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CHECK OUT THE SPECIAL THEME ISSUE ON
Orbital Angular Momentum
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Time-varying orbital angular momentum generated by a metasurface

Researchers encode a metasurface to generate time-varying OAM beams, for a higher order twist on structured light

The orbital angular momentum (OAM) of electromagnetic waves — a kind of "structured light" — is associated with a helical or twisted wavefront. The helical modes are characterized by a topological charge. OAM beams with distinct topological charges are mutually orthogonal, which allows them to carry information and to be multiplexed. OAM multiplexing affords increased channel capacity and spectral efficiency — highly useful in fiber-based and free-space communications. OAM beams also have qualities that are useful for optical trapping, lattices, and more.

Unlocking the potential of OAM has advanced thanks to persistent research efforts globally. As reported in Advanced Photonics, researchers from The Hong Kong University of Science and Technology (HKUST) and City University of Hong Kong (CityU) recently developed time-varying OAM beams using a space-time encoded digital metasurface. They used a field-programmable gate array (FPGA) to control the reflection phase of the atoms at the metasurface in the microwave regime.

By exploiting the flexible programmability of the metasurface, they construct different modes of the time-varying OAM beams having a time-dependent phase profile in each time layer. This allows not only a time-varying topological charge but also a higher-order twist in the envelope wavefront structure of the OAM beam in terms of a nonlinear time-dependence in phase, which functions as an additional degree of freedom to allow greater capacities for application.

For their experimental demonstration, the team developed a two-probe mapping method to dynamically map the time-varying OAM field including amplitude and phase patterns at various instants of time. In addition, they performed spectrum analysis targeting OAM mode decomposition on measured field patterns, which demonstrated the high mode purity of the generated time-varying OAM and the designed higher-order twist in the envelope wavefront structure.

Their innovative approach, combining the metasurface’s space-time digital encoding and the two-probe field mapping technique, results in a versatile platform for generating and observing time-varying OAM — as well as other spatiotemporal excitations.

The proposed time-varying OAM beams have application potential for dynamic particle trapping, time-division multiplexing, information encryption, and beyond. Learn more about time-varying OAM in this video created by the authors.
Metasurface enters laser fiber cavity for spatiotemporal mode control

Metasurfaces are highly versatile for manipulating the amplitude, phase, or polarization of light. During the last decade, metasurfaces have been proposed for a vast range of applications — from imaging and holography to the generation of complex light field patterns. Yet, most optical metasurfaces developed to date are isolated optical elements that work only with external light sources.

Despite their versatility for manipulating a light field spatially, most metasurfaces have only a fixed, time-invariant response and a limited ability to control the temporal shape of a light field. To overcome such limitations, researchers are looking into ways to use nonlinear metasurfaces for spatiotemporal light field modulation. However, most materials for constructing metasurfaces have a relatively limited nonlinear optical response on their own.

One solution to the limited nonlinearity of metasurface materials is near-field coupling to a medium with extremely large optical nonlinearity. Epsilon-near-zero (ENZ) materials, an emerging class of materials with vanishing permittivity, have drawn much attention in recent years. For instance, indium tin oxide (ITO), a conductive metal oxide widely used as transparent electrodes in solar cells and consumer electronics, typically has permittivity beyond zero in the near-infrared regime. An ENZ material, with its linear refractive index approaching zero, is endowed with an extremely large nonlinear refractive index and nonlinear absorption coefficient.

As reported in Advanced Photonics, researchers from Tsinghua University and the Chinese Academy of Sciences recently generated laser pulses with tailored spatiotemporal profiles by directly incorporating an ENZ material coupled to a metasurface in a fiber laser cavity. The researchers used the geometric phase of a metasurface made of spatially inhomogeneous anisotropic metallic nano-antennas to tailor the transverse mode of the output laser beam. The giant nonlinear saturable absorption of the ENZ-coupled system allows pulsed laser generation via a Q-switching process. To provide a prototype, the researchers realized a microsecond pulsed vortex laser with varying topological charges.

This work provides a new route to construct a laser with a tailored spatiotemporal mode profile in a compact form. For further system miniaturization, the metasurface may be integrated on the fiber-end face. According to corresponding author Yuanmu Yang, professor at the Tsinghua University State Key Laboratory of Precision Measurement Technology and Instruments, “We hope that our work may further exploration of metasurface versatility for spatial light field manipulation, with its giant and tailorable nonlinear-ity for generating laser beams with arbitrary spatial and temporal profiles.” Yang notes that this innovative method may pave the way for the next generation of miniaturized pulsed laser sources, which could be used in various applications, such as light trapping, high-density optical storage, superresolution imaging, and 3D laser lithography.
Artificial intelligence assists quantum metrology for greater efficiency with an innovative model-free learning algorithm.

