

Fast and Coherent Optical Control with 256 Visible-Wavelength Channels

Ian Christen^{1,*}, Thomas Propson¹, Hamed Sattari², Gregory Choong², Yves Petremand²,
Ivan Prieto², Adrian J. Menssen¹, Amir H. Ghadimi², Dirk Englund¹

¹Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA,

²Centre Suisse d'Electronique et de Microtechnique (CSEM), 2000 Neuchâtel, Switzerland

*ichr@mit.edu

Abstract: Individual control of hundreds of atomic qubits necessitates individual control of hundreds of optical channels. We implement 256 visible-light modulators in thin-film lithium niobate, actuated and stabilized in parallel by an FPGA-based architecture. © 2023 The Author(s)

1. Introduction

Platforms for quantum information processing of every variety are racing towards the scales needed to realize useful quantum simulation and computing. To retain generality at these scales, systems for addressing and controlling individual qubits must scale proportionally. In atomic systems—such as ions [1], neutral atoms [2], or emitters in solids [3]—control is imparted optically, presenting a technological challenge: hardware for such precise, fast, and large-scale control does not exist, let alone for the *visible-wavelengths* needed to target relevant atomic transitions. In this work, we present an integrated photonic engine for programmable atomic control, now at scales commensurate with state-of-the-art atomic arrays [2]. This architecture is based upon thin-film-lithium-niobate (TFLN) modulators fabricated at CSEM and includes a number of optical enhancements over previous work [4]. Critically, this architecture uses fast electronics that are commercially-available at scale and reasonable cost.

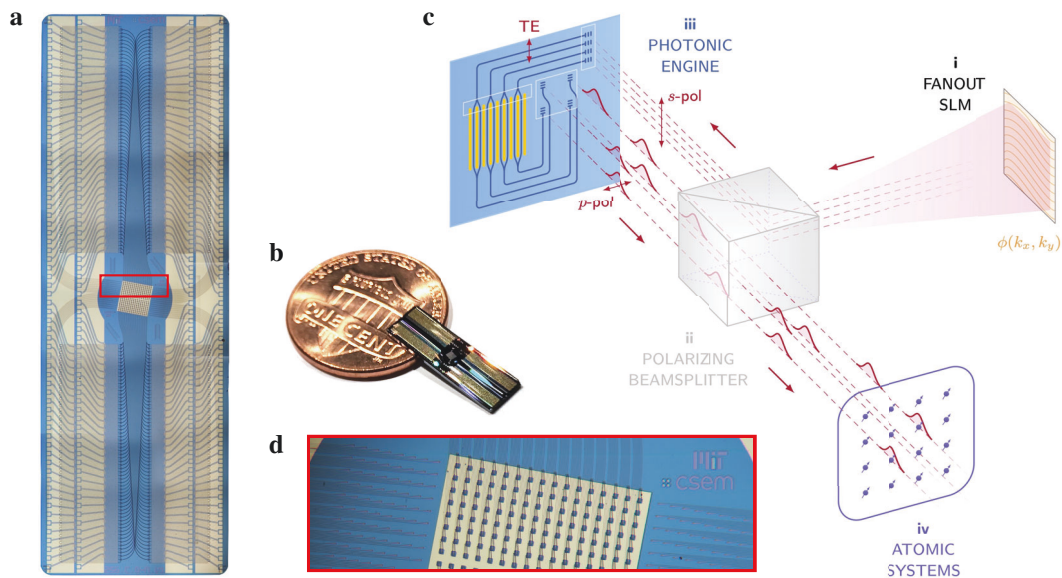


Fig. 1. A 256-channel photonic engine. **a** Integrated TFLN photonic chip of dimension 5×15 mm, **b** with a US penny for scale. **c** Schematic system architecture (simplified to four channels). **d** Zoom upon one side of the coupling region (red inset of **a**), with a metal-shielded 16×16 output vertical coupler array in the center and 8×16 input vertical coupler arrays to the left and right.

