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**InGaAs/InP chip-based mid-infrared optical phased arrays for
communications and sensing**

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by

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Abstract

InGaAs/InP chip-based mid-infrared optical phased arrays for communications and sensing

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The mid-infrared atmospheric transmission windows (wavelengths $\sim 3\text{--}5$ and $8\text{--}14\text{ }\mu\text{m}$) provide a unique opportunity for low-loss transmission in areas such as thermal imaging, lidar, infrared homing, and line-of-sight communications. Additionally, in comparison to traditional operation in the near-infrared, the lower background solar irradiation of the mid-infrared permits higher signal-to-noise detection. In spite of these inherent benefits, the advance of applications in the mid-infrared has lagged their near-infrared counterparts, due to the lack of maturity in material properties, light sources, and detectors specific to the region.

This research seeks to advance the state of the art in on-chip photonics operating in the mid-infrared transmission windows. In particular, in this work I build and demonstrate operation of optical phased arrays (OPAs) operating at a wavelength of $4.6\text{ }\mu\text{m}$. On-chip OPAs provide non-mechanical beam formation and steering in a compact

form factor—an enabling technology for the next generation of miniaturized mid-infrared systems that will be incorporated into, e.g., unmanned aerial vehicles. The work is carried out in an InP-based platform in consideration of the fact that InP-based quantum cascade lasers are now the preeminent mid-infrared light source, therefore conceiving the potential for a fully monolithic integrated OPA solution.

In the first phase of this research, I developed and demonstrated a 1D periodic OPA, that is to say, a 1D periodic array of emitting elements, permitting beam steering in one dimension. The thermo-optic effect was employed for phase tuning and surface gratings were used for emitting elements. An unambiguous steering field-of-view (FOV) of 23° with 38 resolvable points was achieved.

In the second phase of this research, the OPA was revamped to improve performance. First, heat-isolation trenches were incorporated to improve phase tuning efficiency. Second, the emitting elements were changed to total-internal-reflection mirrors, whose small area permitted distribution in a 2D array. Third, the array was made aperiodic—the emitter positions being optimized to maximize the number of resolvable points. Within an observed 23° -diameter-FOV >500 resolvable points were achieved, with an estimate of >1000 resolvable points within the full device FOV.

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Chapter 1: Introduction

This research focuses on the development of integrated photonic devices for operation in the mid-infrared (mid-IR) spectral region (wavelength $\sim 2\text{--}20\ \mu\text{m}$), a region home to applications in spectroscopic sensing, imaging, lidar and heat seeking. Unlike the near-infrared (near-IR) region (up to $\sim 2\ \mu\text{m}$), where integrated photonics has experienced rapid growth over the past two decades, advances in the mid-IR have been much slower, due to challenges in material properties, sources, and detectors across the region [1–3]. Nonetheless, the ongoing research is providing the scientific, health, environmental, and defense communities with ever-increasingly powerful tools for their vocations. This research seeks to contribute to this advance. With bases in the already developed integrated photonic technologies in the visible and near-infrared, as well as the component systems of the mid-IR, it aims to develop more efficient and practical (e.g. portable) mid-IR devices.

More specifically, the research centers on InP-based technology in the first mid-IR atmospheric window (wavelength $\sim 3\text{--}5\ \mu\text{m}$). InP-based quantum cascade lasers (QCLs) are the predominant semiconductor source in this range, so monolithic integration of both passive and active devices is possible when working in this material system [4–7]. Though hybrid integration techniques (e.g., Si passive with InP active) are also a field of active research and serve a purpose [8–11], monolithic integration of one material system is necessary for applications where robustness is required [12–16].

On-chip non-mechanical beam steering is an enabling technology for applications where precise, reliable, and rapid beam steering is needed. In the near-IR spectral region, lidar-based applications for sensing, mapping, and navigation have fueled the rapid progress of such steering devices in recent years [17,18]. Over the course of this progress,

optical phased arrays (OPAs) have emerged as the preeminent technology, and performance optimizations have come to fruition [19, 20]. For example, OPAs with nonuniformly spaced emitters have shown the ability to spread out grating lobe power to provide wider steering ranges [21–27], and sub-wavelength spacing for wide grating-lobe-free range has been proven [28–31].

For compatibility with foundry CMOS fabrication, in the near-infrared the majority of on-chip beam-steering development has focused primarily on silicon-based platforms [32–40]. For improved portability with small size, low weight, low power, and high robustness, on-chip laser integration is highly desirable, necessitating the incorporation of III–V material. Various works have demonstrated the task. This has been accomplished in both a hybrid III–V silicon photonics platform [41], as well as a homogenous InP-based one [42].

Moving to the mid-infrared spectral region changes the technological scenario. Depending on the application, the continued use of hybrid platforms may or may not be possible. Namely, short-range applications at moderate optical power levels (≤ 1 W) may be operable in such a platform. In this case, demonstrated silicon and related mid-IR platforms may take advantage of hybrid bonding techniques (e.g. plasma-assisted direct bonding or intermediate layer adhesives) to achieve hybrid integration [8–10, 43].

On the other hand, long-range applications requiring high optical power levels (≥ 1 W) will prove challenging with a bonded interface. In this regime, considering integration with mid-infrared quantum cascade lasers (QCLs) whose heat generation is on the order of the optical power [44, 45], the thermal properties across such an interface become limiting. Efficient heat dissipation and matched coefficients of thermal expansion (CTEs) are paramount. For instance, for QCLs directly bonded to high-index Si or Ge waveguides, the III–V cladding tends to hover over a significant amount of empty space [8, 9], limiting the

maximal heat dissipation, while the nonmatched CTEs (2.6 or 5.9 ppm/K for Si or Ge, respectively, versus 4.6 ppm/K for InP) can impair physical reliability.

Hence, for the case of high-power operation in the mid-IR, the monolithic integration of QCLs on a native InP-based platform is the default approach for maximal thermal performance and physical robustness. With this motivation, research is now beginning to demonstrate the elements of an integration technology. InP-based low-loss passive waveguides are being developed, as well as coupling schemes between these passive waveguides and active QCL waveguides [12–16]. And first demonstrations of QCL-integrated elevation steering [46] and QCL-based high-power phased arrays [47] have been carried out.

Considering the aforementioned factors, in this research two generations of OPAs are developed to demonstrate the feasibility of on-chip non-mechanical beam steering in the mid-IR spectral range in an InP-based platform. The first-generation device provides the initial experimental proof-of-concept. The second-generation device builds on the first, revamping it for improved efficiency and beam steering characteristics.

Chapter 2: OPA Generation 1

The first generation of our mid-IR InP-based OPA was for proof of validity. Our aim was to create a simple design that could be fabricated and tested in little time—a rapid prototype first generation device, if you will, that would provide lessons on the sensitivity of the device performance to design parameters and fabrication imperfections.

OPA ARCHITECTURE

Our passive platform uses the low-index-contrast lattice-matched $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{InP}$ system (indices of refraction 3.375/3.09 at $\lambda = 4.6 \mu\text{m}$). A schematic of the device structure is shown in Figure 1. The architecture is based on an InGaAs core with InP cladding. We use $\sim 4 \mu\text{m}$ wide ridge waveguides of InP/InGaAs/InP 2.2/1.7/1.6 μm and the basic structure consists of three sections: a 1×32 splitter, phase shifters, and beam emission gratings. The splitter is a tree-array of Y-junctions and 500 μm -radius s-bends, with a total length of 1500 μm . The phase shifters consist of Cr/Au electrode strips running along the top surface of the InP cladding, encased in SiO_2 passivation, with a total length of 2350 μm . Contact openings through the passivation connect the electrodes via overlay metallization to contact pads. The beam emitters have no passivation nor upper cladding, so that the shallow gratings are etched directly into the InGaAs layer, and they extend out a length of 3000 μm . The entire device measures 6.85 mm in length.

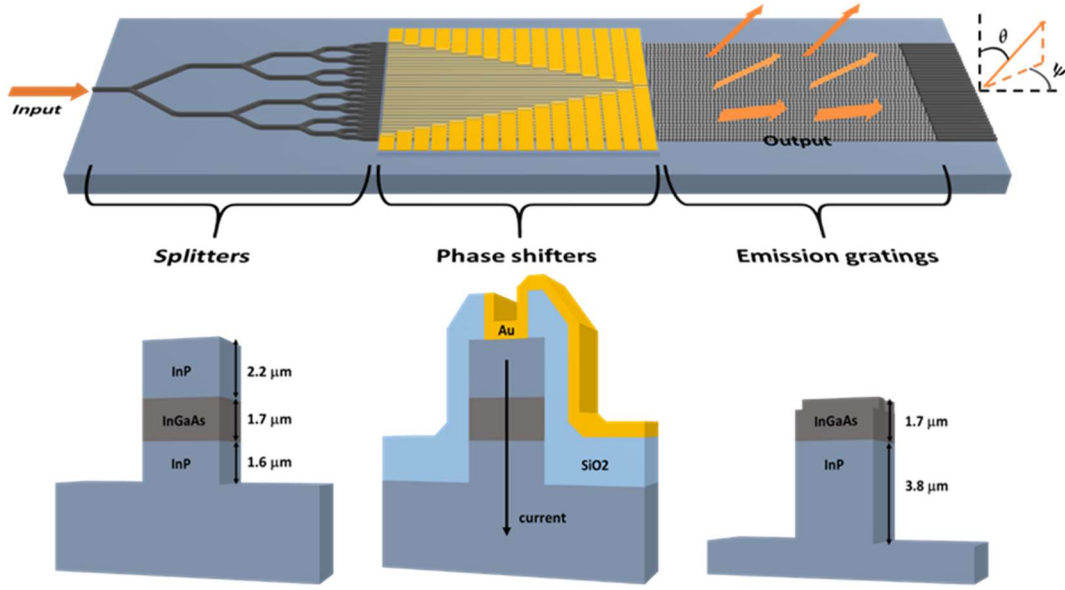


Figure 1: Device schematic of the OPA generation 1 device: overall layout and cross-sections of the three main sections—the splitter tree, the phase shifters and the emitters. Also shown are ψ the azimuthal angle and θ the elevation angle.

For simplicity in experiment, the fundamental transverse electric (TE) mode is used, shown in Figure 2. Also, the splitter tree uses simple 1×2 Y-junctions to split the input light power evenly from one waveguide to two, cascaded five times to produce 32 channels of equal power light. They are considered lossy, but sufficient for this first generation.

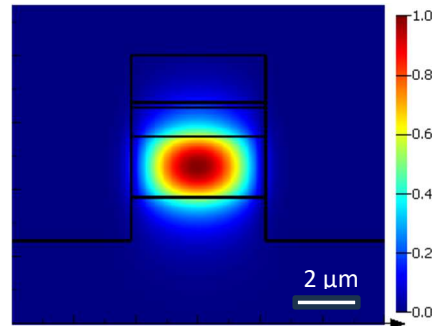


Figure 2: Gen1 OPA waveguide fundamental TE electric field mode profile.

THERMO-OPTIC PHASE SHIFTERS

Channel phase shifting is accomplished by index tuning through the thermo-optic effect. In our design current is injected directly through the undoped ($n \approx 1 \times 10^{15} \text{ cm}^{-3}$) waveguides, thereby effecting ohmic heating of the waveguide. For a waveguide of length L , the accumulated phase for a temperature change ΔT with respect to another reference waveguide is given by

$$\Delta\phi = 2\pi \frac{L}{\lambda} \frac{dn}{dT} \Delta T . \quad (1)$$

Taking $dn/dT \approx 2 \times 10^{-4} \text{ K}^{-1}$ and $L = 2350 \text{ }\mu\text{m}$, a phase shift $\Delta\phi = 2\pi$ requires $\Delta T \approx 10 \text{ K}$. Figure 3(a) shows the simulated temperature profile at this condition. To achieve this temperature profile we employ resistive Joule heating through the semiconductor material itself, that is, current is injected vertically through the waveguide and substrate, as shown in Figure 3(b). The resistance R of semiconductor material is given by

$$R = \frac{\rho d}{A} = \frac{d}{q\mu_n n A} , \quad (2)$$

where $\rho = 1/q\mu_n n$ is the resistivity, q is the electronic charge, μ_n is the mobility, n is the carrier concentration, d is the distance, and A is the cross-sectional area. The electron mobilities of InP and InGaAs are $\mu_n \approx 4000$ and $\mu_n \approx 1000 \text{ cm}^2/\text{Vs}$, respectively. Given that our material is nominally undoped n-type with a concentration $n \approx 1 \times 10^{15} \text{ cm}^{-3}$, we can calculate the material resistivities as:

InP: $\rho \approx 1.56 \text{ }\Omega \text{ cm}$, and

InGaAs: $\rho \approx 0.63 \text{ }\Omega \text{ cm}$.

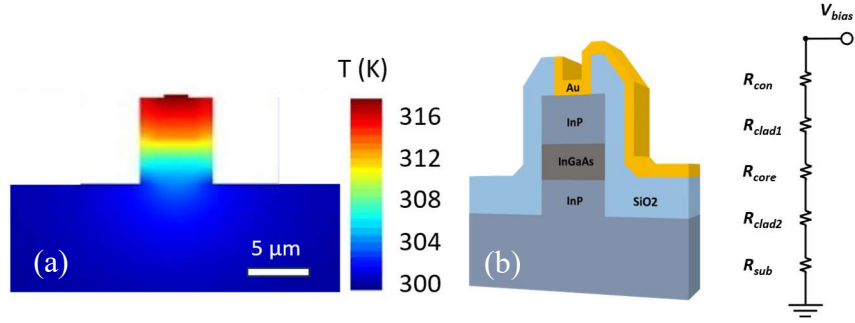


Figure 3: Thermo-optic phase shifter: (a) Simulation of heat profile at 2π phase shift, and (b) representation of electrical resistances.

Considering current flow vertically through a 4- μm -wide, 2350- μm -long waveguide of heights 3.8 μm and 1.7 μm for InP and InGaAs, respectively, the resistances of the InP and InGaAs parts are $R_{clad1} + R_{clad2} \approx 6.3 \, \Omega$ and $R_{core} \approx 1.1 \, \Omega$, respectively, for a total waveguide ridge resistance of $R_{ridge} \approx 7.5 \, \Omega$. However, this calculation will underestimate the resistance, due mainly to geometrical factors such as smaller injection area. A detailed simulation gives $R_{ridge} \approx 17 \, \Omega$. The contact and substrate resistances must also be considered. The specific contact resistance can be estimated as $\rho_c \approx 0.001 \, \Omega \text{ cm}^2$, based on an extrapolation from literature on n-InP ohmic contacts [48]. For a $3 \times 2350 \, \mu\text{m}^2$ cross-sectional area, we calculate $R_c \approx 14 \, \Omega$. Finally, a simulation of the 350- μm -thick substrate yields a resistance of $R_{sub} \approx 31 \, \Omega$. Taken together, the (ideal) total device resistance is $R_{total} \approx R_c + R_{ridge} + R_{sub} = 62 \, \Omega$. Unfortunately, most of this resistance is parasitic, as the mode resides primarily in the core of the ridge waveguide.

