COMMENTARY

PHOTONICS
INSIGHTS

Structured light meets integrated photonics

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In the past two decades, metamaterials and metasurfaces[1,2] have been providing a new playground for light manipulation, establishing concepts and experimental platforms that enable structuring light in compact footprints with exceptional benefits for a wide range of technologies. Metasurfaces, in particular, have been developing a paradigm of compactification of optical components, enabling manipulation of the optical wavefront within subwavelength footprints and unprecedented control over all properties of light, from spectrum to polarization, from wavefront shaping to spatial and temporal coherence[3]. The progress in the past few years has been truly impressive, bringing many of these concepts from proof-of-concept ideas to practical demonstrations ready for commercialization and deployment. As such, it has become imperative to explore ways to integrate metamaterial and metasurface devices into photonic platforms and enable platforms compatible with existing photonic circuits and systems.

J. Wang and his colleagues have put forward an impressive and comprehensive timely review of the state-of-the-art research efforts in bringing together structured light with integrated photonics[4]. In their review, they touch upon many important topics of research, providing examples of how this technological field is rapidly evolving and meeting the tight standards to make an impact at the system level. Among the several topics discussed in the review, I would like to highlight a few that appear timely and ready for prime time.

First, the field of photonic metasurfaces has been moving steadily toward application scenarios that require integrability. Of particular relevance are the recent commercial efforts, e.g., Ref. [5], which have been demonstrating how the new degree of control over nanoscale light enabled by metasurfaces can be relevant for many commercial avenues. In this context, it is important to make sure that the materials and the fabrication techniques employed are compatible with photonic standards, which may pose some restrictions on the practical implementation of these devices. A good example is the sophisticated design of metasurfaces for extreme wavefront transformations, which typically rely on high-quality factors, multi-layered implementations, and high-index materials. By contrast, large-area nanofabrication today has stringent requirements in terms of material use and is typically limited to 2D geometries, limiting some of the implementations. Efforts to meet these requirements at the design stage, possibly using optimization techniques with parameter boundaries, and parallel efforts to extend the nanofabrication capabilities of today's photonic industry are bringing the two worlds closer over the years, and a bright future can be expected moving forward. In parallel, the idea of engineering the nonlocality of optical metasurfaces is another direction of direct relevance to integrability[6]. While conventional metasurface designs are based on structured light locally using subwavelength nanostructures that are optimized to avoid or minimize coupling with their neighbors, nonlocal phenomena in metasurfaces can be leveraged to further enhance the control over the optical wavefront. Virtual reality, augmented reality, and eyetracking devices have been proposed based on these principles, well integrated with modern photonic systems[7]. An interesting opportunity for integrability stems from the fact that these metasurfaces tailor guided-mode resonances; hence they are well-compatible with an integrated platform for excitation. Indeed, a spin-off of this approach has been the implementation of leaky-wave nonlocal metasurfaces, which can integrate complex wavefront shaping within integrated photonic circuits[8].

As discussed extensively in the review, these concepts are amenable to implementation within integrated photonic platforms' topological concepts, which bring inherent robustness and elegant design tools to wavefront structuring, and optical and information transport. These efforts have recently been applied to integrated topological photonics[9,10] to enable light propagation with robust unidirectional features and even robust lasing performance. Topological features for integrated photonics also arise in the context of wavefront structuring around singularities, enabling opportunities for wavefront control and sensing[11], and enabling optical multiplexing, for instance, leveraging orbital angular momentum.

Another area of great relevance in using structured light for integrated photonics is in the context of optical analog computing, which has seen a rapid surge of interest in the quest to minimize energy consumption and latency in data-intensive applications. Metasurfaces and metamaterials have been offering exciting opportunities in this context[12,13], and recent breakthroughs have demonstrated opportunities for integrated photonic circuits compatible with silicon photonic chips that process optical signals and solve complex mathematical problems[14].

As future challenges, enhancing the compatibility of metasurfaces with large-area and inexpensive fabrication techniques, such as roll-to-roll, nanoimprinting, and self-assembly

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techniques, is a promising avenue to fully merge structured wavefronts with integrated photonics. As another important challenge, introducing strongly nonlinear materials, such as polaritonic materials, may address one of the major challenges of photonics at the nanoscale, the inherent weakness of light–matter interactions. Enabling low-energy switching, nonreciprocal responses[15], or other nonlinear operations in metasurface platforms may enable many additional flourishing opportunities for this thriving field of research.

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