Quantum sensing represents one of the most promising applications of quantum technologies, with the aim of using quantum resources to improve measurement sensitivity. In particular, sensing of optical phases is one of the most investigated problems, considered key to developing mass-produced technological devices.

Optimal usage of quantum sensors requires regular characterization and calibration. In general, such calibration is an extremely complex and resource-intensive task—especially when considering systems for estimating multiple parameters, due to the sheer volume of required measurements as well as the computational time needed to analyze those measurements. Machine-learning algorithms present a powerful tool to address that complexity. The discovery of suitable protocols for algorithm usage is vital for the development of sensors for precise quantum-enhanced measurements.

A particular type of machine-learning algorithm known as "reinforcement learning" (RL) relies on an intelligent agent guided by rewards: depending on the rewards it receives it learns to perform the right actions to achieve the desired optimization. The first experimental realizations using RL algorithms for the optimization of quantum problems have been reported only very recently. Most of them still rely on prior knowledge of the model describing the system. What is desirable instead is a completely model-free approach, which is possible when the agent’s reward does not depend on the explicit system model.

As reported in Advanced Photonics, a team of researchers from the Physics Department of Sapienza University of Rome and the Institute for Photonics and Nanotechnologies (IFN-CRN) recently developed a model-free approach that widens the range of possible applications to that of adaptive multiphase estimation. They demonstrated the effectiveness of their model-free approach in a highly reconfigurable integrated photonic platform. They experimentally employ the RL algorithm to optimize estimation of multiple parameters and combine it with a deep neural network that updates after each measurement the Bayesian posterior probability distribution.

According to corresponding author Fabio Sciarrino, head of the Quantum Lab, “The protocol developed by our team provides a significant step toward fully artificial-intelligence-based quantum sensors.”
Distortion-free structured light

Researchers demonstrate structured light that maintains integrity through atmospheric turbulence

An exciting prospect in modern optics is to exploit patterns of light — how the light looks in its many degrees of freedom — often referred to as “structured light.” Each distinct pattern could form an encoding alphabet for optical communication, or might be used in manufacturing to enhance performance and productivity. Unfortunately, patterns of light get distorted when they pass through noisy channels, for instance, stressed optical fiber, aberrated optics, turbid living tissue, and perhaps a very severe example, atmospheric turbulence in air. In all these examples, the distorted pattern can deteriorate to the point that the output pattern looks nothing like the input, negating the benefit. As reported in Advanced Photonics, researchers in South Africa have shown how it is possible to find distortion-free forms of light that come out of a noisy channel exactly the same as they were put in. Using atmospheric turbulence as an example, they showed that these special forms of light, called eigenmodes, can be found for even very complex channels, emerging undistorted, while other forms of structured light would be unrecognizable.

Passing light through the atmosphere is crucial in many applications, such as free-space optics, sensing, and energy delivery, but finding how best to do this has proved challenging. Traditionally a trial-and-error approach has been used to find the most robust forms of light in some particular noisy channel, but to date all forms of familiar structured light have shown to be distorted as the medium becomes progressively noisier. The reason is that light can “see” the distortion. But is it possible to create light that doesn’t see the distortion, passing through as if it wasn’t there? To make this advance, the researchers treated the noisy channel as a mathematical operator and asked a simple question: what forms of light would be invariant to this operator? In other words, light waves that are in the natural modes of the channel behave as if they don’t see the distortion: the true eigenmodes of the channel. The example tackled was the severe case of distortions due to atmospheric turbulence. The answer to the problem revealed previously unrecognized forms of light, i.e., not in any well-known structured light family, but nevertheless completely robust to the medium. This fact was confirmed experimentally and theoretically for weak and strong turbulence conditions.

According to corresponding author Andrew Forbes, SPIE Fellow and Distinguished Professor at University of the Witwatersrand in Johannesburg, “What is exciting about the work is that it opens up a new approach to studying complex light in complex systems — for instance, in transporting classical and quantum light through optical fiber, underwater channels, living tissue, and other highly aberrated systems.” He adds, “Because of the nature of eigenmodes, it doesn’t matter how long this medium is, nor how strong the perturbation, so that it should work well even in regimes where traditional corrective procedures, such as adaptive optics, fail.” Maintaining the integrity of structured light in complex media will pave the way to future work in imaging and communicating through noisy channels, which is particularly relevant when the structured forms of light are fragile quantum states.
Matrix multiplications at the speed of light

Compact silicon photonic computing engine computes tiled matrix multiplication at a record-high 50 GHz clock frequency

“All things are numbers,” avowed Pythagoras. Today, 25 centuries later, algebra and mathematics are everywhere in our lives, whether we see them or not. The Cambrian-like explosion of artificial intelligence (AI) brought numbers even closer to us all, since technological evolution allows for parallel processing of a vast amounts of operations. Progressively, operations between scalars (numbers) were parallelized into operations between vectors and, subsequently, matrices. Multiplication between matrices now trends as the most time- and energy-demanding operation of contemporary AI computational systems. A technique called “tiled matrix multiplication” (TMM) helps to speed computation by decomposing matrix operations into smaller tiles to be computed by the same system in consecutive time slots. But modern electronic AI engines, employing transistors, are approaching their intrinsic limits and can hardly compute at clock-frequencies higher than ~2 GHz.

