

A Hybrid Silicon Nitride / Polysilicon Platform toward Higher Power Free-Space Optical Communications

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ABSTRACT

Free-space optical (FSO) intersatellite links offer large gains in bandwidth, power efficiency, and security over radio-frequency links, but the beam is still pointed by gimbals and tip-tilt mirrors that are heavy, power-hungry, and sensitive to platform vibration. A silicon photonic beam steering chip (BSC), in which a thermo-optic switch tree feeds a grating coupler array in the focal plane of a lens, replaces that function with a device containing no moving parts. We set out the case for the approach and show that for a fixed array span D , the angular range scales approximately as $1/f$ and can therefore be rescaled through the lens focal length(f). We then report a laboratory FSO link based on a silicon-on-insulator (SOI) BSC tested separately as a transmitter and receiver. With a 50 mm lens, the measured vertical steering range was 0.40° , and a 40 Gb/s OOK eye diagram was observed at 1550 nm. Finally, we address the barrier to link-level power, two-photon absorption in SOI, with a hybrid silicon nitride / polysilicon platform that confines silicon to the phase shifters and grating couplers.

Keywords: Free-space optical communications, beam steering, silicon photonics, silicon nitride, focal plane array, pointing acquisition and tracking, two-photon absorption, intersatellite links

1. INTRODUCTION

Free-space optical communication is the preferred route to high-capacity intersatellite links, because the short wavelength delivers far more of the transmitted power to the receiver aperture than radio frequencies can, and because the narrow beam is difficult to intercept.¹ That narrow beam is also what makes the terminal difficult to build. Pointing, acquisition and tracking is conventionally split between a coarse pointing assembly (CPA), usually a gimbal, and a fine steering mechanism (FSM), usually a voice-coil or piezoelectric tip-tilt mirror.² Both contain moving parts, both must be mechanically isolated, and together they take a substantial part of a budget a small satellite does not have.

This paper makes the case for replacing that function with a silicon photonic beam steering chip (BSC), and reports progress towards one that can carry link-level power. Section 2 sets out the argument, Section 3 the circuit, Section 4 a laboratory link built around an existing SOI chip, and Section 5 the hybrid platform that removes the power limit.

2. THE CASE FOR SILICON PHOTONIC BEAM STEERING

A switched photonic array eliminates moving steering elements and therefore reduces self-induced mechanical disturbance and removes bearings, flexures and launch locks that dominate the qualification effort for a mechanical mechanism.² Switching is set by a thermo-optic time constant of tens of microseconds, not a mechanical resonance near 1 kHz. Because the chip is a foundry-manufactured photonic integrated circuit, the modulator, switch tree and eventually the receiver front end can share a die.^{3,4} Radiation testing and in-orbit experiments have shown promising tolerance for particular SOI waveguides, interferometers and modulators.^{5,6}

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Two architectures compete. An optical phased array controls the phase of many emitters to synthesize an arbitrary direction, reaching a wide field of view but needing a phase shifter per element and a demanding calibration.⁷ A switched focal plane array, used here, routes light through a switch tree to grating couplers in the focal plane of a lens; it needs only $\log_2 N$ control decisions rather than N phase settings and no phase calibration, and has been shown at scale for coherent three-dimensional imaging.⁸

2.1 The steering range

For M uniformly spaced emitters of pitch p , the centre-to-centre span between the two outermost emitters is $D = (M - 1)p$. When the array lies in the focal plane of a lens of focal length f , the full edge-to-edge steering range is

$$\theta = 2 \arctan\left(\frac{D}{2f}\right) \approx \frac{D}{f}, \quad (1)$$

where, for small angles, the separation between adjacent states is approximately $\Delta\theta = p/f$. The number of addressable states along one axis and in the square two-dimensional array are therefore

$$M = \frac{D}{p} + 1, \quad N_{2D} = M^2. \quad (2)$$

Thus the present array has $M = 8$ states per axis, seven angular intervals, and $N_{2D} = 64$ two-dimensional states.

