

Integrated Optical Phased Arrays: AR Displays, 3D Printing, Biophotonics, and Beyond

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Abstract—Integrated optical-phased-array-based platforms, devices, and systems for applications in augmented-reality displays, LiDAR sensing for autonomous vehicles, optical trapping for biophotonics, 3D printing, and trapped-ion quantum engineering will be reviewed.

Keywords—silicon photonics, integrated optical phased arrays, LiDAR sensing, augmented-reality displays, optical trapping, 3D printing, trapped ions

I. REVIEW OF OPA-BASED PLATFORMS, DEVICES, SYSTEMS, AND APPLICATIONS

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. In this talk, I 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 [1-5], LiDAR sensing for autonomous vehicles [6-12], optical trapping for biophotonics [13-18], 3D printing [19-20], and trapped-ion quantum engineering [21-22].

ACKNOWLEDGMENT

This work was supported by the Defense Advanced Research Projects Agency (DARPA) Visible Integrated Photonics Enhanced Reality (VIPER) program (Grant No. FA8650-17-1-7713), the Defense Advanced Research Projects Agency (DARPA) Electronic-Photonic Heterogeneous Integration (E-PHI) program (Grant No. HR0011-12-2-0007), the National Science Foundation (NSF) Faculty Early Career Development (CAREER) Program (Grant No. 2239525), and the MIT Center for Quantum Engineering (CQE).

The author thanks Milica Notaros, Sabrina Corsetti, Tal Sneh, Ashton Hattori, Daniel M. DeSantis, Andres Garcia Coletto, Michael Torres, Manan Raval, Christopher V. Poulton, Matthew J. Byrd, Nanxi Li, Zhan Su, Emir Salih Magden, Erman Timurdogan, Michael R. Watts, Thomas Dyer, Kevin Fealey, Seth Kruger, Christopher Baiocco, Alex Stafford, Zachariah A. Page, Kruthika Kikkeri, Joel Voldman, Taehwan Kim, Pavan Bhargava, and Vladimir Stojanovic for their contributions to the work discussed in this review.

REFERENCES

- [1] J. Notaros, M. Raval, M. Notaros, and M. R. Watts, "Integrated-Phased-Array-Based Visible-Light Near-Eye Holographic Projector," in *Proceedings of Conference on Lasers and Electro-Optics (CLEO)* (OSA, 2019), paper STu3O.4.
- [2] J. Notaros, M. Notaros, M. Raval, and M. R. Watts, "Liquid-Crystal-Based Visible-Light Integrated Optical Phased Arrays," in *Proceedings of Conference on Lasers and Electro-Optics (CLEO)* (OSA, 2019), paper STu3O.3.
- [3] M. Notaros, T. Dyer, M. Raval, C. Baiocco, J. Notaros, and M. R. Watts, "Integrated Visible-Light Liquid-Crystal-Based Phase Modulators," *Optics Express* 30(8), 13790-13801 (2022).
- [4] M. Notaros, M. Raval, J. Notaros, and M. R. Watts, "Integrated Visible-Light Liquid-Crystal Phase Modulator," in *Proceedings of Frontiers in Optics (FIO)* (OSA, 2018), paper FW6B.5.
- [5] M. Notaros, J. Notaros, M. Raval, and M. R. Watts, "Integrated Visible-Light Liquid-Crystal Variable-Tap Amplitude Modulator," in *Proceedings of Integrated Photonics Research, Silicon, and Nanophotonics (IPR)* (OSA, 2019), paper ITh2C.6.
- [6] J. Notaros*, N. Li*, C. V. Poulton, Z. Su, M. J. Byrd, E. S. Magden, E. Timurdogan, C. Baiocco, N. M. Fahrenkopf, and M. R. Watts, "CMOS-Compatible Optical Phased Array Powered by a Monolithically-Integrated Erbium Laser," *Journal of Lightwave Technology* 37(24), 5982-5987 (2019).
- [7] J. Notaros*, N. Li*, C. V. Poulton, Z. Su, M. J. Byrd, E. S. Magden, and M. R. Watts, "CMOS-Compatible Optical Phased Arrays with Monolithically-Integrated Erbium Lasers," in *Proceedings of Conference on Lasers and Electro-Optics (CLEO)* (OSA, 2018), paper STu4B.2.
- [8] N. Li, D. Vermeulen, Z. Su, E. S. Magden, M. Xin, N. Singh, A. Ruocco, J. Notaros, C. V. Poulton, E. Timurdogan, C. Baiocco, and M. R. Watts, "Monolithically integrated erbium-doped tunable laser on a CMOS-compatible silicon photonics platform," *Optics Express* 26(13), 16200-16211 (2018).
- [9] T. Kim*, P. Bhargava*, C. V. Poulton*, J. Notaros, A. Yaacobi, E. Timurdogan, C. Baiocco, N. Fahrenkopf, S. Kruger, T. Ngai, Y. Timalina, M. R. Watts, and V. Stojanovic, "A Single-Chip Optical Phased Array in a Wafer-Scale Silicon Photonics / CMOS 3D-Integration Platform," *IEEE Journal of Solid-State Circuits* 54(11), 3061-3074 (2019).
- [10] T. Kim, P. Bhargava, C. V. Poulton, J. Notaros, A. Yaacobi, E. Timurdogan, C. Baiocco, N. Fahrenkopf, S. Kruger, T. Ngai, Y. Timalina, M. R. Watts, and V. Stojanovic, "A Single-Chip Optical Phased Array in a 3D-Integrated Silicon Photonics/65nm CMOS Technology," in *Proceedings of the 2019 IEEE International Solid-State Circuits Conference (ISSCC)* (IEEE, 2019), pp 464-466.
- [11] P. Bhargava*, T. Kim*, C. V. Poulton*, J. Notaros, A. Yaacobi, E. Timurdogan, C. Baiocco, N. Fahrenkopf, S. Kruger, T. Ngai, Y. Timalina, M. R. Watts, and V. Stojanovic, "Fully Integrated Coherent LiDAR in 3D-Integrated Silicon Photonics/65nm CMOS," in *Proceedings of the 2019 IEEE Symposium on VLSI Circuits (VLSI)* (IEEE, 2019).
- [12] Z. Zhang, M. Notaros, Z. Gao, U. Chakraborty, J. Notaros, and D. Boning, "Impact of Spatial Variations on Splitter-Tree-Based Integrated Optical Phased Arrays," in *Proceedings of Optical Fiber Communication Conference (OFC)* (OSA, 2023), paper W2A.35.
- [13] J. Notaros, C. V. Poulton, M. Raval, and M. R. Watts, "Near-field-focusing integrated optical phased arrays," *Journal of Lightwave Technology* 36(24), 5912-5920 (2018).
- [14] J. Notaros, C. V. Poulton, M. Raval, M. J. Byrd, D. Coolbaugh, and M. Watts, "Fresnel-Lens-Inspired Focusing Phased Arrays for Optical

