Nanophotonics
https://doi.org/10.1038/s41565-023-01322-5

Twisted light gets a splash of colour

Andrew Forbes & Leerin Perumal

A technique that blends micro- and nanometre-scale printed elements has been used to sculpture white light into a spatial array of coloured twisted beams, demonstrating sophisticated photonic control even with common incoherent sources of light.

Light-carrying orbital angular momentum (OAM) has seen an explosion in research activity over the past 30 years[1,2], realising high-dimensional encoding schemes for classical and quantum communication, novel rotational metrology tools, edge enhancement in imaging, and magnified chiral response in light-matter interactions, to name but a few. OAM light is easily produced in the laboratory by tailoring the wavefront to be helical, but this, unfortunately, requires highly coherent laser sources, a severe limitation that has hindered the deployment of OAM for widespread practical applications, such as illumination technology and displays, considering that we typically use incoherent white light sources in everyday life.

Reporting in *Nature Nanotechnology*, Wang et al. have now shown OAM beams of multiple wavelengths from an incoherent white light source, imparting both the twist and coherence (spatial and temporal) in a single step[3]. In doing so, the authors demonstrate an array of twisted OAM beams that are controlled in wavelength, position and OAM, and go on to exploit this multi-dimensional control for a 'lock-and-key' encryption tool that needs only ambient white light as its source. Their advance is made possible by 3D printed micro- and nano-structures with elegant functionality, opening opportunities for unconventional light even from conventional sources.

We have known for at least a hundred years that light could carry an OAM, but the rare atomic transitions that gave rise to it made it impractical to harness. This changed 30 years ago when OAM was linked to the spatial structure of light through an azimuthal (spiral) phase[4] for what is colloquially referred to as twisted or vortex light, a nod to its helical (twisted) wavefront forming a ring of light about a central null intensity (the vortex). Each twist of the wavefront per unit wavelength gives rise to an extra quanta ($\hbar$) of OAM per photon, for a potentially infinite encoding alphabet. While the toolkit for OAM wavefront manipulation is relatively well-established, it requires coherent light sources. Based on this seemingly fundamental limitation, how can one tailor incoherent white light sources to produce OAM light of any desired twist and colour?

To overcome this challenge, Wang et al. devise a 3D printed solution that combines both micro- and nano-sized structures: the former to control the spatial properties and the latter to control the spectral properties of the wavefront (Fig. 1). First, the required spiral phase is imparted by a continuous surface resembling a spiral staircase, with the twist of the light proportional to the pitch of the spiral. Ingeniously, rather than one large spiral surface for one twisted beam, the authors create an array of many micro-sized spirals, each forming an effective aperture of roughly 25 µm diameter, thus ensuring that there is spatial coherence in each spiral element by virtue of a pin-hole effect. Next, the micro-structures are overlaid with a periodic pattern of nano-pillars that could be controlled in aspect ratio, but typically of 400 nm diameter and 1–2 µm in height (Fig. 1, inset). Although the exact physics of the mechanism is as yet unclear[5], the general notion is that of structural colour[6], where plasmonic and dielectric nano-antennas control the spectral properties of the light by wavelength selective scattering and interference between the light propagating within and outside of the nano-pillars. The result is an array of unit cells, each producing twisted light of a desired colour and OAM, even though the source has no spatial or spectral structure.

