FLAT OPTICS

Two-dimensional optical edge detection

Using a photonic crystal slab combined with a conventional optical imaging system, a two-dimensional optical image differentiator is experimentally demonstrated for edge detection.

Wei Yan and Min Qiu

How are objects identified in images? Typically, a person identifies an object by its distinctive features. One important type of feature is edges where discontinuities occur in image brightness, colour, texture or other properties. Edge detection is thus a classic tool for object recognition, an essential step in machine vision and microscopy.

Now, writing in *Nature Photonics*, You Zhou and colleagues report the development of a two-dimensional optical image differentiator (2DOID) for image brightness based on photonic crystals[1]. The compactness of the 2DOID, fabricated on a single glass chip free of bulky optical elements (Fig. 1), allows the authors to flexibly integrate the device into conventional optical imaging systems, such as microscopes and cameras, and to apply edge detection to samples of interest, such as biological cells.

In essence, edge detection methods perform spatial differentiation of quantities of image properties, such as brightness for black-and-white images, thereby highlighting sharp changes while filtering out subtle features. Currently, spatial differentiation is mainly carried out with digital electronic computing, which, however, for real-time and high-throughput image processing, has limitations due to energy consumption and computation speed. Analog optical computing — with minimal energy consumption as a result of material absorption and scattering, and with high computing speed empowered by the speed of photons and ultrafast optical switches potentially down to the femtosecond level — offers a feasible solution to overcome the limitations of digital electronic computing[2,3].

Echoing this solution, emerging nanophotonic structures, such as metamaterials, photonic crystals and metasurfaces, offer versatile platforms for designing compact optical image differentiators (OIDs). Experimentally, one-dimensional OIDs (1DOIDs) have already been realized with various nanophotonic schemes, for example excitation of leaky modes in 1D photonic crystals[4], critical coupling to surface plasmon polaritons[5] and geometric phases[6,7]. Since images are mostly 2D, revealing their edges with 1DOIDs requires multiple measurements that are inconvenient.

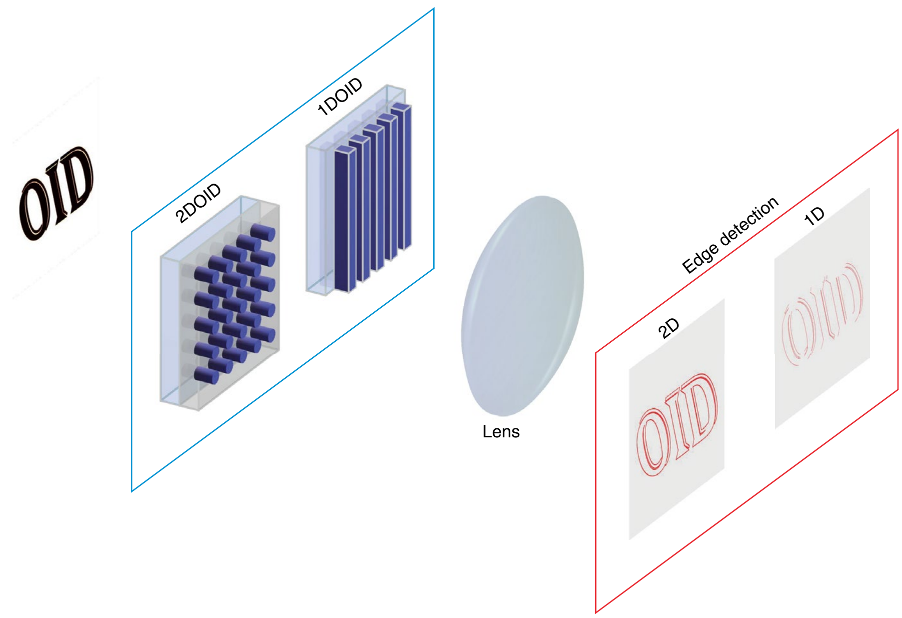

Fig. 1 | Schematic representation of 2DOIDs for edge detection, exhibiting a superior imaging performance over 1DOIDs. A schematic of the 2DOID developed by Zhou and colleagues. It is composed of 2D periodic silicon nanorods embedded in polymethyl methacrylate on a silicon dioxide substrate, and performs the 2D Laplacian operation to incident electric fields. Also shown is the 1DOID reported in ref. [4] (see refs. [5-7] for other designs), which is composed of 1D periodic silicon nanobeams on a sapphire substrate, and performs 1D spatial differentiation to incident fields along the periodic direction. Integrating OIDs into conventional imaging systems allows edge detection to be applied to objects of interest. With a single measurement, 2DOIDs are capable of revealing all edges of a 2D object, while 1DOIDs can only detect edges along one direction.

The work done by Zhou and colleagues experimentally demonstrates 2DOIDs. Mathematically, the 2DOIDs execute the function of a 2D Laplacian operator (second-order spatial differentiation) such that incident electric fields $E_{in}(x, y)$ propagate along the z direction and the device outputs transmission fields $E_{out}(x, y) \propto \nabla^2 E_{in}(x, y)$ (where $\nabla^2 \equiv \partial^2/\partial x^2 + \partial^2/\partial y^2$, and x and y are coordinates of the 2D object and image planes).