- Trapping Applications," in *Proceedings of Conference on Lasers and Electro-Optics (CLEO)* (OSA, 2017), paper STh1M.3.
- [15] J. Notaros, C. V. Poulton, M. J. Byrd, M. Raval, and M. R. Watts, "Integrated optical phased arrays for quasi-Bessel-beam generation," *Optics Letters* 42(17), 3510-3513 (2017).
 - [16] J. Notaros, C. V. Poulton, M. J. Byrd, M. Raval, and M. R. Watts, "Bessel-Beam-Generating Integrated Optical Phased Arrays," in *Proceedings of Conference on Lasers and Electro-Optics (CLEO)* (OSA, 2018), paper SM3I.5.
 - [17] T. Sneh, S. Corsetti, M. Notaros, and J. Notaros, "Focusing Integrated Optical Phased Arrays for Chip-Based Optical Trapping," in *Proceedings of Conference on Lasers and Electro-Optics (CLEO)* (OSA, 2022), paper STh4G.4.
 - [18] M. Notaros, T. Dyer, A. Hattori, K. Fealey, S. Kruger, and J. Notaros, "Flexible Wafer-Scale Silicon-Photonics Fabrication Platform," in *Proceedings of Frontiers in Optics (FiO)* (OSA, 2022), paper FW1E.3.
 - [19] J. Notaros, M. J. Byrd, M. Raval, and M. R. Watts, "Integrated Optical Phased Array Butterfly Architecture for Independent Amplitude and Phase Control," in *Proceedings of Integrated Photonics Research, Silicon, and Nanophotonics (IPR)* (OSA, 2019), paper IM4A.4.
 - [20] S. Corsetti, M. Notaros, T. Sneh, A. Stafford, Z. Page, and J. Notaros, "Visible-Light Integrated Optical Phased Arrays for Chip-Based 3D Printing," in *Proceedings of Integrated Photonics Research, Silicon, and Nanophotonics (IPR)* (OSA, 2022), paper IM2B.4.
 - [21] A. Hattori*, S. Corsetti*, T. Sneh, M. Notaros, R. Swint, P. T. Callahan, C. D. Bruzewicz, F. Knollmann, R. McConnell, J. Chiaverini, and J. Notaros, "Integrated-Photonics-Based Architectures for Polarization-Gradient and EIT Cooling of Trapped Ions," in *Proceedings of Frontiers in Optics (FiO)* (OSA, 2022), paper FM4B.3.
 - [22] T. Sneh*, A. Hattori*, M. Notaros, S. Corsetti, and J. Notaros, "Design of Integrated Visible-Light Polarization Rotators and Splitters," in *Proceedings of Frontiers in Optics (FiO)* (OSA, 2022), paper JTU5A.48.