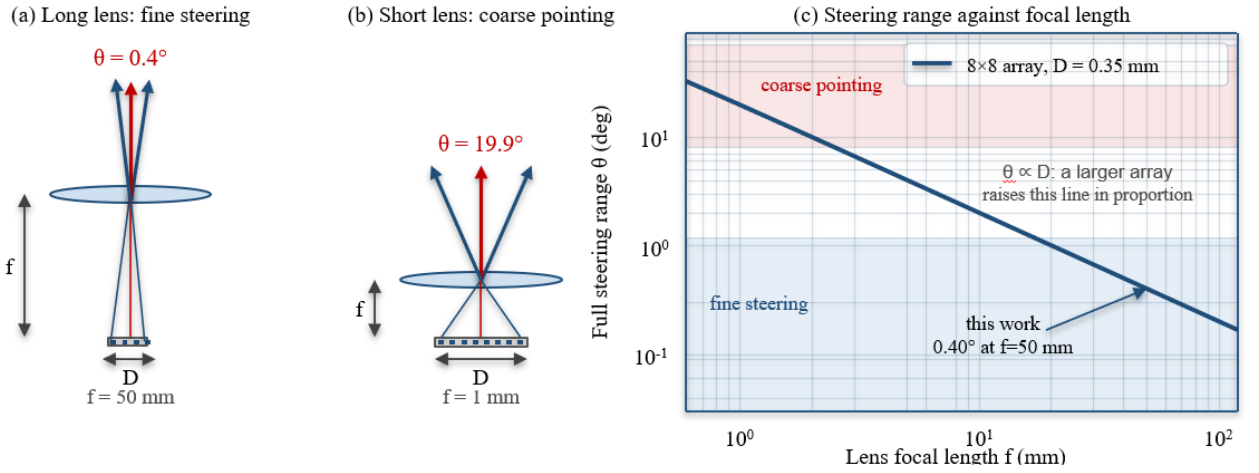


Figure 1. Lens scaling of the array steering range. (a), (b) Schematics, not to scale: emitters in the focal plane of a long and a short lens, with the beam angles exaggerated for legibility and the calculated θ labelled. (c) Range against focal length from Equation 1 for the 8×8 array. Only the 50 mm-lens point was measured; the shorter-focal-length cases are geometrical projections. The shaded bands are representative ranges associated with fine and coarse pointing, not demonstrated operating regimes of this BSC.

Figure 1 illustrates that the same array geometry can be rescaled optically. The demonstrated 50 mm lens places its 64 states within 0.40° vertically; Equation 1 predicts full ranges of 4.0° and 19.9° for 5 mm and 1 mm focal lengths. These shorter-lens cases have not been built or characterised. Aberration, numerical aperture, beam diameter, lens-to-chip packaging and emitter span will have impact on CPA operation.

The principal limitation of the present array is its discrete grid. A recent silicon photonic FPA used thermo-optic prisms to remove blind regions and demonstrate continuous steering over 62° with 45 resolvable points from 15 channels.⁹ Adding such fine steering or substantially increasing the state count would be necessary for continuous precision tracking.

Table 1 sets the architecture against both the mechanical mechanisms it would replace and the integrated steerers that define the state of the art. Its benefits are the absence of moving parts, a range set by choosing a lens rather than by actuator stroke, and one device serving either pointing stage; against those, the grid is quantized and the insertion loss exceeds a mirror's.

Table 1. Comparison with beam-steering technologies for optical intersatellite terminals. Values are representative of the cited work rather than exhaustive; only the first two entries contain moving parts, and their ranges are mechanical tilts.

