Supplementary Information: An integrated photonic engine for programmable atomic control

Ian Christen\textsuperscript{1,*}, Thomas Propson\textsuperscript{1}, Madison Sutula\textsuperscript{1}, Hamed Sattari\textsuperscript{2}, Gregory Choong\textsuperscript{2}, Christopher Panuski\textsuperscript{1}, Alexander Melville\textsuperscript{3}, Justin Mallek\textsuperscript{1}, Cole Brabec\textsuperscript{1}, Scott Hamilton\textsuperscript{3}, P. Benjamin Dixon\textsuperscript{3}, Adrian J. Menssen\textsuperscript{3}, Danielle Braje\textsuperscript{3}, Amir H. Ghadimi\textsuperscript{2}, and Dirk Englund\textsuperscript{1,*}

\textsuperscript{1}Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
\textsuperscript{2}Centre Suisse d’Electronique et de Microtechnique (CSEM), 2000 Neuchâtel, Switzerland
\textsuperscript{3}Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02421, USA

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**FIG. S1:** Fanout SLM amplitude distributions. The measured source amplitude distributions on the fanout SLM \textbf{a}, for 780 nm and \textbf{b}, for 737 nm.

**FIG. S2:** Microlens fill factor conversion. The influence of a variety of $\Delta f_o$ upon the fill factor $\eta_o$ of the output beam: \textbf{a}, $\Delta f_o = 0.5\Delta f_i$, \textbf{b}, $\Delta f_o = \Delta f_i$, \textbf{c}, $\Delta f_o = 1.5\Delta f_i$, and \textbf{d}, collimated output.

*Electronic address: ichr@mit.edu, englund@mit.edu
FIG. S3: **Microlens steering range.** Lens efficiency $\eta$ versus normalized steering range $R$ for twelve channels with $\Delta f_o \approx \Delta f_i$. The $x$ and $y$ axes are normalized to the channel pitch $\Gamma$. Contours denote 80% efficiency.

FIG. S4: **Time domain modulator performance.** a, An input voltage in the form of a square wave (sourced from 70 MHz bandwidth AWG) is imparted to a modulator channel, imparting the signal to b, the optical domain, detected by a 50 MHz bandwidth photodiode.
\[ Z_{xy} = A_{xy} e^{i \varphi_{xy}} \]

**FIG. S5: Modified WGS loop.** Weighted Gerchberg-Saxton (WGS) numerically solves the problem of phase retrieval: what nearfield phase pattern \( \varphi_{xy} \) best approximates a desired farfield amplitude distribution \( a_k^{(0)} \)?

\[ \mathcal{F} \]

- **Amplitude Correction:**
  \( A_{xy} = A_k^{(0)} \)
  \( \varphi_{xy} = \varphi_k^{(0)} \)

\[ \mathcal{F}^{-1} \]

\[ z_{k} = a_k e^{i \theta_k} \]

\[ Z'_{xy} = A'_{xy} e^{i \varphi'_{xy}} \]

**f** Amplitude Correction

**b** If \( k \) ∈ signal,
- Then weight
  \( w_k = \gamma(a_k, t_k) \)
  \( a'_k = \gamma a_k \)

**c** If \( k \) ∈ noise,
- Then attenuate
  \( w_k = \gamma a_k z_k \)
  \( z'_k = w_k \)

**d** If \( k \) ∈ zero,
- Then negate
  \( a'_k = a_k \)

**e** Nearfield correction

- Performs either a discrete Fourier transform of the 2D nearfield \( xy \)
- Resulting in a 2D grid of farfield points \( k \), or a pointwise transformation of the nearfield phase to desired \( k \) points via a kernel specific to each specific \( k \).
- Each iteration is accompanied by corrections to the nearfield or farfield based on known quantities:
- \( b \), WGS balances power between spots to converge on the distribution \( a_k^{(0)} \) while preserving the current estimated phase \( \theta_k \).
- \( c \), MRAF adds a term allowing power to remain in a noise region to better match \( a_k^{(0)} \) in the signal region.
- **d**, We additionally explore an additive destructive interference correction to negate power at a spot.

**f** The nearfield correction fixes the nearfield amplitude to measured values, completing the loop.

\[ \Theta \]

= \[ \Gamma \]

\[ \Phi \]

\[ M \times T \]

\[ M \times N \]

\[ N \times T \]

**FIG. S6: Quantum Circuit Factorization.** Gate rotations are represented as real matrix \( \Theta \) (color corresponds to the strength of a matrix element). In some cases, this matrix can be factored into two others representing the state of fast modulators \( \Phi \) and the configuration of the fanout \( \Gamma \). The case shown here uses \( (M, N, T) = (32, 16, 12) \).

**FIG. S7: Channel-emitter alignment.**

- **a**, Composite blaze scans from each microlens (colored by hue) are used to select an isolated emitter at a target camera pixel for each channel (0-F). Scalebar represents 5 μm.
- **b**, After optimization in \( x \), \( y \), and focus, blaze scans collecting on the target pixel show centered fluorescence. The \( x \) and \( y \) axes use units of blaze angle at the beamsteering SLM in milliradians.
FIG. S8: **Electrical breakdown damage.** a, Overview and b, zoom upon modulator charring and delamination which we attribute to an AWG over-voltage state.

FIG. S9: **Spatial Addressing Data.** a, Target pulse sequence on sixteen channels. Color represents channel amplitude for a given channel at a given time. b, Pulse sequence with our truncated channel count. c, Expected signal (red) as the sum of all globally-collected channels, compared with the measured fluorescence (blue).