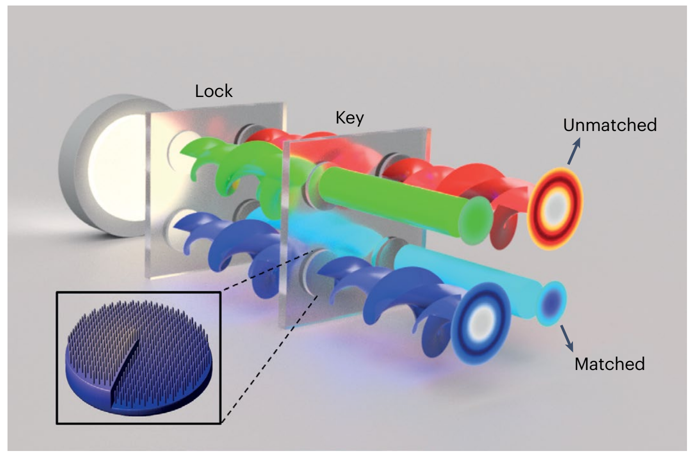

Fig. 1 | Tailoring spectral and spatial structure from ambient white light. A compact optical element (inset) comprising a spiral phase plate, a converging lens and nano-pillars on its surface is 3D printed into a transparent substrate as cells of an array (shown here with four elements). When illuminated by an incoherent white light source, each cell in the 'lock' produces coherent twisted light by virtue of its micro-sized diameter, with its wavelength determined by the nano-filter height and its twistedness by the spiral phase. When the second element, the 'key', is matched with the 'lock' to be its conjugate, the twisted light untwists itself, resulting in coloured Gaussian beams: the beams can be considered 'unlocked'. However, when the cells are unmatched, the twistedness of the light increases, resulting in enlarged coloured rings of light, and the beams are considered still 'locked'. In this way, a selective lock-and-key system is achieved with enormous information capacity, at least in principle.

With these building blocks in place, Wang et al. then demonstrate that two such elements can be used in tandem as lock-and-key to encrypt and decrypt messages. Here they exploit the idea that OAM can be laddered up or down by passing it through successive spiral elements. For instance, an untwisted Gaussian beam ($m = 0$ twists) when passed through a $m = 1$ spiral element will produce OAM of $1\hbar$ per photon; when passed through a second identical element it ladders upwards to become $2\hbar$ per photon, and so on. But if the second element (the key) has the opposite handedness to the lock, the OAM ladders downwards to revert back to untwisted light. In this way, two aligned arrays of such cells (the lock and key) will produce a pattern of bright central spots with no twist (matched) or rings of light with a high twist (unmatched). To make this process efficient, the authors add a lens function to each cell so that the two-element lock-and-key resembles a pattern recognition system.

In this first demonstration, the efficiency of the device was relatively low (~30–40%), the elements were hard-coded as physical structures, while the short focal length of approximately 60 µm necessitated alignment precision in the 1–2 µm range. These limitations could be overcome by nanotechnology that exploits the functionality of meta-atoms rather than continuous phase profiles, for instance, using bound states in the continuum for efficient spectral control, while progress in reconfigurable metasurfaces may hold promise for dynamic elements in the future.

Historically, incoherent white light shaping has been confined to bulky refractive solutions that seek to redirect and redistribute the intensity of the light, predominately for illumination purposes. Excitingly, the present work can be viewed as a combination of mode division multiplexing (OAM) and space division multiplexing (array position of the OAM), perhaps opening a new pathway to OAM LiFi (the visible light version of WiFi) for multiplexed communications from ambient room lighting. The possibility to combine this technology with other on-chip electro–optical OAM devices[7] would see an important leap in integrated photonic functionality with only simple light-emitting diodes as the source. This may yet see OAM transition from the laboratory to real-world applications, a long overdue leap for this promising form of light.

Andrew Forbes ✉ **& Leerin Perumal**
School of Physics, University of the Witwatersrand, Johannesburg, South Africa.
✉e-mail: andrew.forbes@wits.ac.za

Published online: 13 February 2023

References

1. Franke-Arnold, S. *Nat. Rev. Phys.* **4**, 361 (2022).
2. He, C., Shen, Y. & Forbes, A. *Light Sci. Appl.* **11**, 205 (2022).
3. Wang, H. et al. *Nat. Nanotechnol.* https://doi.org/10.1038/s41565-023-01319-0 (2023).
4. Allen, L. et al. *Phys. Rev. A* **45**, 8185–8189 (1992).
5. Wang, H. et al. *Nano Lett.* **21**, 4721–4729 (2021).
6. Rezaei, S. D. et al. *ACS Photon.* **8**, 18–33 (2021).
7. Ni, J. et al. *Science* **374**, eabj0039 (2021).

Competing interests

The authors declare no competing interests.