Technology		Demonstrated angular capability	Response	Main limitation in cited demonstration
Conventional voice-coil / piezoelectric FSM ²		Continuous, device-dependent range and resolution	Typically sub-kHz to kHz class	Moving optic, actuator and launch-lock requirements
Piezoelectric FSM ¹⁰	MEMS	$\pm 2.16 / \pm 2.18$ mrad mirror tilt; $0.3 \mu\text{rad}$ minimum measured resolution	0.41 ms settling; 2.083 kHz bandwidth	10 mm moving mirror; approximately $1.1 \mu\text{rad}$ repeatability
Liquid-crystal steerer ¹¹	beam	Continuous; range is device- and wavelength-dependent	μs to ms class	Temperature, polarization and material constraints
Integrated OPA ^{7, 12, 13}	SOI	Continuous steering; up to 180° in specialised arrays	Thermo-optic, μs class	Per-element phase control; optical power handling not reported
Metalens FPA, SOI ⁹		62° ; continuous, 45 points from 15 channels	$8.8\text{--}22.3 \mu\text{s}$	16.5 dB loss; 1.46 W maximum electrical drive
Switched FPA, SOI (this work)		0.40° vertical; 8 states/axis, 64 total	Not measured on this chip	Discrete grid; optical power handling limited due to TPA
Hybrid building blocks (this work)	SiN/poly-Si	Complete steering not yet demonstrated	Switching time not measured; $15.52 \text{ mW}/\pi$ on one test device	NA

3. CIRCUIT LAYOUT

The chip used for the link is similar to a previously published work for LIDAR applications.¹⁴ Light is coupled from a fibre into an on-chip waveguide and routed through a six-stage cascade of thermo-optic 1×2 Mach-Zehnder interferometer (MZI) switches forming a 1×64 tree. Each output ends in a grating coupler, and the 64 form an 8×8 grid of $0.35 \text{ mm} \times 0.35 \text{ mm}$, a pitch of $50 \mu\text{m}$ (Figure 2(a),(b)). Steering is achieved by switching between outputs; reciprocally, a beam arriving at a given angle is focused onto one coupler, and the tree is set to route it back to the fibre (Figure 2(c)).

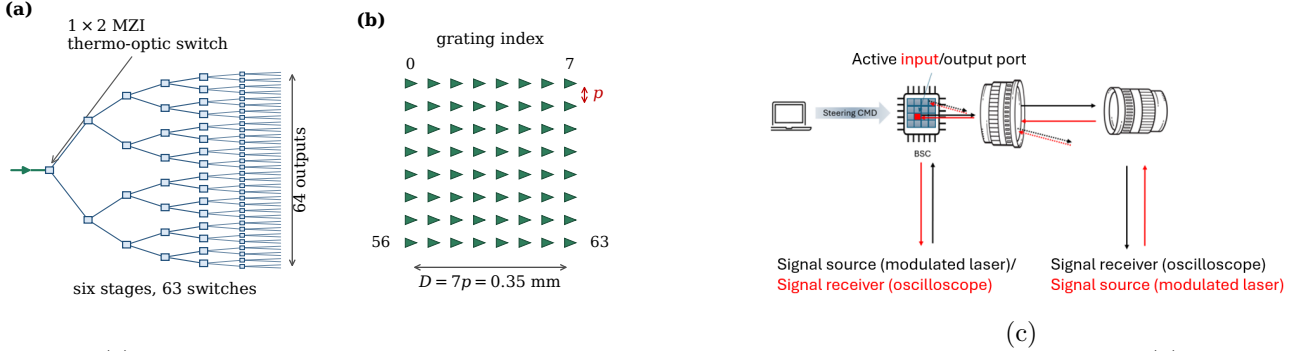


Figure 2. (a) The 1×64 switch tree: 63 MZI switches in six stages, of which a selected route traverses six. (b) The 8×8 grating coupler array and its index convention, with pitch p and centre-to-centre span D . (c) The BSC in an FSO system, as sender (black) and as receiver (red).

Each direction requires the correct voltage on all six switches along its route, and with six 8-bit digital-to-analogue converters (DACs) in series a manual search is impractical. A closed-loop system was therefore built: an infrared camera monitors the scattering from the array, a PC locates and indexes the 64 couplers to sub-pixel accuracy, and the six DAC values and grating index go over UART to an FPGA driving the DACs and a demultiplexer. Calibration was posed as an optimization whose objective is the brightness of the selected coupler penalized by a distance-weighted sum of all the others. Differential evolution was used for optimization;¹⁵ a representative run used a population of nine and converged by 90 generations, producing the steering lookup table.