EMITTER ARRAY

For multiple in-phase emitters constructive interference in the far-field (in the azimuthal direction ψ , as depicted in Figure 1) is given by

$$\sin \psi = \frac{m\lambda}{d}, \quad (3)$$

where m is the diffraction order ($0, \pm 1, \pm 2, \dots$), λ is the (free-space) wavelength and d is the periodic separation distance between emitters. By adjusting the emitter-to-emitter phase relation, the peaks may be “steered” in the far field. Of course, our interest is with steering the single central peak, within a field-of-view uninhabited by other peaks. Letting φ be the incremental phase shift from emitter-to-emitter we note that a swing of φ from 0 to 2π shifts each peak to the location of the next order. Thus, for the central peak to move within a field-of-view, without such a field-of-view being invaded by another incoming order, the phase shift is one half the cycle, i.e., φ from 0 to π . Replacing m with $\varphi/2\pi$ in Eq. (3) gives the relation for the steering angle of the central peak:

$$\sin \psi = \frac{\varphi}{2\pi} \frac{\lambda}{d}. \quad (4)$$

Note that the steering relation goes inversely with d , that is, that smaller emitter-to-emitter distances give larger fields-of-view (and that a theoretical maximum steering field of $\psi = \pm 90^\circ$ with $\varphi = \pi$ would require $d = \lambda/2$). Additionally, the beam envelope is inversely related to a single emitter width. So, both the emitter spacing and individual size are reduced to increase the breadth of steering. But reducing these dimensions increases waveguide crosstalk, so there is an inherent tradeoff between field-of-view and crosstalk.

The emitter-to-emitter spacing is determined from our program requirement, which stipulates a lateral steering range of 20° (i.e., $\pm 10^\circ$). From Eq. (3) we find that spacings of $d = 2.5\lambda$ and 3.0λ give peak separations of 23.5° and 19.5° , respectively. This translates to FOVs of $\pm 11.5^\circ$ and $\pm 9.6^\circ$, respectively. These are shown in Figure 4 and are the spacings we use in our design.

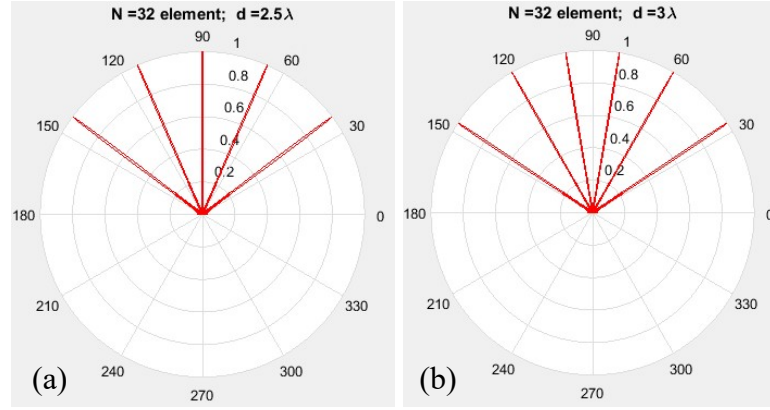


Figure 4: Effects of emitter-to-emitter spacing on far-field patterns. Red lines are azimuthal peaks. (a) $d = 2.5\lambda$ yields peak separations of 23.5° (FOV = $\pm 11.5^\circ$), and (b) 3.0λ yields peak separations of 19.5° (FOV = $\pm 9.6^\circ$).

As mentioned above, the waveguide spacing is ultimately limited by the evanescent coupling between waveguides. Here we check this effect. We simulate the crosstalk at the more rigorous spacing of 2.5λ . (Gratings have periodicity $\Lambda = 1.4 \mu\text{m}$, 50% duty cycle, and etch depth = 400 nm.) Figure 5 shows the amount of crosstalk vs. both wavelength and propagation length. We see that up to $\lambda = 4.7 \mu\text{m}$ crosstalk is below an innocuous 0.075%. The inset shows the E-fields in the waveguides at $\lambda = 4.6 \mu\text{m}$ at the propagation length of 500 μm .

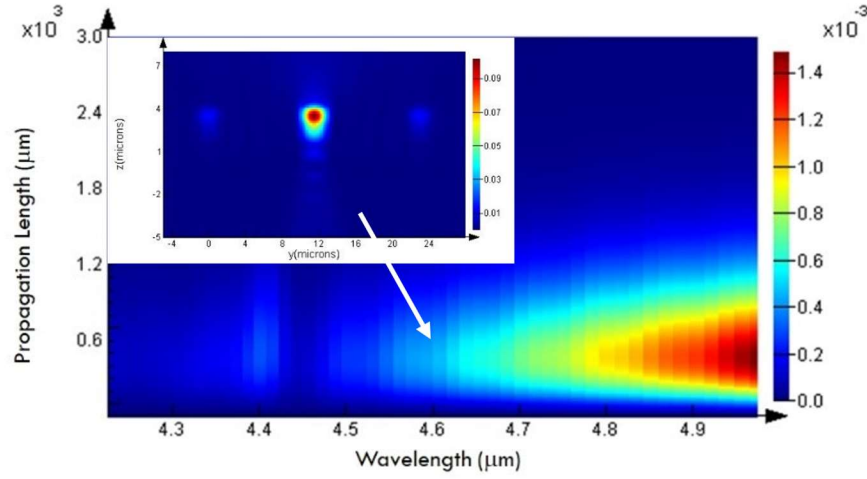


Figure 5: Simulated optical crosstalk between waveguide emitters versus free-space wavelength and propagation distance, for an emitter spacing of $d = 2.5 \lambda$. The inset shows the E-field at the point indicated by the arrow, that is, for $\lambda = 4.6 \mu\text{m}$ and a propagation length of $500 \mu\text{m}$.

GRATINGS

Since diffraction from a periodic grating is dependent on wavelength, longitudinal beam steering can be effected by the combination of an appropriately designed grating and laser wavelength tuning. Importantly, the grating periodicity is less than $\lambda_0/2$, so that only a single diffraction order is emitted. The diffraction angle θ , with respect to the normal, is given by

$$\sin \theta = n_{eff} - \frac{\lambda}{\Lambda}, \quad (5)$$

where n_{eff} is the effective index of the waveguide and Λ is the grating periodicity. Considering that current state-of-the-art QCLs achieve tuning ranges of $\sim 300 \text{ nm}$, Eq. (5) translates to $\sim 13^\circ$ of tuning. For the current passive structure though, and in the absence of a tunable laser, the demonstration of Eq. (5) is sought by incorporating devices with

different emission grating pitches. In accordance with the equation and $n_{eff} \sim 3.2\text{--}3.4$, we use gratings with pitches from 1.20 to 1.75 μm .

The effect of grating etch depth on transmission was simulated in our wavelength range of interest. The result for etch depth = 500 nm is shown in Figure 6. We see nearly ~46% transmission upwards to air and ~48% transmission downwards to the substrate; the remaining ~6% considered to pass through the grating domain, here 1500 μm . So, we target an etch depth of 500 nm, but extend the emitter lengths out well beyond 1500 μm (to 3000 μm) to maximize emission and avoid reflection.

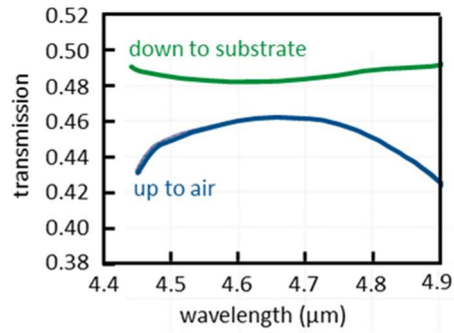


Figure 6: Simulation results for emitter emission with grating etch depth = 500 nm.

OPA DEVICE FABRICATION

The fabrication process on the epitaxial wafer is shown in Figure 7 and begins with a selective wet etch (HCl-based) of InP in the emitter region, leaving the InGaAs layer exposed. Then the phase shifter electrodes are formed by deposition and lift-off of Cr/Au (5nm/70nm). Subsequently, the emission gratings are patterned by e-beam lithography and dry etched 500 nm into the InGaAs layer by Cl_2/N_2 inductively coupled plasma. Next, the waveguides are etched by $\text{Cl}_2/\text{CH}_4/\text{H}_2$ inductively coupled plasma, etching through the InP

and InGaAs layers and into the InP substrate to a total depth of 5.5 μm . The waveguides are then passivated in the phase-shifter region with 2 μm plasma-enhanced chemical vapor deposition (PECVD) SiO_2 (for 1 μm sidewall coverage), and contacts are opened along the top of the waveguides by CHF_3/Ar reactive ion etching. Finally, another lift-off process is used for the metal traces and probe pads. A sequence of three of Ti/Au (10nm/200nm) depositions are carried out—the first is for general coverage, the extra two are off-angle ($\sim 30^\circ$ off the vertical) to ensure good sidewall coverage of the waveguides. Photos of the fabricated device are shown in Figure 8.

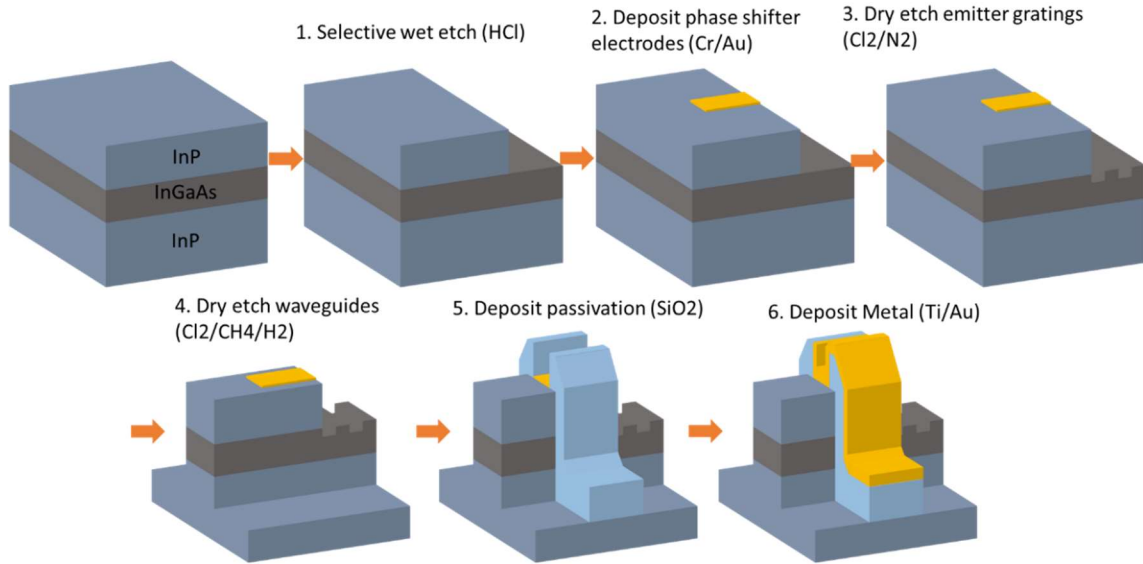


Figure 7: Fabrication process of the first generation OPA device. The three main regions—splitter tree, phase shifters, and emitters—are represented schematically in three sections of the block from left to right.

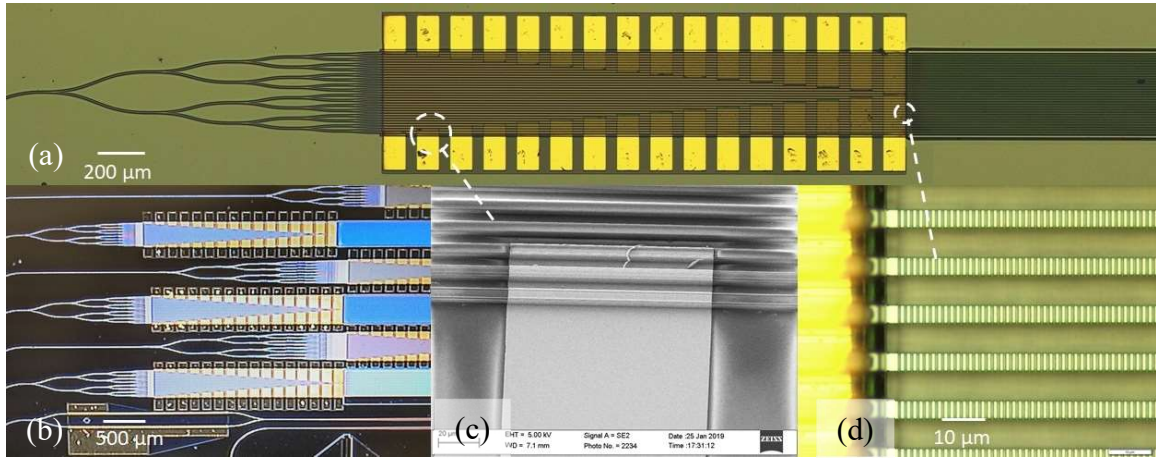


Figure 8: Photos of the fabricated first generation OPA chip: (a) one full device, (b) multiple devices on the chip, (c) SEM of one phase shifter, and (d) the subwavelength grating emitters.

Following front-side processing, the chip is further prepared for testing. The backside is lapped to remove the residue from the fabrication. Then the chip is cleaved at the waveguide input facets and mounted to an aluminum block with indium. The lapped surface plus indium provide together mechanical and electrical integrity (as the substrate will be used for ground during biasing).

PRELIMINARY CHARACTERIZATIONS

Prior to beam steering characterization there are a couple of preliminary steps that need to be carried out. The first one is an evaluation of the phase shifting performance. For this purpose, a symmetric Mach-Zehnder interferometer (MZI) was fabricated on the same chip. Figure 9 shows the device and test setup. Input light was end-fire coupled into the cleaved facet on one side of the chip, and the output light from another cleaved facet on the other side of the chip was viewed and measured with the mid-infrared camera (input and output facets were offset to avoid stray input light blinding the output). One arm of the

MZI was biased by a contact probe and the substrate was grounded. The optical output vs. input electrical power is shown in Figure 9(d), from which we estimate π -phase-shift to occur at ~ 225 mW electrical power. This value was a little larger than initially expected as will be explained below.