Although the 2DOIDs developed by Zhou and colleagues share many functional and structural similarities with an early theoretical proposal by Guo and colleagues[8], for example relying on 2D photonic crystals, Zhou and colleagues' 2DOIDs benefit from a different physical mechanism that has not previously been discovered. Specifically, the Laplacian operation originates from the excitation of a resonance mode supported by a carefully designed 2D photonic crystal layer, which evolves from a bound state in the continuum (BIC) with a diverging quality (Q) factor at normal incidence ($k = 0$, where k is the wavenumber in the transverse (x–y) plane) to a leaky guided mode with a finite Q factor at oblique incidence ($k \neq 0$). The modal evolution accompanies the reduction of the Q factor following $Q(k) \sim 1/k^2$, that is, reciprocally an increase of couplings between the incident waves and the resonance mode, thereby rendering the 2D photonic crystal layer the Laplacian function for transmission. This physical mechanism might explain why such 2DOIDs have a large numerical aperture of ~0.32, one order of magnitude larger than that of previous theoretical work[8].

The structure of the 2DOIDs designed by Zhou and colleagues is remarkably simple. A 2D photonic crystal composed of silicon nanorods is embedded in polymethyl methacrylate on a silicon dioxide substrate (Fig. 1). The architectural simplicity reduces the burden of nanofabrication. As exemplified by the team, the device can be fabricated by employing either electron-beam lithography or self-assembly-based nanosphere lithography. In particular, self-assembly-based nanosphere lithography facilitates large-scale nanofabrication, and the team successfully fabricated centimetre-scale 2DOIDs.

Another advantage of such 2DOIDs is compactness. The whole device is fabricated on a single glass chip without using any bulky optical elements. As a result, the 2DOIDs can be combined with conventional imaging systems, conveniently adding edge detection to their existing functionalities. For instance, it is shown that a 2DOID, with a size of ~3.5 mm × 3.5 mm, fabricated with electron-beam lithography can be integrated into a commercial optical microscope (Axio Vert.A1) by simply placing the 2DOID below the sample stage on top of the microscope objective. Using the integrated microscope, the authors applied edge detection to image microscale biological cells including onion epidermis, pumpkin stem and pig motor nerve, and they observed high-contrast cell boundaries that are less discernible with bright-field microscopy.

Besides this, the authors also integrated a 2DOID, with a size of ~1 cm × 1 cm, fabricated with self-assembly-based nanosphere lithography into a near-infrared camera for edge detection of centimetre-sized plastic flower moulds, outlining potential application in machine vision. As a further step towards a monolithic image processing system, Zhou and colleagues successfully combined the 2DOID with a flat metasurface lens on a single chip.

Although these results represent substantial progress, the limitation that the 2DOIDs work only for one polarization cannot be overlooked. The limitation relates to the physical mechanism discussed earlier. The BIC and its evolved leaky modes only couple with *p*-polarized waves due to the modal symmetry. The spatial differentiation is thus carried out only on *p*-polarized waves, while the *s*-polarized waves are completely blocked in transmission. Therefore, for imaging applications that use coherent polarized light, the light polarization requires an object-dependent optimization to attain maximal image brightness and a higher signal-to-noise ratio, while for those that use incoherent unpolarized light, only half of the light is utilized for edge detection. A 2DOID with polarization insensitivity and further improved transmission efficiency is thus highly desirable. This remains to be developed in the near future.

In addition, unitizing the 2DOIDs for edge detection in practical problems, for example biological imaging and machine vision, should be comprehensively explored in order to derive qualitative conclusions about the advantages and disadvantages of optical image differentiation. Compared with electronic-computing-based image processing, optical image processing, for example, with the 2DOIDs, has the advantages of higher computation speed and lower energy consumption, but at a cost of lower image quality. However, with the rapid progress of artificial intelligence in this decade, image processing with electronic digital computing has been substantially improving in terms of computation speed, especially for difficult problems, and, accordingly, energy consumption per task has been reduced significantly. This naturally begs the question of to what extent the envisioned significant gain of employing optical imaging processes can be kept up? ❐

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EXCITONICS

Strain creates a trion factory

Exciton funnelling due to non-homogeneous strain was previously thought of as an efficient neutral exciton transport mechanism. New findings suggest that exciton funnelling might be negligible compared with another strain-dependent process, the conversion of neutral excitons into trions.

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Strain engineering of the electronic properties of two-dimensional (2D) materials is a strategy of interest made possible by the exceptional mechanical resilience of 2D materials, due mostly to the absence of dangling bonds at their surfaces[1]. In fact, strain engineering has already led to the observation of ultra-large pseudo-magnetic fields in graphene and it has been used to tune the bandgap of 2D semiconductors[2,3]. Moreover, unlike in strain engineering experiments with conventional 3D materials, where the strain is typically applied by forcing the epitaxial growth of a material on top of another