4. LOW-POWER BEAM-STEERING CHIP EXPERIMENTS

The link is shown in Figure 3(a). A short-wavelength infrared imaging lens of 50 mm focal length and F/1.4 aperture sits above the chip, collimating the output on transmit and focusing the incoming beam on receive, with a mirror folding the beam horizontal. The far end of the 1.64 m link is a fibre collimator that launches the modulated beam or collects it into a fibre to the photodetector, and a beam splitter sends part of the beam to a screen so the steering can be filmed while data is received. The 50 mm focal length matches the beam to the collimator, fixing the range at 0.4° .

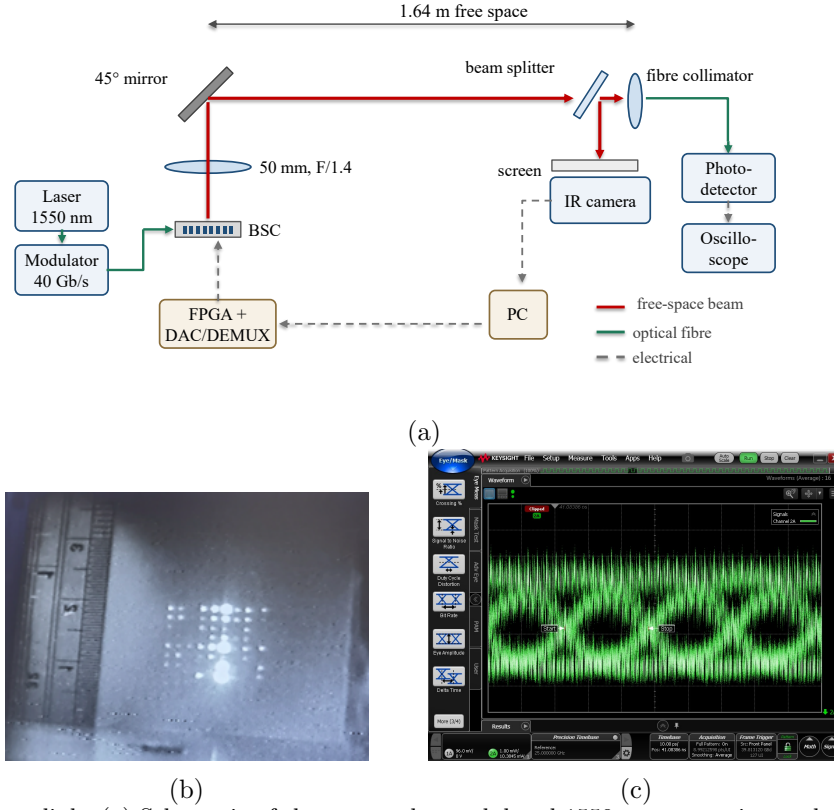


Figure 3. The free-space link. (a) Schematic of the setup: the modulated 1550 nm source is coupled into the BSC, whose grating array sits in the focal plane of a 50 mm F/1.4 lens; a 45° mirror folds the collimated beam into a 1.64 m path to a fibre collimator and photodetector, and a beam splitter diverts part of the beam to a screen recorded by an IR camera. (b) Emission without selective switching projected onto a screen 1.7 m from the lens against a ruler; the 1.2 cm vertical extent corresponds to 0.40° . (c) Eye diagram recorded at 40 Gb/s.

Emission from each coupler in turn was projected onto a screen 1.7 m from the lens. Across the individually selected outputs, the projected spots spanned 1.2 cm vertically; (Figure 3(b)) shows the complete array footprint under non-selective excitation; the vertical extent of 1.2 cm corresponds to 0.40° vertically and 0.57° along the diagonal, agreeing with Equation 1 to better than one per cent. Power was measured at four points: 19.16 mW at the source fibre before the BSC, $494 \mu\text{W}$ emitted from the chip with the lens removed, $549 \mu\text{W}$ after the lens, and $129 \mu\text{W}$ after the free-space path and recoupling into the receiver fibre. The $494 \mu\text{W}$ value is an underestimate because the 5 mm detector did not collect the full diverging beam. From after the lens to after the receiver fibre, the measured transmission is 23.5%, or 6.29 dB loss. This measurement combines free-space propagation, 3 db from beam-splitter and collection losses, recoupling and the receiver fibre; the individual contributions were not separated.