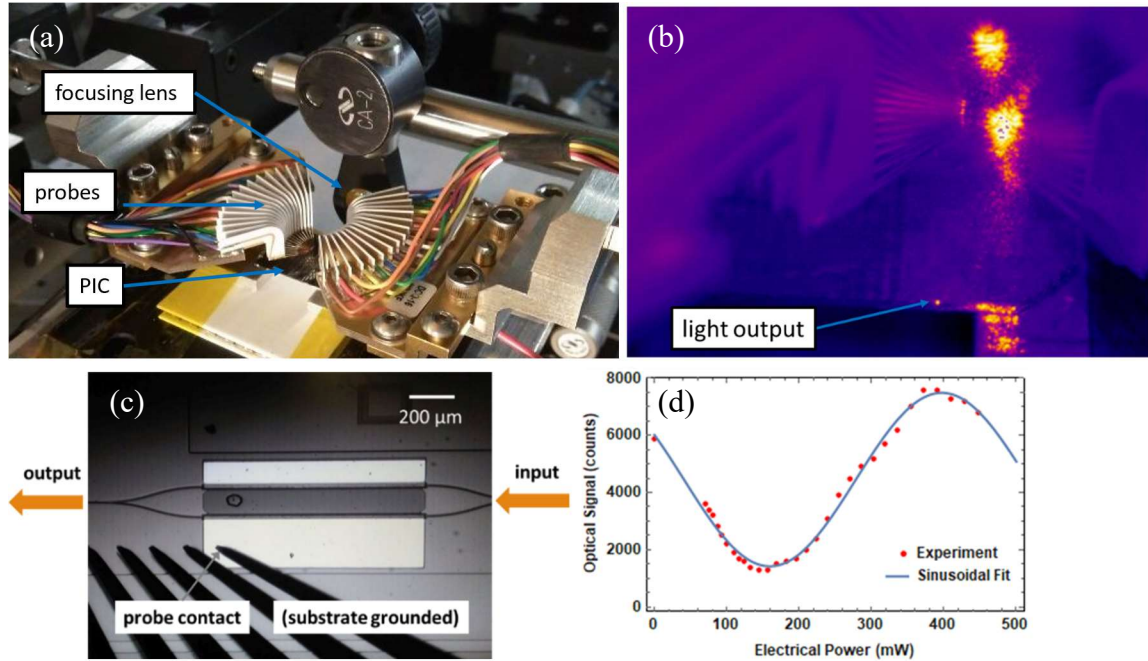


Figure 9: MZI device characterization: (a) the PIC chip on the testing stage, (b) MWIR camera image showing the light at the output facet of the MZI, (c) the MZI device with probe contact, and (d) the experimental MZI operation curve.

The second preliminary step is a check of the resistances of each of the 32 phase shifters of the OPA. Ideally, all phase shifters are the same resistance. Unfortunately, this was found not to be the case, again likely due to the contact resistance issue, but manifesting properties of the array. Figure 10 shows the resistances of each channel of an OPA device. Most values lie within the range $385\text{--}667\ \Omega$, with a definite trend across the array. The overlay metallizations of the phase shifters are staggered with a period $150\ \mu\text{m}$.

The overlay of channel # 0 is at the end of the waveguide, channels # 7,8 are at the center of the waveguide, and that of channel # 15 is again at the end of the waveguide. Likewise for channels # 16–31. Thus, we see the trend is that the resistances are low in the center of the waveguide, and gradually increase towards their ends. We can understand this effect with the aid of Figure 11. In the ideal case, with low resistance contact metal, the injection current spreads evenly across the waveguide. However, in the case of a high resistance contact metal, the injection current is localized to the vicinity of the overlay metal. However, the localized current injection, and therefore localized heating, is not necessarily an issue in itself. Rather, the localized heating being located in the vicinity of the overlay metal means that it has this pathway through which to dissipate heat. In consequence, the power required for a particular phase shift is increased, and the effect is amplified as the overlay moves from the center of the waveguide towards the edge. (For the MZI device, the metal overlay extends across the waveguide, enabling this pathway of heat dissipation and raising the phase shift power.) Taking into account the distribution of resistances across the channels permits a better estimation of the required channel powers for a given phase gradient.

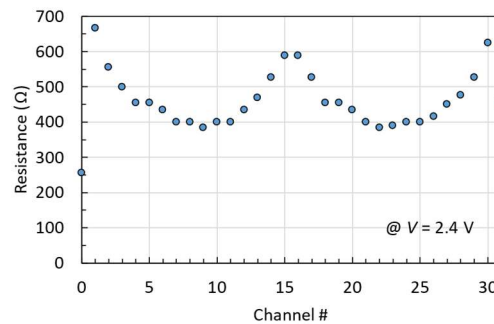


Figure 10: OPA device channel resistances. End channel values are anomalous due to defects at the edges of the device.

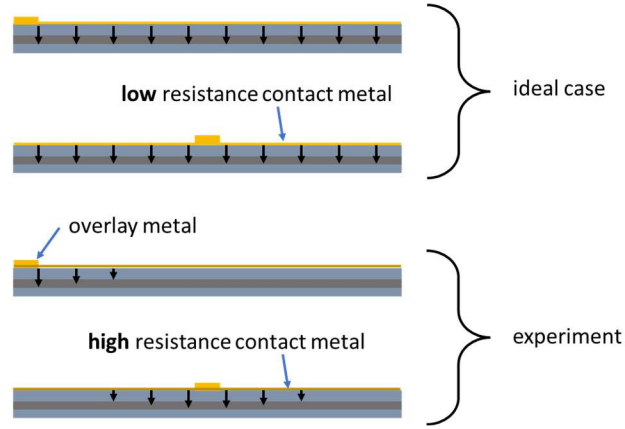


Figure 11: Schematic representation of phase shifter current crowding effect. Black arrows indicate current injection.

OPA AZIMUTHAL BEAM STEERING CHARACTERIZATION

Figure 12 shows different elements and perspectives of the test setup. The OPA chip mounted on its aluminum block is positioned with a precision motorized stage (Newport). A Fabry-Pérot quantum cascade laser (Adtech Optics) was focused onto the device's cleaved facet with a $\frac{1}{2}$ " diameter CaF_2 bi-convex lens of focal length = 16 mm at $\lambda_0 = 4.6 \text{ } \mu\text{m}$ (Thorlabs). Two multi-contact probes (FormFactor DCQ-16), with 16 independent probe tips each, were used for contacting the 32 probe pads, as shown in Figure 12(d). The flat paper screen was mounted 12 cm above the chip surface and the beam was observed on the screen with a mid-infrared (3-5 μm) camera (FLIR A6752sc).

The laser provided continuous-wave TE-polarized light, and its power was measured by a thermopile detector (Thorlabs) as $\sim 12 \text{ mW}$ (at a drive current of 575 mA). Assuming a Gaussian beam profile with FWHM of $\sim 30 \text{ } \mu\text{m}$, an input waveguide width of $20 \text{ } \mu\text{m}$, and a Fresnel reflection of 28%, the input power to the waveguide was calculated as $\sim 0.6 \text{ mW}$. The power in the main lobe was measured to be $\sim 9 \text{ } \mu\text{W}$, that is, a total loss of

~ 18 dB from the input power. We estimate this loss to be broken down as follows: ~ 7 dB from the 1×32 tree-array splitter, ~ 2 dB from the phase shifter region, and ~ 9 dB from the emitters (including radiation to secondary lobes).

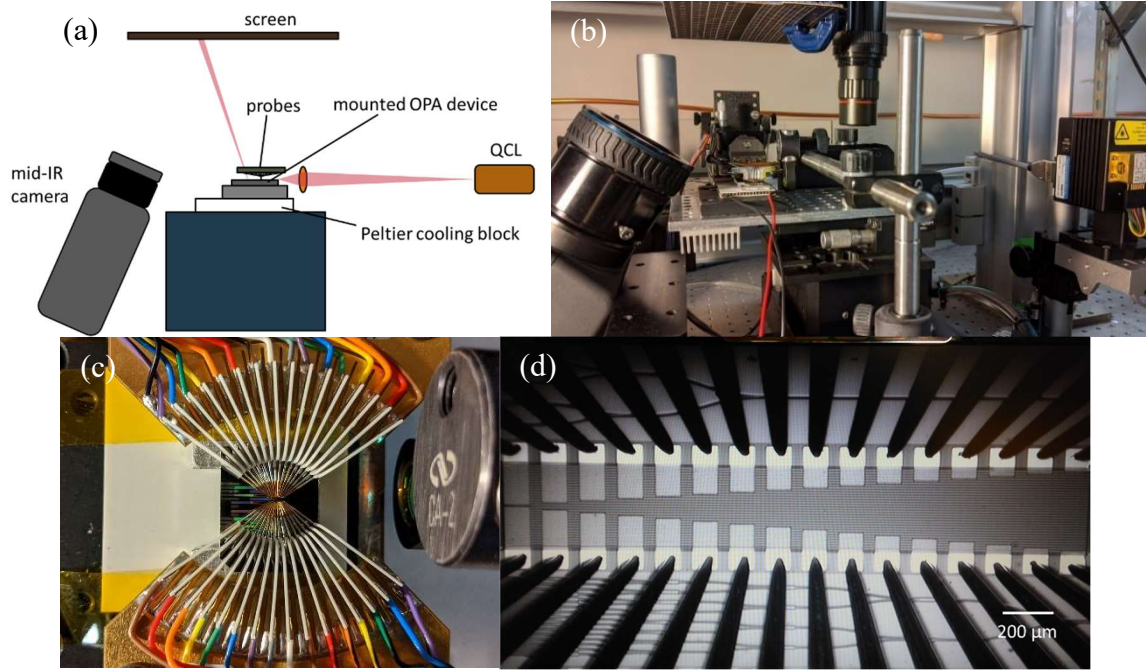


Figure 12: OPA beam steering characterization (a) schematic representation and (b) photograph of test setup; (c) overhead view of chip with 32 probes, and (d) microscope photo of 32 phase shifters contacted by the probes.

As described previously, beam steering requires application of a phase gradient across the channels, modulo 2π . This being the case, the first two simplest phase increments are π and $\pi/2$. Channel phase shifts for these two cases, respectively, are:

- i) $0, \pi, 0, \pi, 0, \pi$, and so on; and
- ii) $0, \pi/2, \pi, 3\pi/2, 0, \pi/2, \pi, 3\pi/2$, and so on.

Based on the MZI characterization, the powers for channels with $\pi/2$, π , and $3\pi/2$ phase shifts are approximately 112, 225, and 337 mW, respectively. However, since the channel

resistances vary, the powers too accordingly vary. Figure 13 shows the estimated voltages across all channels of an OPA device for both are π - and $\pi/2$ -steering. Power supplies were wired directly to the channels for voltage biasing.

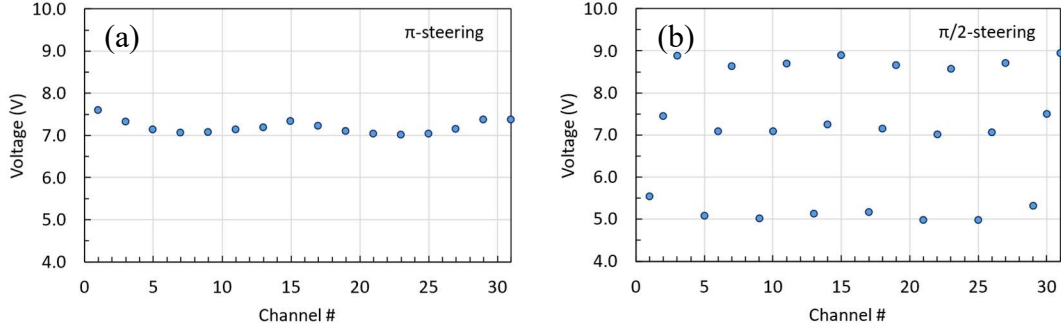


Figure 13: OPA device channel voltages for the cases of (a) π -steering and (b) $\pi/2$ -steering.

Figure 14 shows mid-IR images of azimuthal beam steering for the cases of (a) 0-phase-increment, (b) $\pi/2$ -phase-increment, and (c) π -phase-increment. With an emitter-to-emitter spacing of $d = 2.5\lambda$, $\pi/2$ -phase-increment and π -phase-increment correspond to steering angles of $\psi = 5.7^\circ$ and 11.5° , respectively. Considering the geometrical factors, and to within measurement error ($\pm 0.4^\circ$), these are the values observed and denoted in Figure 14. We note that at π -phase-increment, due to symmetry, two beams are seen at opposite extents, since this is the maximum steering range before the field-of-view is infringed by a grating lobe.

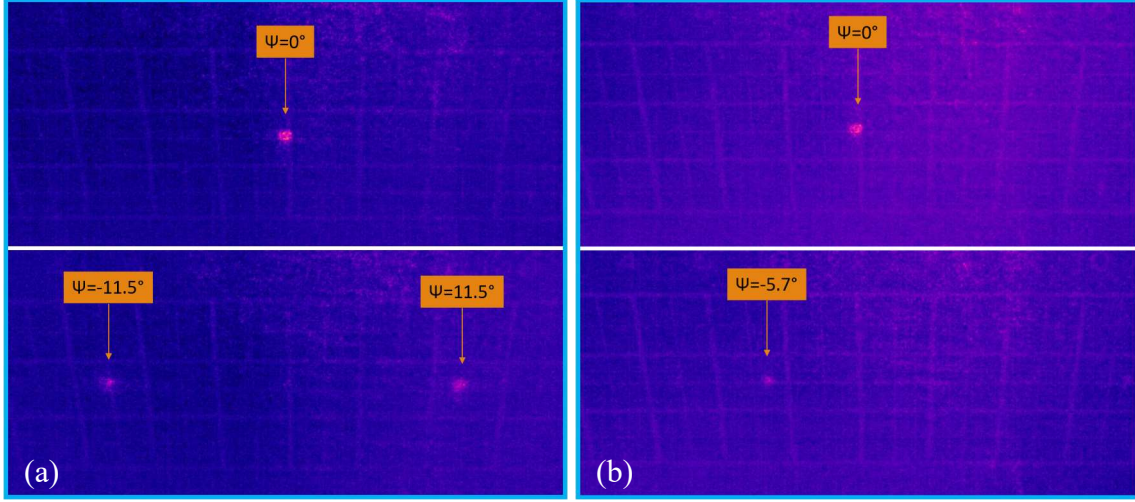


Figure 14: Mid-infrared images of azimuthal beam steering for two cases: (a) 0-phase-increment and π -phase-increment, and (b) 0-phase-increment and $\pi/2$ -phase-increment. Azimuthal angles are indicated.

The azimuthal beam divergence ($\delta\psi$) of the main lobe was measured as 0.6° . This value is within measurement error ($\pm 0.1^\circ$) of the theoretical value given by the expression $\delta\psi = (0.866 \lambda)/(Nd) = 0.63^\circ$ [49]. With this divergence, and the steering range of $\pm 11.5^\circ$, the number of resolvable points is $\sim 2 \times 11.5^\circ / 0.6^\circ = 38$. (Elevation beam divergence ($\delta\theta$) was also $0.6 \pm 0.1^\circ$, as seen by the nearly circular beam spots shown in Figure 14.

OPA ELEVATION ANGLE CHARACTERIZATION

Additionally, the diffraction angle was measured to compare with expected theoretical values. The diffraction angle θ is given by

$$\sin \theta = n_{eff}(\lambda_0) - \frac{\lambda}{\Lambda}, \quad (6)$$

where $n_{eff}(\lambda_0)$ is the effective index of the waveguide, λ is the free-space wavelength, and Λ is the grating pitch. Multiple devices were fabricated with Λ varying from ~ 1.20 to $1.75 \mu\text{m}$. Figure 15(a) shows a scanning electron microscope photo of the gratings. Figure 15(b)

shows the experimental diffraction angle for each of the gratings, spanning a range of $\sim 80^\circ$. Using an effective index $n_{eff} = 3.1758$ in Eq. (6) to calculate the theoretical diffraction angles, the experimental diffraction angles match nicely to theoretical curve.