The compelling credentials of light — ultrahigh speeds and significant energy and footprint savings — offer a solution. Recently a team of photonic researchers of the WinPhos Research group, led by Nikos Pleros, from the Aristotle University of Thessaloniki, harnessed the power of light to develop a compact silicon photonic compute engine capable of computing TMMs at a record-high 50 GHz clock frequency. As reported in Advanced Photonics, they employ silicon-germanium electro-absorption modulators and a novel neuromorphic architectural design capable of encoding and computing data. According to corresponding author George Giamougiannis, “This work paves the way for the resolution of DL-based applications that require line-rate computations,” and the work promises to contribute significantly to data center cybersecurity.

Undoubtedly, the AI burst has equipped both benign and wicked users with strong toolkits to speed-up and automate their activities. With the data travelling in the data centers (DCs) augmenting by ~13 percent year-by-year, they have become a major target for malicious individuals who aim to compromise sensitive data, e.g., financial data, personal information, and intellectual property of many organizations, including government agencies, military forces, hospitals, and financial institutions. On that account, DC cybersecurity is imperative to prevent invaders accessing classified information.

Indeed, threat detection mechanisms face a new set of requirements resulting from the quantity of data flowing through the vast number of servers and switches within contemporary DCs. Real-time threat detection is imperative; packet inspection must be processed at ultrahigh speeds. Moreover, threats must be detected as early as possible within the route of the malicious packets: every DC node should be equipped with a powerful cybersecurity toolkit.

Exploiting their ultrafast processor, the researchers from Aristotle University of Thessaloniki, in collaboration with NVIDIA’s experts in the field of DC cybersecurity, successfully merged silicon photonics with AI to establish a framework to identify successfully and swiftly one of the most common types of DC attacks, namely distributed denial-of-service (DDoS) attacks, in NVIDIA’s servers at line-rates. Thanks to this novel computational scheme, the number may soon be up for DC attacks — at least for the time being.

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We can frequently find in our daily lives a localized wave structure that maintains its shape upon propagation—picture a smoke ring flying in the air. Similar stable structures have been studied in various research fields and can be found in magnets, nuclear systems, and particle physics. In contrast to a ring of smoke, they can be made resilient to perturbations. This is known in mathematics and physics as topological protection. A typical example is the nanoscale hurricane-like texture of a magnetic field in magnetic thin films, behaving as particles that is, not changing their shape—called skyrmions. Similar doughnut-shaped (or toroidal) patterns in 3D space, visualizing complex spatial distributions of various properties of a wave, are called hopfions. Achieving such structures with light waves is very elusive.

Recent studies of structured light revealed strong spatial variations of polarization, phase, and amplitude, which enable the understanding of—and open up opportunities for designing—topologically stable optical structures behaving like particles. Such quasiparticles of light with control of diversified topological properties may have great potential, for example as next-generation information carriers for ultralarge-capacity optical information transfer, as well as in quantum technologies.

As reported in Advanced Photonics, collaborating physicists from UK and China recently demonstrated the generation of polarization patterns with designed topologically stable properties in three dimensions, which, for the first time, can be controllably transformed and propagated in free space. As a consequence of this insight, several significant advances and new perspectives are offered. “We report a new, very unusual, structured-light family of 3D topological solitons, the photonic hopfions, where the topological textures and topological numbers can be freely and independently tuned, reaching far beyond previously described fixed topological textures of the lowest order,” says Yijie Shen of University of Southampton in the UK, the lead author of the paper. “Our results illustrate the immense beauty of light structures. We hope they will inspire further investigations towards potential applications of topologically protected light configurations in optical communications, quantum technologies, light-matter interactions, superresolution microscopy, and metrology,” says Anatoly Zayats, professor at King’s College London and project lead.

This newly developed model of optical topological hopfions can be easily extended to other higher-order topological formations in other branches of physics. The higher order hopfions are still a great challenge to observe in other physics communities, from high-energy physics to magnetic materials. The optical approach proposed in this work may provide a deeper understanding of this complex field of structures in other branches of physics.

Light shaped as a smoke ring behaves like a particle

Researchers report a new, highly unusual, structured-light family of 3D topological solitons, the photonic hopfions, where the topological textures and topological numbers can be freely and independently tuned.
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