quantum information processing for a number of reasons. First, silicon photonics fabrication techniques are well-established in the semiconductor industry and are scalable, with high-level device integration. Second, high-speed silicon optical modulators are available[10]. Third, single-photon superconducting detectors can be integrated onto the optical waveguides made of silicon[11]. This enables high-speed and high-efficiency single-photon detection. Finally, the nonlinear optical properties of silicon and other CMOS compatible materials are the resources for generating photon pairs[12,13] and could be employed for achieving deterministic two-photon gates via coherent photon conversion[14]. Thus, although there are many new practical challenges on the path towards the use of integrated photonic techniques for quantum applications, the quantum technology that Metcalf and colleagues and others are developing fuels expectation for the on-chip implementation of more sophisticated quantum algorithms. ❐

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NON-INVASIVE IMAGING

Peeking through the curtain

Exploiting the 'memory' properties of scattered light allows for single-shot imaging through thin opaque layers, including biological tissue.

Jacopo Bertolotti

A simple glance at your own hand is enough to tell you that your body is opaque. Although it's true that skin and flesh do absorb visible light, the main reason you can't see through your hand is because biological tissue is a very strong scatterer of light and is thus highly effective at scrambling any signal that tries to pass through. As a consequence, non-invasive *in vivo* optical imaging is usually limited to superficial investigation[1]. Now, writing in *Nature Photonics*, Katz and co-workers[2] report a single-shot imaging technique that can retrieve the shape of an object hidden behind a strongly scattering layer.

The interaction of light with matter is a very complex topic, but a simplified picture can carry us a long way. When thinking about light propagating through a disordered medium such as biological tissue, it is intuitively useful to picture a collection of balls (light) that must traverse a pinball machine (the medium) crowded with bumpers and kickers (scatterers made from local inhomogeneities). If there are just a few bumpers, most of the balls will be able to cross the machine, interact with any object on the other side, and come back to you. It is then possible to reconstruct the shape of the object by measuring how many balls come back from each direction, and this is exactly what our eyes do when we look around. Even if there are many bumpers, a few lucky balls will still manage to avoid them all and pass through unscattered, thus forming an image. What one must do is select those lucky few by discarding any that have undergone scattering[3]. If the situation is not too complex, another option is to measure — and thus compensate for — how the pinball machine scatters the balls[4].

However, once the number of bumpers in the machine increases, the problem becomes more complex and therefore more difficult to address. At a certain point there are no more balls that can traverse the machine unscattered, and any ball thrown in will be bounced around in a seemingly random and completely unpredictable way, making any form of compensation impossible. Of course, the presence or absence of an object behind our pinball machine will still have a small effect on how many balls we get back, and from which direction they come. One can try to infer the position of the object by carefully measuring all the balls[5], but this approach is limited in its capability.

Because this pinball analogy is so limited, our simplified picture cannot carry us any further. Thus it is time to abandon this picture and consider light as a wave; coherent light will not only scatter but also interfere, forming complex fringe patterns that complicate the situation even further. Fortunately, interference carries phase information that allows us — at least in principle — to characterize and compensate for the disorder, despite its complexity[6].

The trick used by Katz and colleagues[2] has its roots in astronomy, where a turbulent atmosphere acts as a scattering medium that blurs any picture taken from the ground. One consequence of wave scattering is that the light emerging from a disordered medium is in the form of a complex and seemingly random speckle pattern. This is often considered a hindrance by those trying to use laser light for displays and imaging, because it introduces unwanted artefacts, but it has a few surprising properties that can be exploited to unravel disorder. One of the more counter-intuitive of these properties is the optical memory effect[7] (also known as intrinsic isoplanatism): despite all the scrambling, some memory of the appearance of a light pattern on one side of the scattering medium is retained on the other side. More specifically, if the light coming from a point source produces a given speckle pattern, the light coming from a point source at a small distance d from the first one produces exactly the same speckle pattern, but shifted by d. So, in a sense, some memory is preserved. As a consequence, information about the shape of an object hidden behind a scattering layer is actually encoded inside the apparently random speckle pattern created by the scattered light. Decoding this information