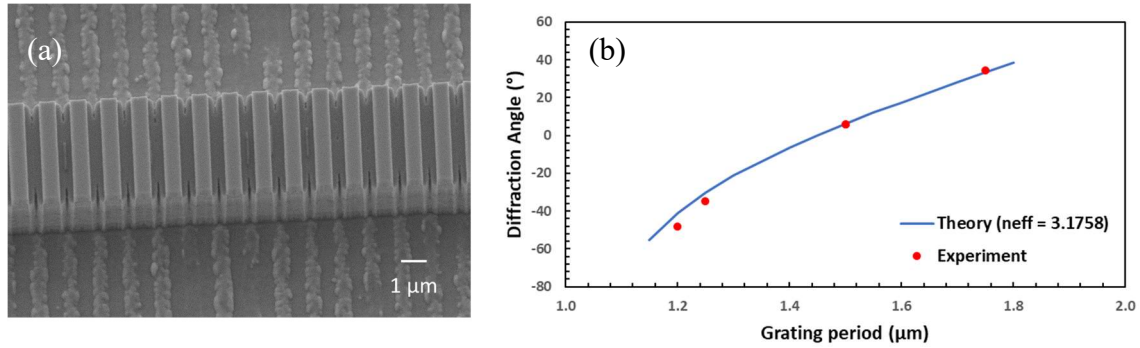


Figure 15: Emitter diffraction. (a) SEM of waveguide emission gratings. The pitch is 1.5 μm. (b) Experimental and theoretical diffraction angle vs. grating period.

Regarding phase error, it is noteworthy that in general virtually no phase error was observed for our 4.3-μm-wide devices. For all five of these fabricated devices, the beam lobes were well-defined from the outset of testing, with no need for phase calibration. Our 3.3-μm-wide devices, on the other hand, did show some slight phase error. The phase error is a consequence of fluctuations in the effective index due to fabrication imperfections of the waveguide [39, 50–53]. Thus, we see that the threshold in waveguide width for phase-error-free propagation lies in the 3–4 μm range.

Chapter 3: OPA Generation 2

INTRODUCTION

The first generation (gen1) device was the first demonstration of an OPA in the InGaAs-InP platform. Though not trivial, as a first proof-of-validity, its performance was not exceptional, and the waveguide design itself did not take into account future integration compatibility with QCLs. In our second-generation effort, we looked to produce a higher-performance device parting from waveguides designed with integration compatibility in mind.

WAVEGUIDES

The waveguide structure, in particular the vertical thicknesses of the core and cladding layers, is of great importance for future coupling to a QCL active region. The layer thicknesses and their respective indices of refraction will dictate mode confinement factors and serve as a starting point for the design of coupling tapers [54,55]. Based on the analyses therein described, the InGaAs-InP core and cladding thicknesses have been set to 850 nm and 1450 nm, respectively. We have also incorporated a 150 nm InGaAs etch stop layer within the cladding layer 400 nm above the core. With the epitaxial thicknesses set, modal analysis of varying waveguide widths was performed in Ansys Lumerical Mode Solutions. Figure 16(a) shows the first few modes versus waveguide width, where it is observed that below 5 μm the waveguide supports just the two fundamental transverse electric (TE) and transverse magnetic (TM) modes. There will always be advantages and disadvantages of different waveguide sizes. For this reason, we have chosen to investigate two waveguide widths—a “near 3 μm ” version ($3.3 \pm 0.1 \mu\text{m}$) and a “near 4 μm ” version ($4.3 \pm 0.1 \mu\text{m}$). Figure 16(b) shows a waveguide cross-section with TM mode profile.

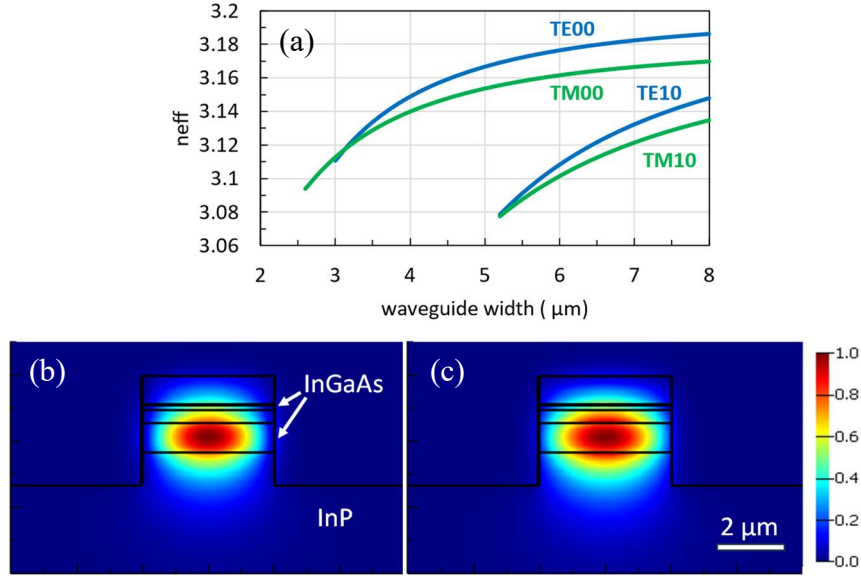


Figure 16: Second generation InGaAs/InP waveguides: (a) Mode effective indices vs. waveguide widths for our 850-nm-InGaAs-core/InP-cladded material platform, (b) TE00 electric field profile, and (c) TM00 electric field profile.

POWER SPLITTERS

For power distribution we again used a 5-stage 1×2 power-splitting tree, producing (initial) 32 channels. However, to reduce the insertion loss, we replaced the simple 1×2 y-branches with optimized 1×2 multi-mode interferometers (MMIs). The starting point for the computer optimized MMI design is the traditional rectangular MMI with tapered ends, shown schematically in Figure 17. For traditional rectangular MMIs, the optimum length for a symmetric 1×2 device is given by [56]:

$$L_{MMI} = \frac{n_{eff} W_{eff}^2}{2 \lambda} \quad (7)$$

where n_{eff} is the ridge waveguide effective index, λ is the free-space wavelength, and W_{eff} is the interferometer effective width, which takes into account the lateral mode penetration

depth into the cladding associated with the Goos-Hänchen shift at the ridge boundary, and is given for TM and TE polarizations by:

$$W_{eff,TM} \cong W + \left(\frac{n_{clad}}{n_{eff}}\right)^2 \frac{\lambda}{\pi \sqrt{n_{eff}^2 - n_{clad}^2}}, \quad W_{eff,TE} \cong W + \frac{\lambda}{\pi \sqrt{n_{eff}^2 - n_{clad}^2}}, \quad (8)$$

where W is the interferometer width and n_{clad} is the lateral cladding index. It is noted that, due to the extra factor $(n_{clad}/n_{eff})^2 < 1$ for the TM case, in general $W_{eff,TM} < W_{eff,TE}$. As an example, for our InGaAs ridge waveguides with $\lambda = 4.6 \mu\text{m}$, $n_{clad} = 1$ (air) and $W = 12 \mu\text{m}$, a mode solver gives $n_{eff} = 3.176$ and 3.193 for TM and TE polarizations, respectively. From Eq. 8, $W_{eff,TM} = 12.05 \mu\text{m}$ and $W_{eff,TE} = 12.48 \mu\text{m}$. Then, Eq. 7 gives $L_{MMI,TM} = 50.13 \mu\text{m}$ and $L_{MMI,TE} = 54.06 \mu\text{m}$. Thus, MMI dimensions (width $\times$ length) for rectangular multi-mode regions would be, approximately, $12 \mu\text{m} \times 50.1 \mu\text{m}$ for TM polarization and $12 \mu\text{m} \times 54.1 \mu\text{m}$ for TE polarization. Additionally, tapers at the ends of the MMI region are known to reduce reflections. The taper full angle should be greater than the full beam divergence [57]:

$$2\theta \approx \frac{4\lambda}{\pi n_{eff} d} \quad (9)$$

where d is the e^{-2} field diameter of the single-mode waveguide, approximated as the waveguide width. For our $3.3\text{-}\mu\text{m}$ and $4.3\text{-}\mu\text{m}$ -wide devices, $2\theta \approx 33^\circ$ and 25° , respectively.

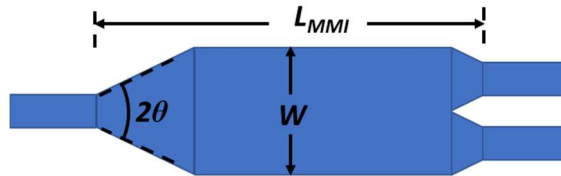


Figure 17: Traditional rectangular tapered multi-mode interferometer (MMI).

In our design, we chose to focus on TM polarization, since this is the polarization that would be introduced by integrated QCLs. Starting from the rectangular tapered MMI

with dimensions $W \times L = 12 \text{ } \mu\text{m} \times 53.8 \text{ } \mu\text{m}$ and $2\theta > 33^\circ$, the contour of MMI region was divided into 12 sections of cubic splines, whose dimensions could be used as inputs to an optimization routine. With a variational finite difference time domain simulation tool (varFDTD, Ansys Lumerical), a particle swarm optimization (PSO) was used to adjust the contour for maximum transmission through the MMI device. Following optimization with varFDTD, a full 3-dimensinal finite difference time domain (FDTD) solver was used to characterize the device's transmission more accurately. The resultant structures for both the 3.3- μm and 4.3- μm -wide access waveguide devices are shown in Figure 18; their transmission characteristics are shown in Figure 19. For both devices in the (design) polarization TM, transmission is better than 99% at $\lambda = 4.6 \text{ } \mu\text{m}$, with a 0.5 dB bandwidth $\Delta\lambda_{0.5dB} > 1.7 \text{ } \mu\text{m}$. Complementarily, for both devices in the (non-design) polarization TE, transmission is $> 97\%$ at $\lambda = 4.6 \text{ } \mu\text{m}$, with a 0.5 dB bandwidth $\Delta\lambda_{0.5dB} > 1.5 \text{ } \mu\text{m}$.

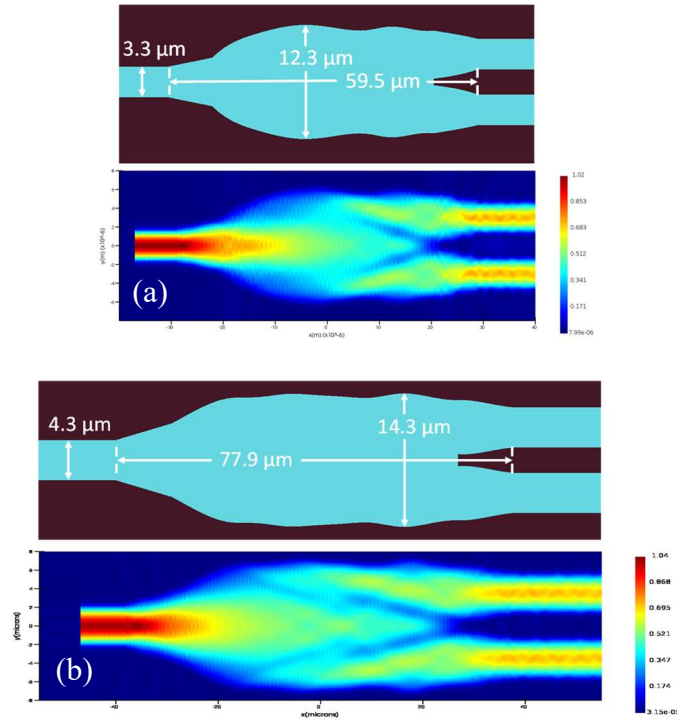


Figure 18: Particle swarm optimized MMIs: Top images show the shape and dimensions, bottom images show the simulated electric field profiles, for (a) 3.3- μm -wide access waveguides, and (b) 4.3- μm -wide access waveguides.

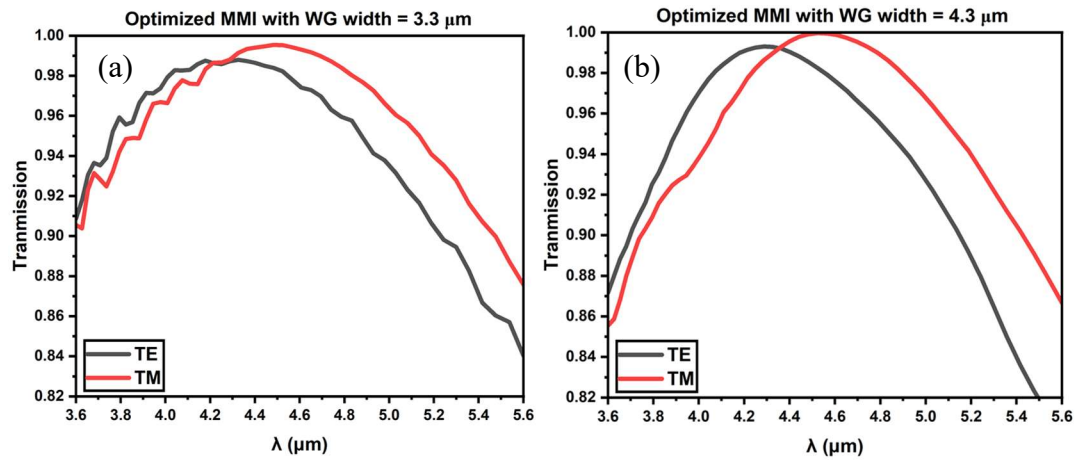


Figure 19: Particle swarm optimized MMIs, transmission vs. wavelength (simulation), for (a) 3.3- μm -wide access waveguides, and (b) 4.3- μm -wide access waveguides.

A series of optimized MMI devices were laid out in a photomask design and fabricated to characterize their performance in comparison to a simple Y-branch. MMI pairs (1×2 and 2×1) were inserted into waveguides in quantities of 1, 2, 3, and 4. The waveguides span the width of the chip, with inverse tapers to $20\text{-}\mu\text{m}$ -width at the ends for coupling. Figure 20 shows the photomask layout. The fabrication process involves a single photolithography step and a single dry etch step. Following fabrication, the device chip was cleaved on both ends. Testing is done by end-fire coupling to one end, while monitoring the output with a mid-wave infrared (MWIR) camera at the other end. Figure 21(c) and (d) show the testing results $3.3\text{-}\mu\text{m}$ -wide and $4.3\text{-}\mu\text{m}$ -wide access waveguide devices, respectively. Higher intensity out means less loss. Though the uncertainty in the readings precludes their precise determination, the trend shows a clear difference between the MMIs and the y-branches. The MMIs show no discernible loss, whereas the y-branches demonstrate $\sim 1\text{ dB/device}$.