For data transmission a 1550 nm source was modulated at 40 Gb/s by a silicon photonic modulator. With the chip as sender the signal appears at the receiver only when the beam is steered onto the collimator; as receiver the spot is stationary and the link closes when the tree routes the in-coupled light to the fibre. The recovered eye is shown in Figure 3(c). The data rate was set by the modulator driver, not by the chip or the link.

5. PATHWAY TO A HIGH-POWER LINK

At high guided optical intensities, the power-handling capability of silicon waveguides is limited by two-photon absorption (TPA). Free carriers generated by TPA introduce additional loss through free-carrier absorption.^{16,17} Overcoming this limitation requires a material platform that combines high optical-power handling with efficient switching. Because no single material readily provides both properties, a hybrid silicon nitride/polycrystalline silicon (SiN/poly-Si) platform offers a practical and manufacturable alternative.

5.1 The two-photon absorption limit in SOI

To quantify the limit of TPA of SOI waveguide we used Lumerical Mode solution¹⁸ with a custom python script for non-linear behavior. For 1 W guided input power launched at 1550 nm over 5 mm, the standard 450 nm $\times$ 220 nm TE waveguide transmits 36.6 mW, and a 3000 nm $\times$ 500 nm cross-section gives only 148 mW — short of the project’s 300mW output target, and over less than half the 10–20 mm the circuit requires. A delocalized TM mode reaches 309 mW but sits largely in the cladding, making the couplers, splitters and switches hard to design. None of the evaluated passive SOI cross-section met the requirement.

5.2 The hybrid silicon nitride / polysilicon platform

Silicon nitride has negligible TPA at 1550 nm and lower propagation loss than SOI,¹⁹ but a small thermo-optic coefficient of $2.45 \times 10^{-5} \text{ K}^{-1}$ and a lower index compared to silicon,²⁰ so its phase shifters are inefficient and its grating couplers lose over 10 dB in the device compared with 5–7 dB for standard CORNERSTONE SOI grating couplers at 1550 nm.⁴ Prior silicon nitride thermo-optic switches needed close to 300 mW each, against the 70 mW per switch our driver supplies across 63 switches. Our platform therefore splits the three functions between two layers (Figure 4(a)). Nitride carries the routing, so almost the whole path is TPA-free. Where a phase shifter is needed, a polysilicon strip above the nitride waveguide is tapered so the light transfers up, is modulated using silicon’s much larger thermo-optic coefficient, and transfers back. The total polysilicon path stays below 0.75 mm. The grating couplers are formed the same way, and three-dimensional FDTD²¹ simulation predicts over 75% upward efficiency against under 10% for a conventional nitride coupler.