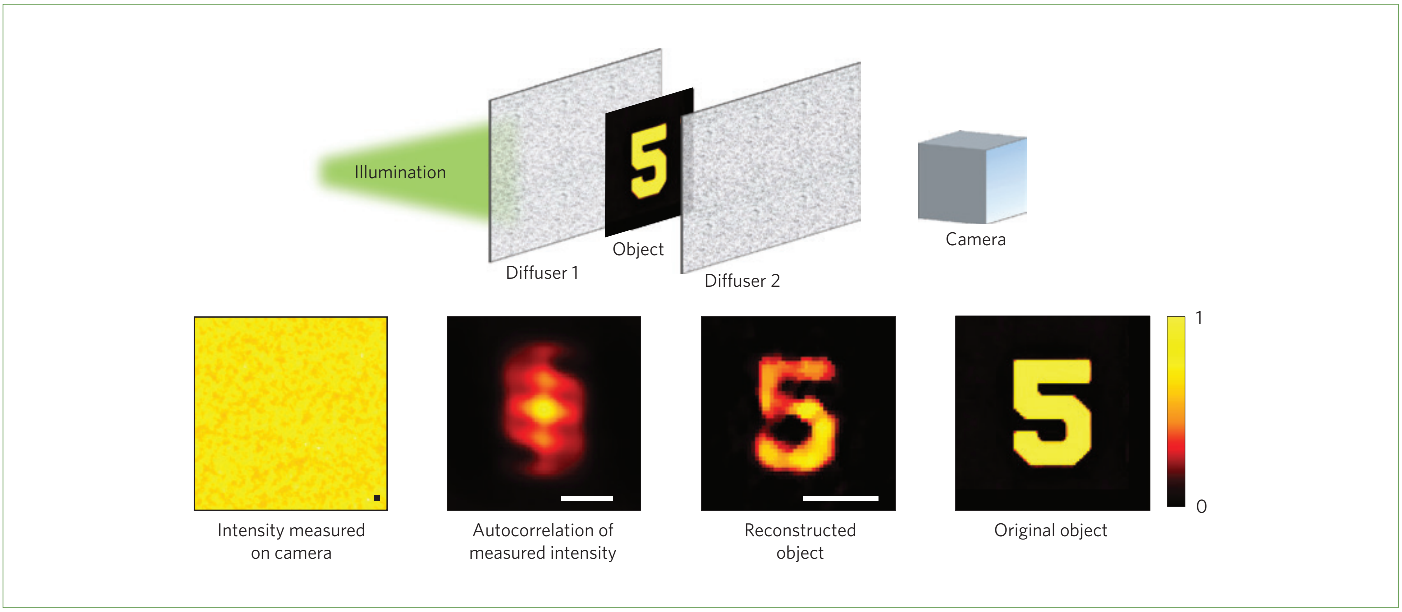

Figure 1 | An object enclosed between two diffusive screens is illuminated by monochromatic light. The light is scrambled as it passes through the first screen. The light then illuminates the object, which is a simple pattern carved in a black screen; when illuminated from the back, the object behaves like an extended source. The light is scrambled again as it passes through the second diffuser, and is then detected by a camera. The measured image looks like an almost flat intensity pattern with some small, seemingly random, fluctuations on top of the background. Information about the object can be retrieved by autocorrelating the measured intensity[8,10] and thus numerically extracting the shape of the original object[9]. The scale bars correspond to 450 μm at the object plane.

to obtain the original shape of the hidden object requires some complex mathematical machinery, but it can be done[8,9].

Ground-based astronomy usually requires us to image the stars through a distorting atmosphere. And because stars are inherent light sources, this ‘stellar speckle interferometry’ approach is relatively straightforward, yielding diffraction limited images of celestial objects through even the most turbulent atmosphere. Unfortunately, applications of this technique in microscopy require complex illumination and long scanning times[10,11].

Katz and co-workers[2] have found a simple and elegant solution to this problem by treating objects hidden behind a scattering screen as if they were stars (Fig. 1). First, they hide an object (actually a screen with an object-shaped hole) behind a scattering medium such as frosted glass, zinc oxide paint or a thin (~300 μm) slice of chicken breast, and then consider each position on the object to be a point source of light. The light from each point is scattered to form identical speckle patterns that are shifted with respect to one other. The seemingly random light intensity pattern that results can be captured, and its autocorrelation is the same as that of the object[8,10]. This autocorrelation can then be numerically inverted and the shape of the hidden object retrieved with very high resolution. The result is a single-shot measurement technique that takes milliseconds to complete and requires only very simple equipment: a high-quality camera and a computer. As an added bonus, Katz and co-workers realized that exactly the same principles can be exploited to image an object positioned around a corner by looking at the light coming from the object and scattered from the wall. It turns out that this procedure is simple enough to be implemented using a smartphone camera.

Of course, this method comes, like every other imaging technique, with its own baggage of limitations and problems yet to be solved — chiefly the limited field-of-view. In fact, the memory effect is valid only in a relatively small range[7], and there is currently no known way of extending it. Furthermore, this method is only valid when looking through a thin scattering layer; if the object is hidden deeply within a scattering medium, the memory effect range will be effectively zero, thereby making imaging impossible. A more delicate point lies on the phase-retrieval algorithms required to ‘decode’ the information about the hidden object[9]. Despite the fact that variants of these algorithms have been known for almost 40 years, obtaining the desired answer without getting stuck at a false solution is still more art than science, thus rendering this method unreliable. Katz and co-workers carried out their experiments using a hole in a black screen as the object, which minimized stray light and thus increased the signal-to-noise ratio. This is a sensible choice when the goal is to demonstrate a new method, but such a simplified geometry is unlikely to perform well in a real microscopy experiment.

The goal of a truly non-invasive technique for imaging hidden objects is still far from reality. But we are making big steps in that direction, and I wouldn’t be surprised if major breakthroughs are forthcoming.

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