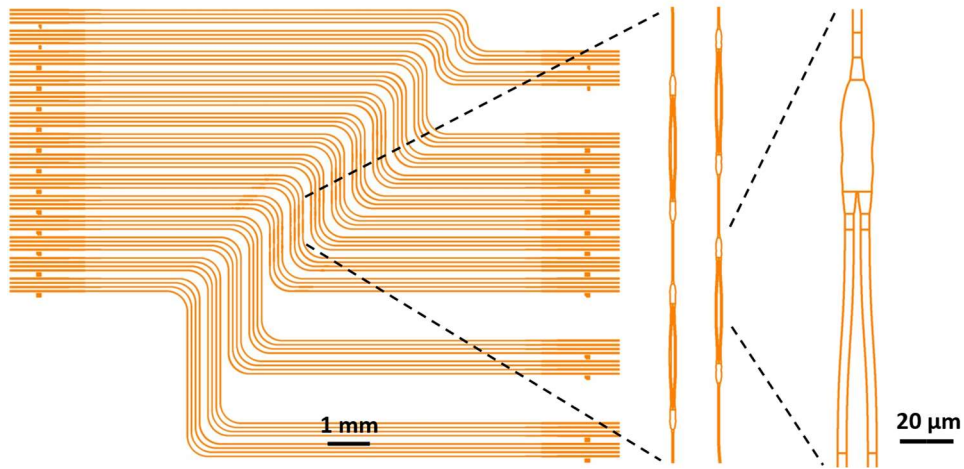


Figure 20: MMI characterization photomask layout.

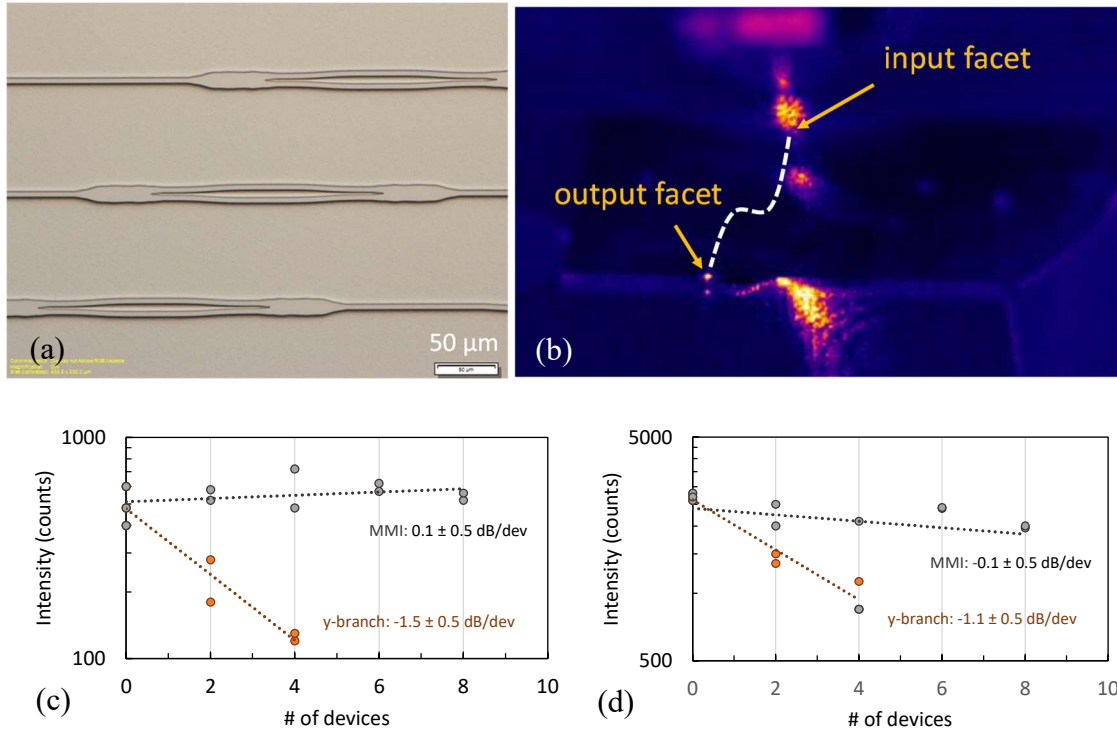


Figure 21: MMI characterization: (a) Microscope photo of fabricated MMI devices, (b) mid-IR photo of MMI device under test, (c) and (d) test results of various devices, with loss extracted from slope. (c) and (d) correspond to 3.3-μm and 4.3-μm-wide waveguide-accessed devices, respectively.

THERMO-OPTIC PHASE SHIFTERS

For phase-shifting, as in the gen1 device, we again employ the thermo-optic effect. However, due both to the revised waveguide structure and the aim of improved power tuning efficiency, the configuration is necessarily revised. For starters, the waveguide's reduced profile precludes direct placement of metal on top of the waveguide, as it would induce high-loss plasmonic modes. Thus, passivation is required to separate the metal from the semiconductor. Similarly, the sidewall passivation must be sufficiently thick to prevent high-loss plasmonic modes from the metal trace overlay. Simulations were performed with

a photonic mode solver (Lumerical MODE) to analyze these effects. Figure 22 shows the results. It is seen that, to avoid extra loss, the top passivation thickness should be greater than ~ 300 nm, and likewise the side passivation thickness should be greater than ~ 1.2 μm .

However, the trade-off with phase tuning efficiency must be considered. A thermal solver (Ansys Lumerical HEAT) was used to investigate the relationship. Figure 23 shows the effect of passivation thickness on waveguide temperature and corresponding phase. It is seen that an addition of 2 μm of passivation will reduce the waveguide core temperature by $\sim 0.1^\circ$ and the corresponding phase by ~ 0.06 radians. Hence, the effects are minimal and can be tolerated.

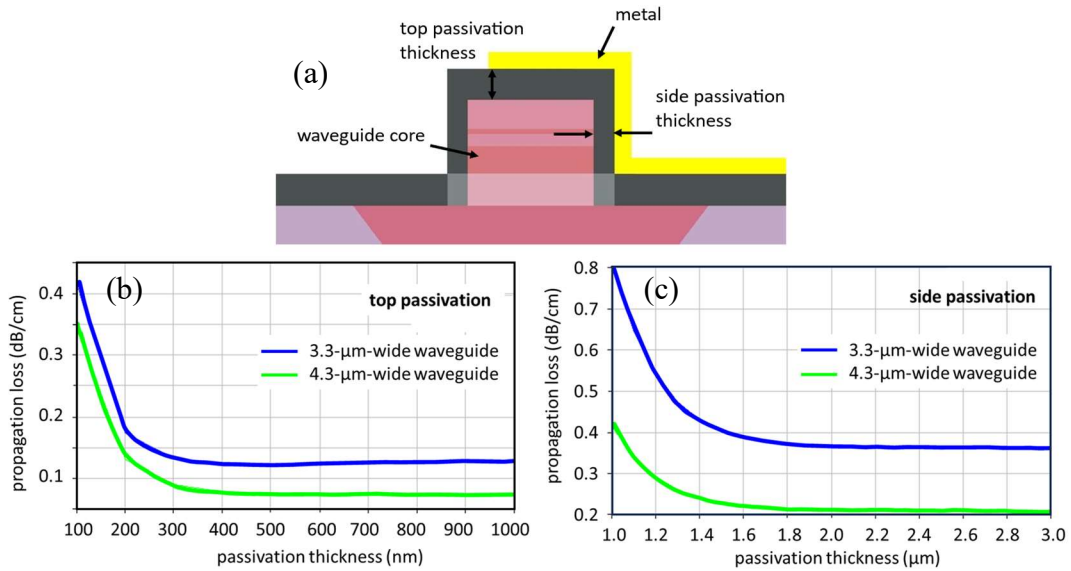


Figure 22: Effect of metallization proximity to waveguide on propagation loss (simulation): (a) Waveguide schematic cross-section, (b) propagation loss vs. top passivation thickness, and (c) propagation loss vs. side passivation thickness.

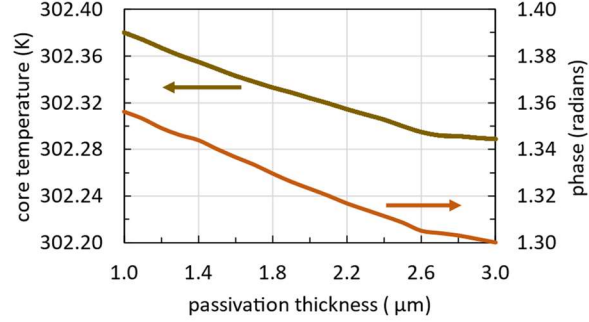


Figure 23: Effect of passivation on thermal tuning efficiency (simulation): waveguide core average temperature and phase vs. passivation thickness. A heater power of 50 mW was assumed.

A standard PECVD SiO₂ process will yield a sidewall oxide thickness $\sim 1/2$ times the top oxide thickness. Since in our case we needed the side passivation thickness (> 1.2 μm) greater than the top passivation thickness (> 300 nm), a standard PECVD SiO₂ process was inconvenient. Rather, a spin-on-glass (SOG) approach was more suitable—such an approach will significantly raise the sidewall passivation thickness in comparison to the top passivation thickness. Additionally, it has the benefit of sloping the sidewall which will facilitate good metal step coverage. Our SOG coating process yields ~ 400 nm on planar surfaces, ~ 100 nm on top of our waveguides, and builds up around the sidewalls of the waveguides. Figure 24 shows a schematic cross-section of an SOG-passivated waveguide.

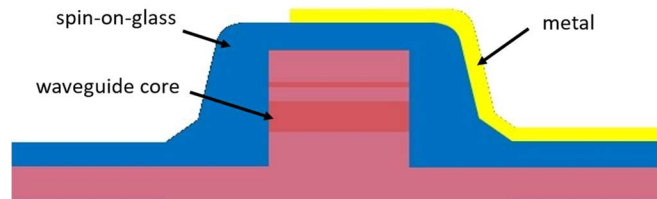


Figure 24: Schematic cross-section of spin-on-glass-passivated waveguide with overlay metallization.

Thermal tuning efficiency is dependent on the geometry surrounding the waveguide. Different methods have been used to improved tuning efficiency[43, 58, 59], a common and simple one being the use of heat isolation trenches. To investigate the tuning efficiency of our waveguide structure, an integrated optical mode/thermal transport simulation was carried out (Ansys Lumerical MODE and HEAT). Three situations were considered: a waveguide with no heat isolation structure, a waveguide with vertically etched air trenches, and a waveguide with air trenches etched obliquely underneath the waveguide. Vertical trenches are easily accomplished via dry etching, and oblique etching is possible with crystallographic wet etching. Additionally, waveguide widths of both 3.3 μm and 4.3 μm were considered. Waveguide height and length were maintained at 4.3 μm and 2000 μm , respectively. A 1.0- μm -thick silicon dioxide layer separates the semiconductor from the metal strip heater. The setups are shown in Figure 25(a,b,c). Recall from Eq. (1) that the phase change $\Delta\phi$ is induced by the change in effective refractive index n_{eff} due to a temperature change ΔT . In this configuration, the change in temperature is proportional to the applied electrical power P_{elec} per area normal to the direction of heat flow:

$$\Delta T \propto \frac{P_{elec}}{w L}, \quad (10)$$

where w is the waveguide width and L is the length of the waveguide. Substituting Eq. (10) into Eq. (1) we see that the phase change is directly proportional to the applied electrical power:

$$\Delta\phi \propto \frac{2\pi}{\lambda} \frac{dn_{eff}}{dT} \frac{P_{elec}}{w}. \quad (11)$$

For an applied electrical power, the thermal solver is used to find the temperature profile across the waveguide, thereby determining the cross-sectional refractive index profile $n(y,z)$ of the waveguide. The mode solver then uses the refractive index profile to determine the effective index n_{eff} of the propagating mode (TE00), and therefore the

phase shift $\Delta\phi$ due to the applied power. Figure 25(d) shows a representative temperature profile—that of the oblique etch at 2π -phase-shift. Figure 25(e) shows the result of the combined simulations.

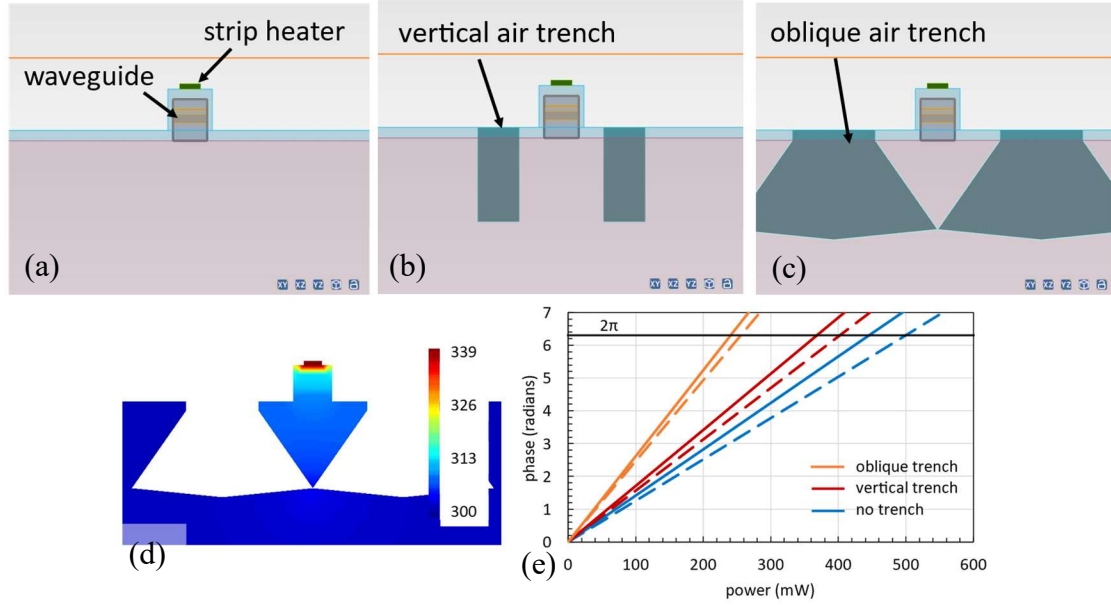


Figure 25: Thermo-optic phase tuning of InGaAs/InP waveguide (simulation). Three different scenarios: (a) no trench, (b) vertical trenches, and (c) oblique trenches. (d) Temperature profile at 2π -phase-shift with oblique trenches, and (e) phase shift vs. applied electrical power for each case. Solid and dashed lines correspond to waveguide widths $3.3\ \mu\text{m}$ and $4.3\ \mu\text{m}$, respectively.

From Figure 25(e), the effect of the heat isolation trenches is easily recognized. For a $3.3\text{-}\mu\text{m}$ -wide waveguide without trenches $P_{2\pi} \sim 444\ \text{mW}$. However, with vertical trenches this is reduced to $\sim 367\ \text{mW}$, and with oblique trenches to $\sim 240\ \text{mW}$. For this reason, the formation of oblique trenches was investigated and implemented into our structure. The oblique etch process was developed based on an a crystallographic etch of both InP and

InGaAs. A 4 vol% bromine-methanol solution was used. The solution etches along the (110) crystal planes in both InP and InGaAs, producing an angle of 55° with the semiconductor surface [60].

A series of 32 balanced MZIs were designed, fabricated, and tested to characterize and optimize the phase tuning efficiency. The main factor affecting the effectiveness of the trenches to isolate heat is their proximity to the waveguide. The closer they are to the waveguide the more efficient the tuners operate. However, etching too close to the waveguide may compromise the waveguide's quality, so a balance is needed. In this regard, the main parameter investigated was the "trench separation distance"—the distance from one trench to another across a waveguide. Figure 26 shows the MZI photomask layout along with a magnified view of a waveguide and surrounding trenches.

