Invited Paper

Integrated Optical Phased Arrays for Augmented Reality, Biophotonics, 3D Printing, and Beyond

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ABSTRACT

Integrated optical phased arrays (OPAs), fabricated in advanced silicon-photonics platforms, enable manipulation and dynamic control of free-space light in a compact form factor, at low costs, and in a non-mechanical way. This talk will highlight our work on developing OPA-based platforms, devices, and systems that enable chip-based solutions to high-impact problems in areas including augmented-reality displays, LiDAR sensing for autonomous vehicles, optical trapping for biophotonics, 3D printing, and trapped-ion quantum engineering.

Keywords: Integrated photonics, silicon photonics, integrated optical phased arrays, beam steering, LiDAR, augmented reality

1. INTRODUCTION TO INTEGRATED OPTICAL PHASED ARRAYS

Integrated optical phased arrays (OPAs), fabricated in advanced silicon-photonics platforms, enable manipulation and dynamic control of free-space light in a compact form factor, at low costs, and in a non-mechanical way. As such, integrated optical phased arrays have emerged as a promising technology for many wide-reaching applications, including light detection and ranging (LiDAR) for autonomous vehicles, free-space optical communications, three-dimensional (3D) holography for augmented-reality displays, optical trapping for biophotonics, laser-based 3D printing, and trapped-ion quantum computing.

Here, recent advances in integrated optical phased array architectures, results, and applications will be reviewed.

2. REVIEW OF BEAM-STEERING INTEGRATED OPAS FOR LIDAR

LiDAR has emerged as a vital and widely-used sensing technology for autonomous systems, such as autonomous vehicles, since it enables 3D mapping with higher resolution than traditional RADAR. However, current commercial LiDAR systems utilize mechanical beam-steering mechanisms that decrease reliability and increase production cost. To address these limitations, integrated optical phased arrays, which enable low-cost, high-speed, and compact non-mechanical beam steering, have emerged as a promising solution for next-generation LiDAR.[1–8]

The first beam-steering integrated optical phased array powered by an on-chip erbium-doped laser will be shown;[1–3] this system represents the first demonstration of a rare-earth-doped laser monolithically integrated with an active CMOS-compatible silicon-on-insulator photonics system. Additionally, the first beam-steering optical phased array heterogeneously integrated with CMOS driving electronics[4,5] and the first single-chip coherent LiDAR with integrated optical phased arrays and CMOS receiver electronics,[6] both in a novel 3D-integrated electronics-photonics platform, will be presented; this 3D integration scheme allows for photonics and CMOS electronics to be independently optimized and scaled, while maintaining dense interconnections. These laser- and electronics-integration demonstrations are important steps towards practical commercialization of low-cost and high-performance integrated LiDAR systems for autonomous vehicles.

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3. REVIEW OF NEAR-FIELD INTEGRATED OPAS

Motivated by the initial application of LiDAR, integrated-optical-phased-array demonstrations to date have primarily focused on systems that form and steer beams in the far field of the array. However, there are many high-impact application areas that require near-field optical manipulation that would greatly benefit from the compact form factors and large standoff distances enabled by integrated optical phased arrays.

A variety of integrated optical phased arrays with novel components, architectures, and functionalities for optical manipulation in the near field will be reviewed. First, passive integrated optical phased arrays that focus radiated light to tightly-confined spots in the near field will be discussed;[9,10] this focusing modality has the potential to advance a number of important application areas, such as optical trapping for biological characterization,[11–13] laser-based 3D printing,[14,15] trapped-ion quantum computing,[16–19] and short-range LiDAR and data communications. Second, generation of a quasi-Bessel beam using a passive integrated optical phased array will be shown;[20,21] owing to its elongated central beam output, this chip-based Bessel-beam generator has applications in a range of fields, including multiparticle optical trapping, increased-depth-of-field microscopy, and adaptive free-space optical communications. Third, an active scalable two-dimensional integrated optical phased array architecture with cascaded butterfly-shaped pixels will be presented;[22] this novel architecture enables compact, in-line independent amplitude and phase control with power recycling for space- and power-efficient near-field operation.

4. REVIEW OF OPA-BASED HOLOGRAPHIC DISPLAYS FOR AR

Augmented-reality (AR) head-mounted displays that display information directly in the user's field of view have many wide-reaching applications in defense, medicine, engineering, gaming, etc. However, current commercial head-mounted displays are bulky, heavy, and indiscreet. Moreover, these current displays are not capable of producing holographic images with full depth cues; this lack of depth information results in users experiencing eyestrain and headaches that limit long-term and wide-spread use of these displays (an effect known as the vergence-accommodation conflict).

Recent advances in the development of VIPER (Visible Integrated Photonics Enhanced Reality), a novel integrated-photonics-based holographic display, will be reviewed.[23–31] The VIPER display consists of a single discreet chip that sits directly in front of the user's eye and projects visible-light 3D holograms that only the user can see. It presents a highly-discreet and fully-holographic solution for the next generation of augmented-reality displays.

First, a novel 300-mm-wafer foundry platform for visible-light integrated photonics will be presented. Second, a novel large-scale passive VIPER display that generates a holographic image of a wire-frame cube using 1024 optical-phased-array-based pixels passively encoded to emit light with the appropriate amplitudes and phases will be discussed.[23] Third, the first integrated visible-light liquid-crystal-based phase[24–26] and amplitude[27,28] modulators will be shown (with device lengths an order of magnitude smaller than traditional inefficient thermo-optic visible-light modulators). Fourth, the first actively-tunable visible-light integrated optical phased array will be presented.[29–31]

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