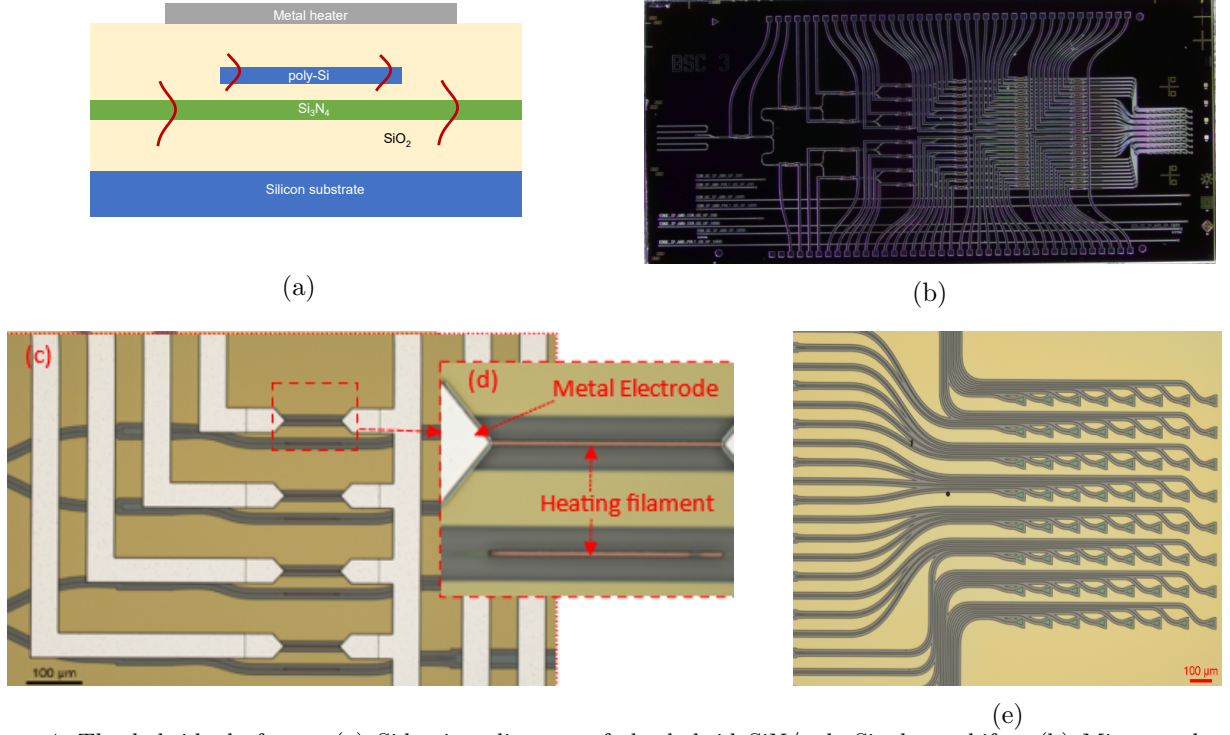


Figure 4. The hybrid platform. (a) Side-view diagram of the hybrid SiN/poly-Si phase shifter (b) Micrograph of a fabricated die. (c) MZI switches in the switching tree. (d) Heater filament and connected electrode. (e) The output grating coupler array, gratings patterned in the polysilicon above the nitride waveguides.

5.3 Fabrication and measured component performance

The chips were fabricated by the CORNERSTONE photonic foundry service using a bespoke fabrication run.⁴ The wafer carries 300 nm of Si_3N_4 on 3 μm of buried oxide; a 150 nm oxide spacer and 200 nm of polysilicon are deposited and annealed and patterned for the grating couplers, phase shifters and optical mode converters, the nitride is patterned for the waveguides and passives, and the stack is finished with a PECVD oxide cladding, a TiN heater of thickness 300 nm and aluminium pads. The measured cutback losses are given in Table 2; all match simulation except the mode converter pair, whose 1.32 dB against the 0.06 dB predicted we attribute to fabrication imperfections, including SiN/poly-Si layer misalignment, may explain the discrepancy.

Table 2. Measured performance of hybrid platform building blocks.

Building block	Measured performance
SiN waveguide	0.35 dB/cm
1×2 / 2×2 MMI	0.20 / 0.19 dB (through), 0.44 dB (cross)
SiN to poly-Si mode converter pair	1.32 dB/converter pair
Poly-Si waveguide	10.80 dB/cm
Thermo-optic phase shifter	15.52 mW per π , $> 4\pi$ range

6. CONCLUSION

We showed a silicon photonic BSC that removes moving steering elements. The 8×8 SOI array demonstrated here provides eight states per axis and 64 two-dimensional states. With a 50 mm lens its measured range is

0.40° vertically and 0.57° diagonally. Shorter-lens calculations show how the angular grid could be rescaled. The same BSC was tested separately in transmitter and receiver configurations in a 1.64 m link, all 64 states were calibrated automatically, and a nominal 40 Gb/s OOK waveform was observed. To overcome nonlinear-loss problem in SOI we then showed the hybrid SiN/poly-Si platform which addresses the problem at the material and component level. It has demonstrated 0.35 dB/cm low-power SiN propagation loss and 15.52 mW/ π on one phase-shifter test device. High optical power testing of the poly-Si sections and operation of a complete hybrid BSC in the link remain future work.

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