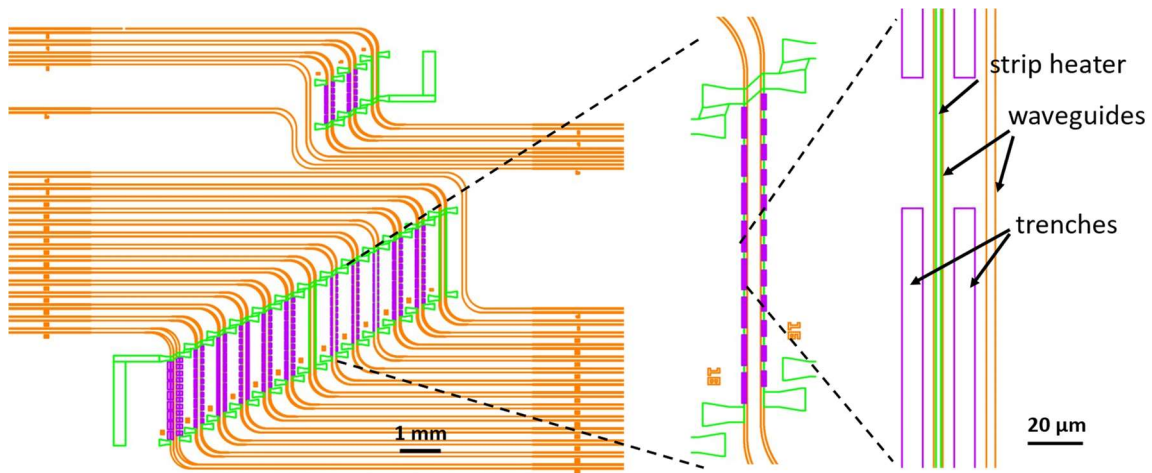


Figure 26: MZI characterization photomask layout.

The development of a fabrication process required a few iterations. The basic steps of the fabrication process are: waveguide etch, passivation deposition, trench etch, metal strip deposition, metal interconnect deposition, and passivation removal (in the non-phase-

shifter regions). However, the exact order of the steps at first was not so obvious. In our first iteration, we attempted the trench etch before the metal (gold) patterning and found it nearly impossible to achieve the required photolithographic resolution in the vicinity of the trenches due to resist sliding into the trenches. Hence, we switched the metal patterning to before the trench etch. This change, however, meant that the metal would be exposed to the trench etchant (methanol-bromine), and gold is readily etched by such halide solutions. This led us to switch our metallization scheme to aluminum (at least the bulk of it for the moment), which we found to be negligibly etched by the bromine-based solution. Table 1 lists the major steps of the MZI fabrication process, which served as a foundation for the full OPA device fabrication process. Figure 27 shows a schematic representation of the process flow. Various views of fabricated MZIs are shown in Figure 28.

1	Waveguide photolithography
	Waveguide etch to $\sim 3.5 \mu\text{m}$
2	Passivation deposition: 200 nm PECVD SiO_2 + 400 nm SOG + 100 nm PECVD SiO_2
3	Metal strip heater photolithography
	Metal strip heater deposition and liftoff, $\sim 300\text{nm}$
4	Metal interconnect photolithography
	Metal interconnect deposition and liftoff, $\sim 600 \text{ nm}$
5	Trench photolithography
	Trench passivation etch
	Trench etch to $\sim 10 \mu\text{m}$
6	Passivation removal photolithography
	Passivation removal etch

Table 1: MZI fabrication process main steps.

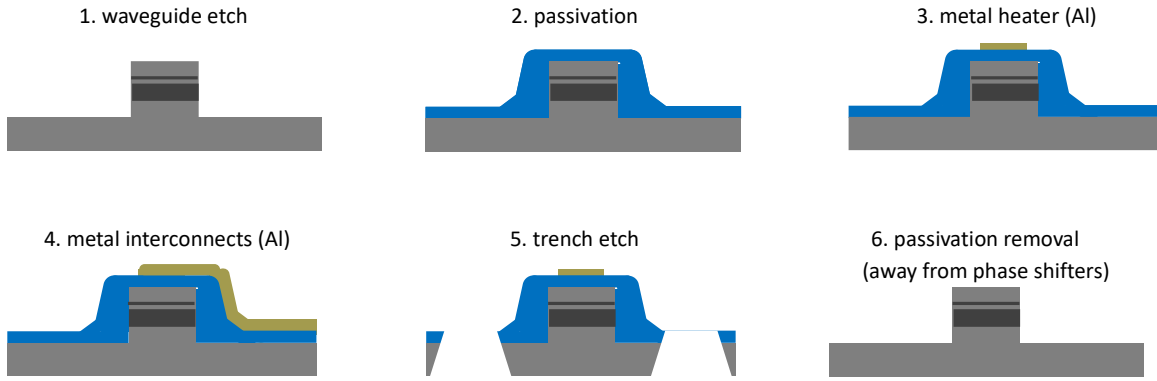


Figure 27: Schematic representation of MZI fabrication process flow.

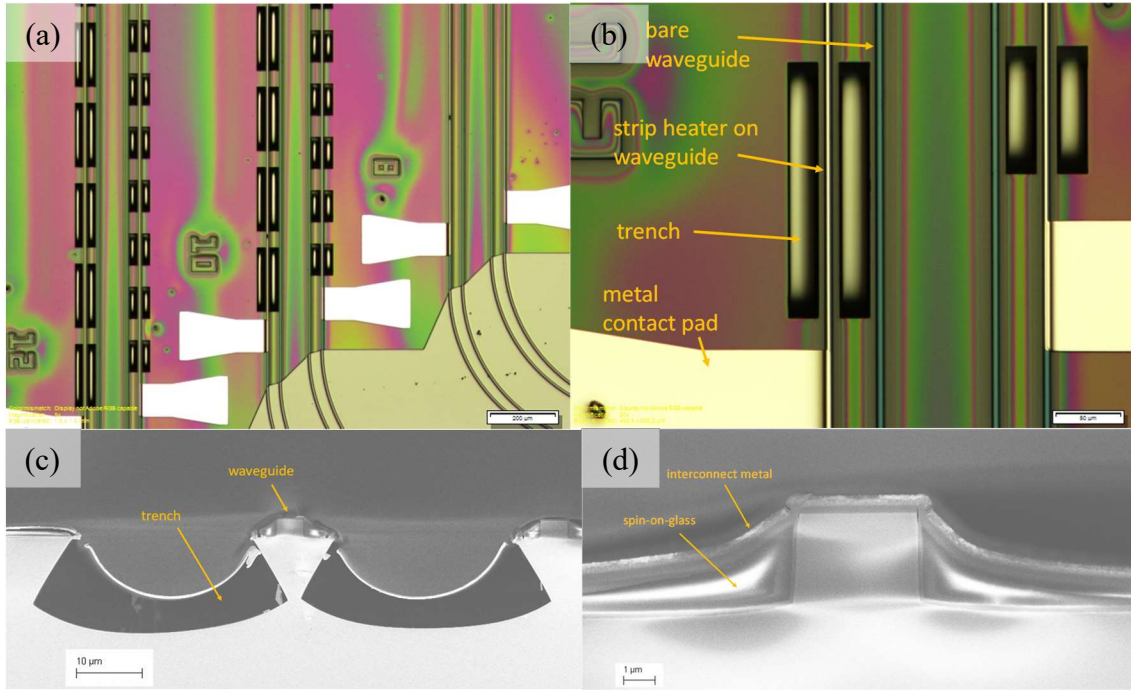


Figure 28: Photos of fabricated MZI devices. (a) OM overhead view, (b) OM zoomed view, (c) SEM cross-section through waveguide and trenches, and (d) SEM cross-section close-up of waveguide.

The MZI chips were cleaved on two sides through inversely tapered access waveguides to permit end-fire coupling and light-out detection. Hence, optical testing was

the same as with the MMIs (recall Figure 21(b)). Additionally, electrical biases were applied to the strip heaters, such that full on/off cycles were evidenced. A number of devices with different trench-separation-distances and waveguide widths were measured across two chips. Figure 29 shows the result of two notable devices, as well as a summary of the 2π -phase-shift power ($P_{2\pi}$) across all devices. The expected general trend of decreasing $P_{2\pi}$ with decreasing trench separation distance is evident, as well as the generally lower power for the thinner waveguide. (Note: variation occurs among equal trench-separation-distance devices due to variation in etch depths, these in turn due to different etch window sizes, and general variability within and across chips.) Figure 29(a) is the typical result for a 12- μm -separation-distance device, demonstrating a $P_{2\pi}$ of ~ 250 mW, about half that of the control device without trenches, and in good agreement with the simulation (recall Figure 25). Figure 29(b), on the other hand, is the result of a particularly exemplary device, demonstrating a $P_{2\pi}$ of ~ 90 mW (explained below). The two devices at the minimum trench-separation distance of 8 μm followed the general trend with a $P_{2\pi}$ below ~ 200 mW. However, the extinction ratio ($= I_{on}/I_{off}$) for these two devices was poor. While for most devices the extinction ratio was $\sim 10\text{--}20$ dB, for these smaller-trench-separation devices it was $< \sim 5$ dB (and others of these devices were completely inoperable). As mentioned previously, it is expected that the trench etches associated with these devices has gotten too close to the waveguides and degraded their quality.

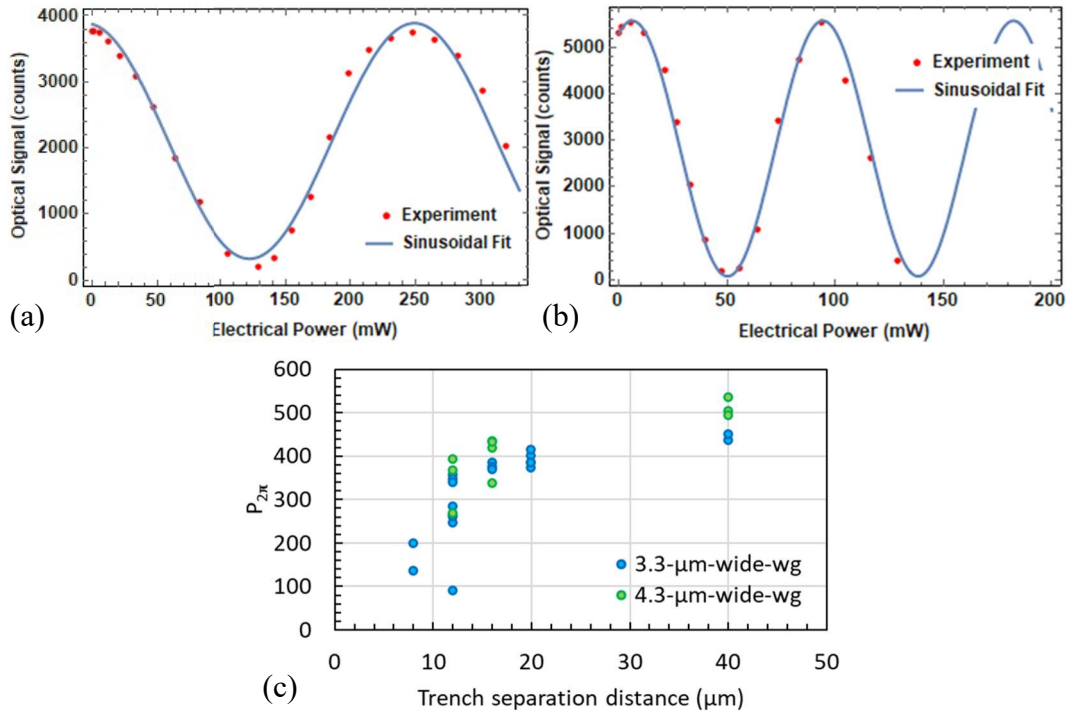


Figure 29: MZI thermo-optic phase shifting experimental results. Modulation curves: (a) typical 12-μm-separation-distance device with $P_{2\pi} \approx 250$ mW, and (b) exemplary 12-μm-separation-distance device with $P_{2\pi} \approx 90$ mW. (c) $P_{2\pi}$ vs. trench separation distance for various devices. (Note: control devices with no trenches placed arbitrarily at 40 μm for comparison.)

For insight into the difference in phase shifting efficiencies across devices, scanning electron microscope (SEM) cross-section images were taken of various devices. Figure 30 shows two 12-μm-separation-distance MZI devices. Figure 30(a) is that of a typical device with measured $P_{2\pi} \approx 280$ mW. The oblique etches from the sides of the waveguide come to $\sim 1\text{--}2$ μm from each other under the waveguide, matching very well with the simulated structure, hence its $P_{2\pi}$ also matching well. Figure 30(b), on the other hand, is that of the $P_{2\pi} \approx 90$ mW device, showing a completely undercut waveguide. This is the most optimum etch and the reason for its superior performance, even beyond that

which was possible with a simple 2D simulation. (Note that although these devices possessed the same trench separation distance, the trench opening size differed, affecting the amount of undercut etch.)

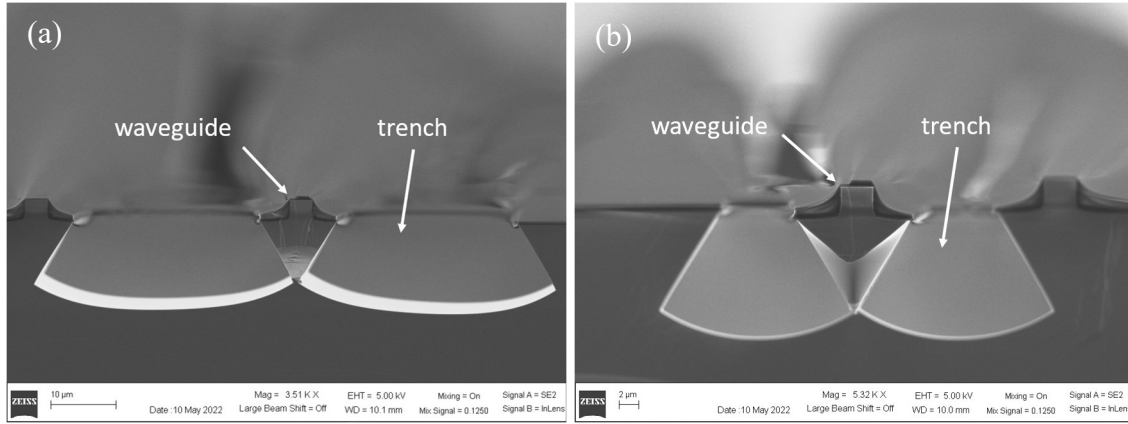


Figure 30: SEM cross-section images of two 12- μm -separation-distance devices: (a) corresponding to $P_{2\pi} \approx 280$ mW, and (b) corresponding to $P_{2\pi} \approx 90$ mW. The complete undercut of the device in (a) is the reason for its superior efficiency.