2. Optical Architecture

Light is coupled from free-space to the array of 256 TFLN modulators via vertical couplers (Fig. 1a, 1d, 1c.iii). A liquid-crystal-on-silicon (LCoS) spatial light modulator (SLM; Fig. 1c.i) shapes a static hologram which distributes and balances power to all the channels using weighted-Gerchberg-Saxton (WGS)-type algorithms [5] implemented in an open-source package [6]. The input vertical couplers here are arranged in two 8×16 channel input arrays. Novel methods for vertical coupling in two dimensions will be discussed.

The light propagates through the TFLN modulators, which are implemented as coiled Mach-Zehnder interferometers (MZIs). Such coiling accomplishes two tasks. First, it allows the directional couplers which form each interferometer to be fabricated adjacent to each other (rather than separated by millimeters), with the goal of reducing the coupling variation which is expected to reduce the level of achievable extinction. Second, coiling effectively lengthens the phase accumulation of the modulator and thus reduces the switching voltage, in this case by a factor of ~ 3 .

The light is coupled off-chip by the central 16×16 channel output array and towards the target atomic systems (Fig. 1c.iv). This output is monitored by a fast camera and used to feedback upon channel stabilization and uniformity. A second SLM (not pictured) is used to individually form the spatial state of each channel, whether by steering to novel topologies or by shaping to unique holograms [4].

3. Electronic Control

Any programmable technology must be developed in tandem with an associated electronic interface. For unamplified high-speed modulation, such electronic interfaces generally have CMOS-compatible voltages of less than three volts. For this reason, the choice of TFLN as a platform is not to achieve high bandwidth or low waveguide propagation loss, but rather because of TFLN's strong Pockels effect and corresponding low switching voltage.

Control of 256 channels is accomplished via commercial electronics consisting of three ~ 500 MHz 96-channel field programmable gate array (FPGA) mezzanine boards for digital switching (Opal Kelly; 0-3.3V) and four ~ 500 kHz 64-channel analog output boards for zero-point trimming (General Standards Corp; 0-10V). The FPGAs represent a most economical option for high-speed modulation on many channels and are synchronized in a phase-locked loop (PLL). Such a dual-speed architecture combines the speed and scale achievable using digital modulators with the analog trimming necessary to replicate the control and stabilization implemented previously [4]. As an additional benefit, this hardware can operate in a fully-analog mode, albeit at slower speeds than the digital mode.

The FPGA mezzanine boards plug directly into the printed circuit board (PCB) hosting our photonic chip, to maintain speed, efficiency, and signal integrity. The analog boards are connected via other cabling. These digital and analog signals are connected to the photonic chip via four rows of 129 pads, two on each side of the chip, representing close to the reasonable limit that can be achieved with wirebonding (limited by chip perimeter). Notably, the analog signals are wired in place of grounds, in a analog-digital-analog configuration mimicking the standard ground-signal-ground. While this layout (and coiled MZI) sacrifices bandwidth for density (~ 1 GHz bandwidth targeted vs ~ 100 GHz state-of-the-art), this loss is negligible considering the ~ 500 MHz operating speed of our driving electronics.

Remarkably, as the development of this optical hardware shifts from using bulk scientific electronics designed for generality to using application-specific CMOS circuitry, we have found that the cost-per-channel decreases exponentially to the point that the *total* cost of each subsequent generation is less than the proceeding generation, despite the exponentially-scaled channel counts, illustrating the scalability of electronic-photonic co-design.

4. Outlook

Our device and photonic architecture pushes at the boundaries of structured optical modulation, in terms of speed, scale, and operating wavelength. Future work will continue to scale this architecture and refine performance, towards the ultimate goal of a fast coherent optical *display* for atomic control.

References

1. S. Debnath, N. Linke, C. Figgatt et al. *Nature* **536**, 63–66 (2016).
2. S. Ebadi, T.T. Wang, H. Levine et al. *Nature* **595**, 227–232 (2021).
3. N. H. Wan, T.-J. Lu, K. C. Chen et al. *Nature* **583**, 226 (2020).
4. I. Christen, M. Sutula, T. Propson et al. *In Review* arXiv:2208.06732 (2022).
5. R. Di Leonardo, F. Ianni, G. Ruocco *Opt. Express* **15**, 1913–1922 (2007).
6. <https://github.com/QPG-MIT/slmsuite>