototyping and was flexible enough to match our design requirements.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Tim Gerke and Rafael Piestun envisage that their work will be of interest not only to the general optics community, but also to researchers involved with holography, photonic crystals and metamaterials.

What is the physical mechanism behind your work?

The outcome of a design obtained by the volume-scattering approach is a prescription for the refractive index variations inside a volume. Hence, the resulting device could operate on different phenomena depending on the index contrast, spatial gradient, critical dimensions and so on. For instance, if the prescribed index variations are sharp and well-confined, we will have mostly scattering effects, whereas if they are distributed and smooth we will have mostly refraction effects. In our study we defined volumetric pixels spanning a few wavelengths in size, so the dominant effect was diffraction. This ambiguity is interesting because it raises questions as to what the boundaries are among the phenomena of scattering, diffraction, radiation and refraction. Although some scientists might feel strongly about these definitions, they may be satisfied by considering all the definitions to be manifestations of the electromagnetic nature of light described by Maxwell's equations. It is for this reason that we have avoided specific terms such as diffractive, scattering or holographic when describing volume optical elements, as they would unnecessarily limit the generality of the approach.

What are the implications of your findings?

I believe we have established a general methodology for the design of numerically generated volumetric optics. We have succeeded in demonstrating the concept through the design, fabrication and characterization of volume optics that can multiplex arbitrary optical wavefronts in space and wavelength. Volume optics will open up the possibility of exploring new optical phenomena, and will have a wide range of applications in integrated and free-space optics. The possibility of creating aperiodic designs that can improve well-known periodic solutions is particularly intriguing. Because volume optics can generate arbitrary wavefronts while multiplexing in space or frequency, they can find applications in multidimensional pulse- and beam-shaping devices for quantum information and coherent control, for example in multiplexing specialized spatial filters, anti-counterfeiting or spectral imaging. Applications in computational optical sensing are also fascinating because they could exploit the dimensionality advantage of volume optics to perform compressive sensing tasks.

What are the challenges and future work?

We are currently limited by computational and fabrication limitations. One could think of the current state of volume optics as analogous to the state of diffractive optics in the 1960s. For example, it is still a challenge to design and fabricate large 3D strongly scattering structures to the proper level of precision. We are optimistic, however, that ever-increasing computer power and new micro- and nanofabrication techniques will allow more complex designs. Many issues remain to be addressed in future work, including in the fundamental limits, design algorithms and manufacturing scalability.

INTERVIEW BY RACHEL WON

Tim Gerke and Rafael Piestun have an Article on aperiodic volume optics on page 188 of this issue.