TOTAL INTERNAL REFLECTION MIRROR EMITTERS

The OPA gen1 device employed long (several 100 μm s) waveguide gratings for emission to free-space, with phase adjustments to realize 1D (azimuthal) beam steering. To enable 2D (both azimuthal and elevation) beam steering based solely on phase tuning, a 2D arrangement of emitters is needed, necessitating small area emitter structures. For this purpose, the OPA gen2 device employed total internal reflection (TIR) mirror emitters [61]. Again, the structure takes advantage of the crystallographic preferential etching of InP/InGaAs by a bromine-methanol solution. Figure 31 shows the configuration. The etchant produces a smooth facet along the (110) plane, which forms a 55° angle with the

semiconductor surface. The high index contrast of InGaAs ($n = 3.375$) to air ($n = 1$) establishes a TIR critical angle $\theta_c = \sin^{-1} (1/3.375) = 17.2^\circ$. Since the incident angle (with respect to the facet normal) is 35° , TIR is realized.

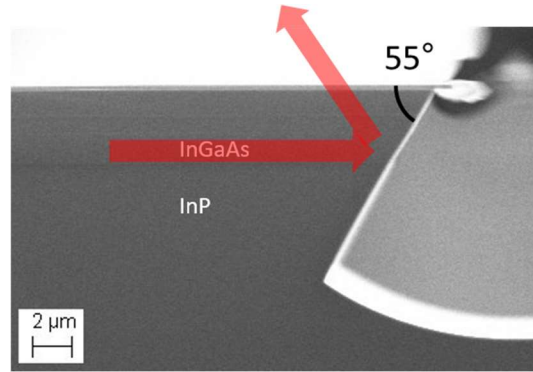


Figure 31: TIR mirror emitter: SEM cross-section image of InP/InGaAs epitaxial structure with (110) wet-etched facet, with schematic representation of TIR overlaid.

The far-field light pattern center and envelope are determined by the emission profile of a single emitter. For better insight into these attributes, as well as the associated emission power, simulations (Lumerical Ansys FDTD) of individual emitters were carried out, for each combination of TE and TM polarization, and for facets defined by either air or SiO₂. Figure 32 shows the vertical electric field profiles for each case. For each case, the fundamental mode is injected from the left side of the simulation region and reflects off the mirror near the center. (It is apparent that there is significant loss downwards into the substrate.) Figure 33 shows the resultant far-field profiles for each case, and Table 2 summarizes the characteristics of each case. In general, upwards transmission is greater for TM in comparison to TE, as well as for an oxide facet in comparison to an air-facet. (For this reason, we have left our device facet coated with oxide.) The elevation angle θ is larger for TM, as is the elevation 3dB width θ_{3dB} .

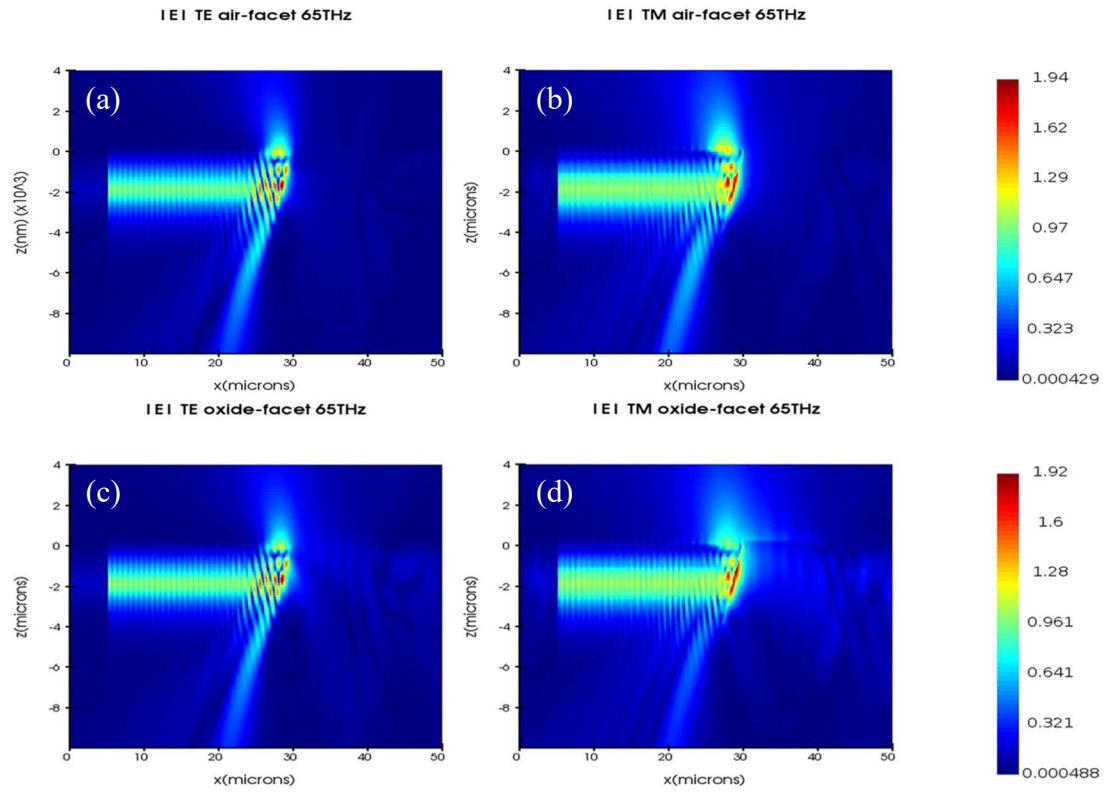


Figure 32: Single emitter electric field profiles (simulation): (a) TE air-facet, (b) TM air-facet, (c) TE oxide-facet, and (d) TM oxide-facet.

	air-facet		oxide-facet	
	TE	TM	TE	TM
transmission upwards (into air)	0.24	0.34	0.32	0.43
transmission downwards (into the substrate)	0.73	0.61	0.62	0.44
transmission backwards (into the waveguide)	0.02	0.03	0.02	0.04
Elevation angle, θ	30.5°	46.8°	25.0°	33.3°
Elevation 3dB width, θ_{3dB}	50°	63°	65°	89°

Table 2: Single emitter characteristics (simulation).

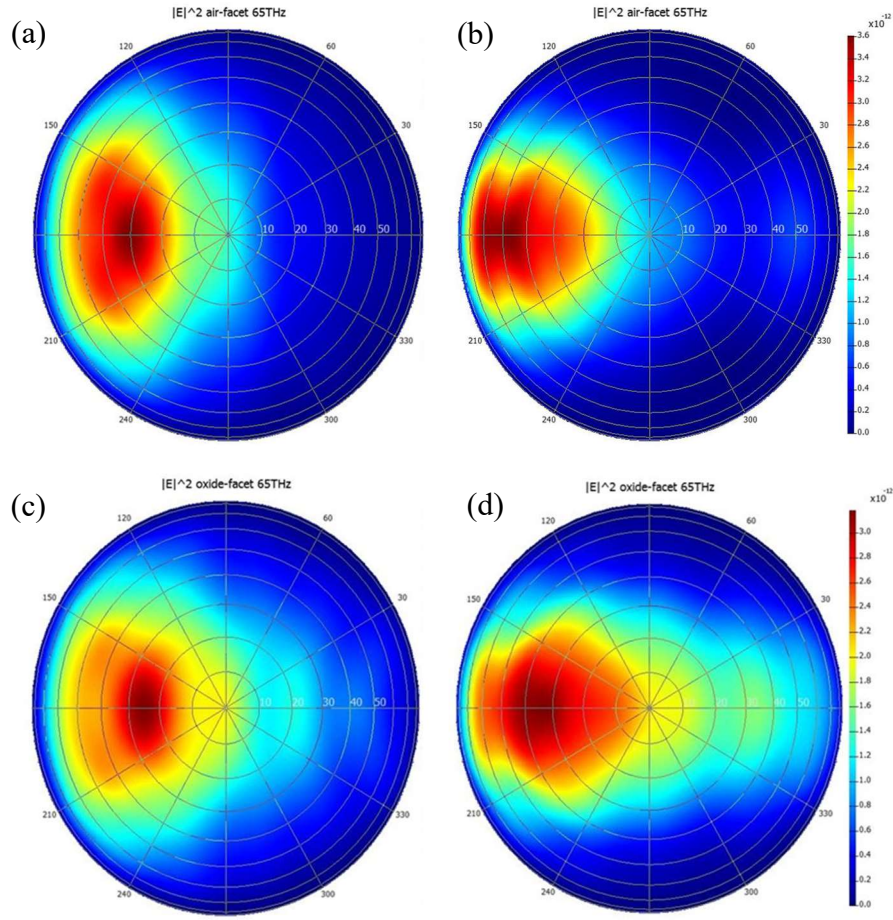


Figure 33: Single emitter far-field patterns (simulation): (a) TE air-facet, (b) TM air-facet, (c) TE oxide-facet, and (d) TM oxide-facet.

APERIODIC 2D EMITTER ARRAY

The OPA gen1 device employed a periodic array of emitters. As described in the previous chapter, the device's FOV and beam size were limited by details of the periodicity. In particular, the array spacing and relative location between the emitters affect the far-field characteristics significantly. Making use of a sparse non-periodic array, the FOV and beam size can be improved, albeit at the cost of slightly larger side-lobe levels.

The FOV is improved via the appropriate arrangement of emitters to suppress grating lobes, and the beam size is improved via the larger aperture size.

The design of a sparse aperiodic array—that is, optimization of the emitters' positions—can be carried out by different methods [62, 63]; we chose to use a particle swarm optimization algorithm. A minimum waveguide spacing of $2\lambda = 9.2 \mu\text{m}$ was established to avoid coalescence of emitter etch pits. The optimization routine iteratively adjusts the emitters' positions and calculates the corresponding far-field patterns. It was found that the best results are produced when emitter-to-emitter vectorial length is non-redundant, as in a Costas array [25]. Our sparse non-periodic array is shown in Figure 34, along with the simulated far-field pattern based on this array. Our proposed OPA provides a beam steering range of $\pm 14^\circ$ in both the longitudinal and azimuthal directions, with a beam width of $0.6^\circ \times 0.6^\circ$, for a resolution of ~ 2178 points. (For comparison, a periodic array of equivalent number of emitters with the same steering range would give a beam width of $\sim 4^\circ \times 4^\circ$, for a resolution of ~ 48 points.)

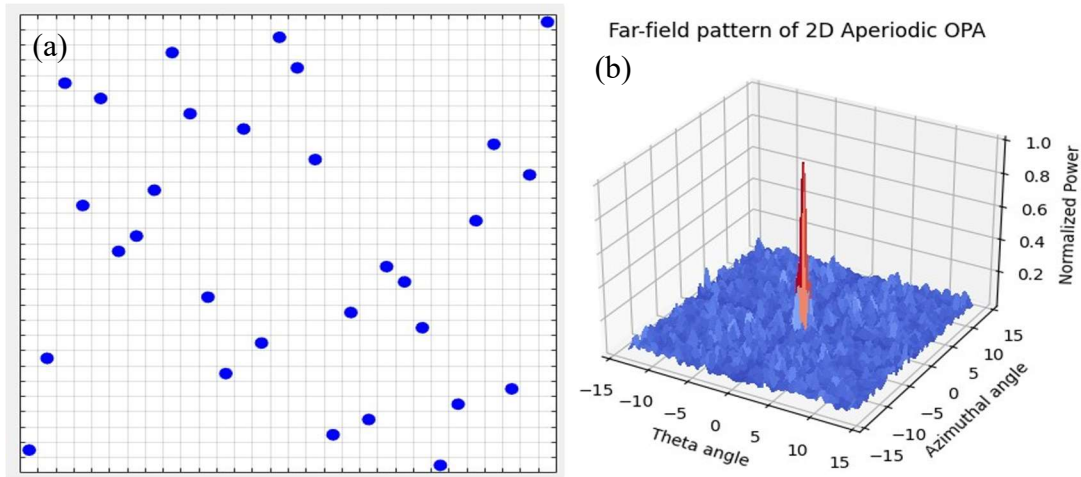


Figure 34: Optimized aperiodic 2D emitter array: (a) emitter positions, with grid step size $2\lambda = 9.2 \mu\text{m}$, (b) far-field pattern within steering FOV (simulation).

The far-field pattern of an OPA is given by the Fourier transform of the near-field. In general, this operation produces the far-field pattern $U(\theta_x, \theta_y)$ as the product of the far-field waveform of a single emitter (first bracket) and the array factor (second bracket):

$$U(r, \theta_x, \theta_y) = \left\{ F(\theta_x, \theta_y) \frac{\exp(-jkr)}{r} \right\} \cdot \{ AF(\theta_x, \theta_y) \}, \quad (12)$$

where $k = 2\pi/\lambda$ is the free-space wavevector. For a 2D array of (arbitrarily spaced) $M \times N$ emitters, the array factor is:

$$AF(\theta_x, \theta_y) = \sum_{m=1}^M \sum_{n=1}^N A_{mn} \exp(-jk(x_m \sin \theta_x + y_n \sin \theta_y) + j\varphi_{mn}), \quad (13)$$

where (x_m, y_n) is the emitter's position, and A_{mn} and φ_{mn} are the emitter's excitation amplitude and phase, respectively. Assuming all antennas provide equal amplitude $A_{mn} = 1$, beam steering is effected by adjusting the phases φ_{mn} to maximize Eq. (13) at each steering point $(\theta_{x,s}, \theta_{y,s})$, i.e., by choosing:

$$\varphi_{mn} = k(x_m \sin \theta_{x,s} + y_n \sin \theta_{y,s}). \quad (14)$$

In other words, for example, to steer to point $(\theta_{x,s}, \theta_{y,s}) = (5^\circ, 10^\circ)$ would require:

$$\begin{aligned} \varphi_{11} &= k(x_1 \sin 5^\circ + y_1 \sin 10^\circ), \\ \varphi_{12} &= k(x_1 \sin 5^\circ + y_2 \sin 10^\circ), \\ \varphi_{13} &= k(x_1 \sin 5^\circ + y_3 \sin 10^\circ), \\ &\vdots \\ \varphi_{21} &= k(x_2 \sin 5^\circ + y_1 \sin 10^\circ), \\ \varphi_{22} &= k(x_2 \sin 5^\circ + y_2 \sin 10^\circ), \\ \varphi_{23} &= k(x_2 \sin 5^\circ + y_3 \sin 10^\circ), \\ &\text{etc., for all } M \times N \text{ emitters.} \end{aligned}$$

Additionally, notice that if we write the phase as a sum of two components $\varphi_{mn} = \varphi_m + \varphi_n$, we can write Eq. (14) as:

$$\varphi_m + \varphi_n = k(x_m \sin \theta_{x,s} + y_n \sin \theta_{y,s}), \quad (15)$$

and write:

$$\varphi_m = kx_m \sin \theta_{x,s} , \quad (16)$$

$$\varphi_n = ky_n \sin \theta_{y,s} . \quad (17)$$

In other words, the steering directions are separable. If, for example, we set $\theta_{y,s} = 10^\circ$, then the φ_n s are fixed by Eq. (17), and steering to each angle $\theta_{x,s}$ is tantamount to solving Eq. (16) for every φ_m at each angle $\theta_{x,s}$.

In summary, beam steering becomes a problem of finding the appropriate emitter phases φ_{mn} for each steering angle point $(\theta_{x,s}, \theta_{y,s})$. In general, the appropriate phases are not readily prescribed, due to inevitable phase error resulting from fabrication imperfections. For this purpose, we developed a phase calibration routine, described in section the section “OPA Test Setup and Calibration Routine.”

OPA ARCHITECTURE AND FABRICATION

Our OPA device layout must take into account our test setup, which consists of end-fire coupling to one side of the chip, probes on the lateral sides, and screen and camera on the opposite side from the input, as shown in Figure 39. Our OPA layout design is shown in Figure 35. Since our TIR mirrors reflect light back past the normal, to incorporate our mirrors we find it necessary to provide a 180° turn of the waveguides, so that emission can occur towards our camera. The phase shifters are incorporated along a waveguide length of $1660 \mu\text{m}$ —there are 8 trenches of length $166 \mu\text{m}$, yielding a duty cycle of 80%. We use a 1×32 MMI tree to divide the light evenly among 32 channels, but two channels on the sides will be used for light monitoring, leaving 30 channels for emission. Five full devices are incorporated into the mask design: three with $3.3 \mu\text{m}$ -wide waveguides and two with $4.3 \mu\text{m}$ -wide waveguides.

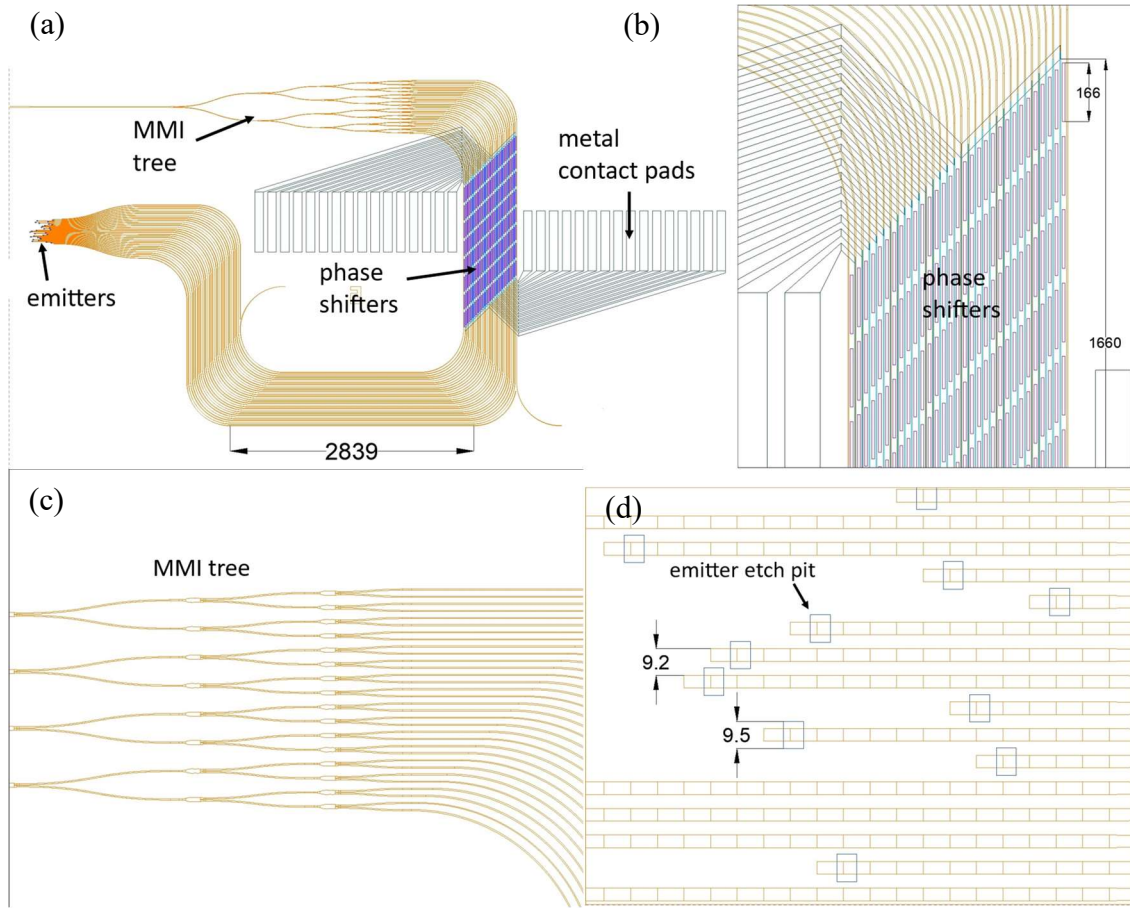


Figure 35: OPA layout: (a) entire device, (b) phase shifter region, (c) end of MMI tree, and (d) emitter region. Dimensions are in microns.

The OPA device fabrication process basically follows the process developed previously for the MZIs (described in Table 1 and Figure 27), with the addition of the TIR mirror etch. All layers can be patterned by UV lithography. All semiconductor structures are formed by either reactive ion etching or wet etching, and the phase shifters are formed by a metal lift-off process.

Recall that our low-index contrast waveguide design consists of an 850-nm-thick InGaAs core in an InP cladding. The upper cladding thickness is 1450 nm (and also

includes a 150-nm-thick InGaAs etch stop layer), while the bottom cladding thickness is determined by the etch depth, typically 1000–2000 nm. The fabrication process begins with the deposition of a 600-nm-thick SiO₂ hard-mask layer on the epitaxial wafer by pressure-enhanced chemical vapor deposition (PECVD). The SiO₂ layer is patterned by UV lithography and etched in a reactive-ion etch (RIE) chamber. Finally, the III-V material is etched in an inductively-coupled plasma (ICP)-RIE chamber to construct the optimized MMI trees and waveguides, an example of which is shown in Figure 36.

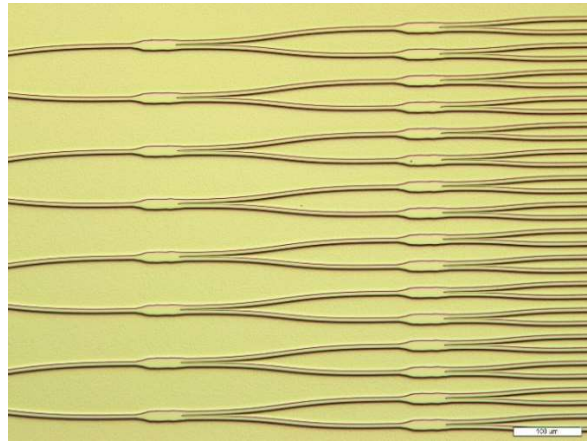


Figure 36: MMI tree with 3.3- μm -wide waveguides

The suspended thermal-optic phase shifters consist of 240-nm-thick 2- μm -wide metal strip heaters atop the waveguides—the waveguides separated from one another by air trenches. Fabrication begins with the deposition of a 250-nm-thick SiO₂ layer by PECVD which serves to prevent the photonic mode from being affected by the metal heater. Next, an 800-nm spin-on-glass layer is applied which serves to minimize the slope between the base and the top of the waveguide and enable better continuity for the subsequent metallization. A lift-off process is used for the metallization—first the pattern

is defined by UV lithography, then the metal is deposited by electron-beam evaporation, and finally the excess metal is lifted-off by soaking the chip in a photoresist stripper. One lift-off process is used for the formation of the metal strip heaters and a separate lift-off process is used for the formation of the metal traces and pads. The metal strip heater target thickness is 240 nm, while the metal pads and traces utilize two depositions of 220 nm each, angled at about 30° off normal to ensure coverage of the slope.

In the first iteration of our OPA fabrication process, aluminum was used for the metallization process, as was done for our characterization MZI devices. However, tool difficulties led to likely contamination/oxidation during the deposition procedure, leading to extremely high resistances (into the M Ω range) of the strip heaters, rendering them useless. Consequently, all aluminum material was removed, and the metallization process was re-performed with gold.

Following the metallization process is the trench creation process. Again, UV lithography was used to pattern the trenches between the waveguides. (The trenches occupy an 80% on-off duty cycle along the length of the phase shifting region.) With the 4 vol% bromine-methanol wet-etching process, the reverse mesa-shaped trenches were created through the preferential etching of the (110) plane in InP. Thus, the thermal phase shifters are nearly undercut by the left and right trenches and the thermal confinement is greatly enhanced. Figure 37 shows a picture of the gold strip heaters, trenches, and gold pads.

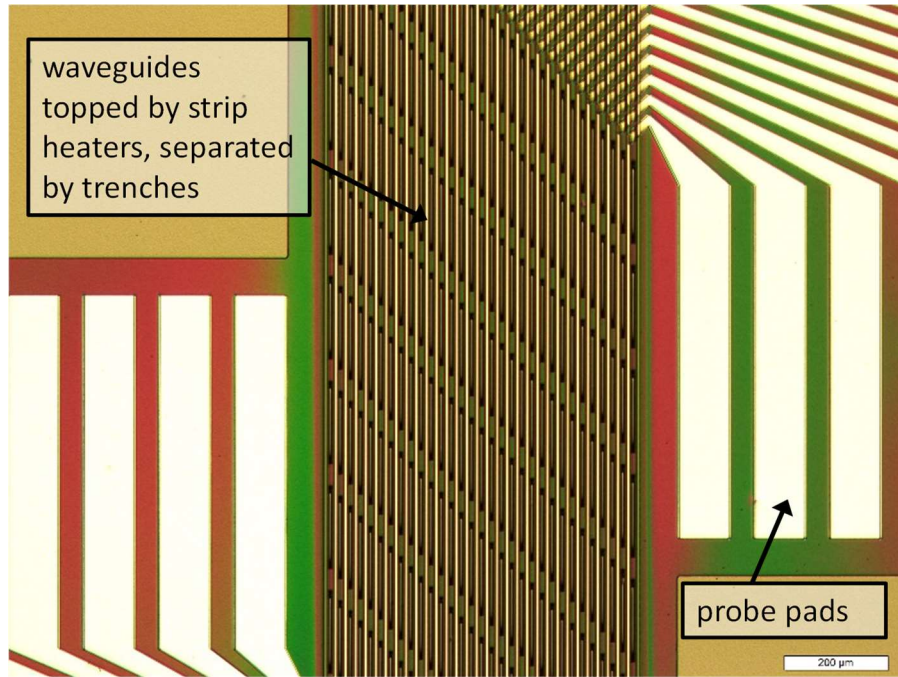


Figure 37: Gen2 fabricated thermo-optic phase shifters.

The fabrication process begins with the realization of total internal reflection (TIR) mirror emitters. Carrying out this etch prior to the waveguide etch permits a smooth facet to be formed. While our main interest is the undercut along the waveguide direction for the creation of our mirror facet, the etch also etches preferentially laterally, forming a V-groove which limits the amount of downward etch. Hence, the lateral dimension of the etch pit is critical to defining the depth of the etch. This dimension itself is limited by the waveguide-to-waveguide spacing—in our case $2\lambda = 9.2 \mu\text{m}$.

A 400-nm-thick SiO_2 layer (deposited by PECVD) is used as a hard etch mask, patterned lithographically. In the first attempt of this process, ultra-violet (UV) lithography with a chrome photomask was used; however, the lateral dimension was found to be too wide—nearby etch pits merged and degraded the structure. Therefore, a switch was made

to in-house e-beam lithography (EBL) to be able to run a few iterations and calibrate the design. The array of emitters was patterned and the SiO_2 hard mask was etched in our RIE chamber. The TIR mirrors were formed by the preferential etching of the (110) plane in InGaAs/InP with the 4 vol% bromine-methanol solution. Figure 38 shows images of the TIR mirrors both prior and subsequent to waveguide formation, along with the full array.

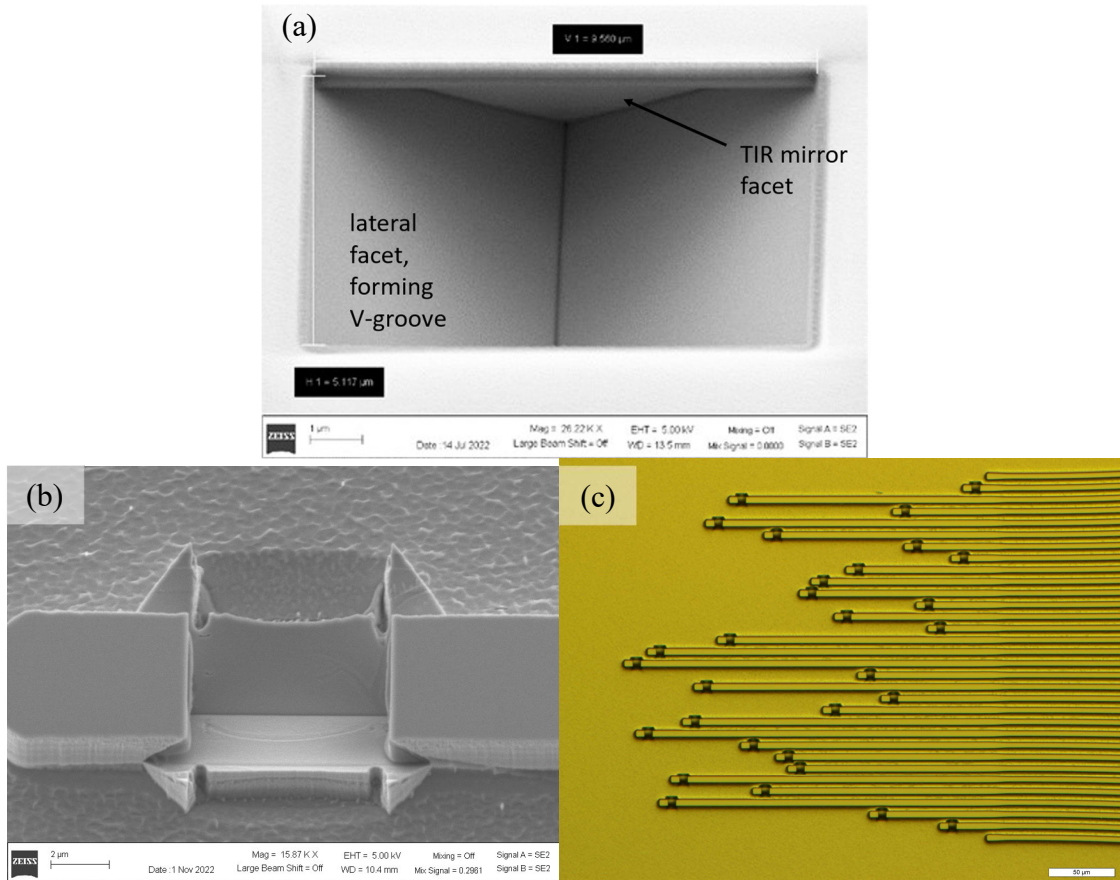


Figure 38: TIR mirror emitters: (a) SEM prior to waveguide formation, (b) SEM following waveguide formation, and (c) visible photo of emitter array.

OPA TEST SETUP AND CALIBRATION ROUTINE

A schematic diagram and photograph of the entire test setup are shown in Figure 39. As with the gen1 device, the device is end-fire coupled, the beam being focused by a 15-mm-focal length plano-convex lens onto the input facet of the device. The chip sits atop a Peltier cooling block for temperature control, and the bias channels are connected to via a set of 32 probes—30 for channel biasing and 2 for ground. An imager system consisting of three lenses and a pinhole, and a MWIR camera are used to observe the beam.

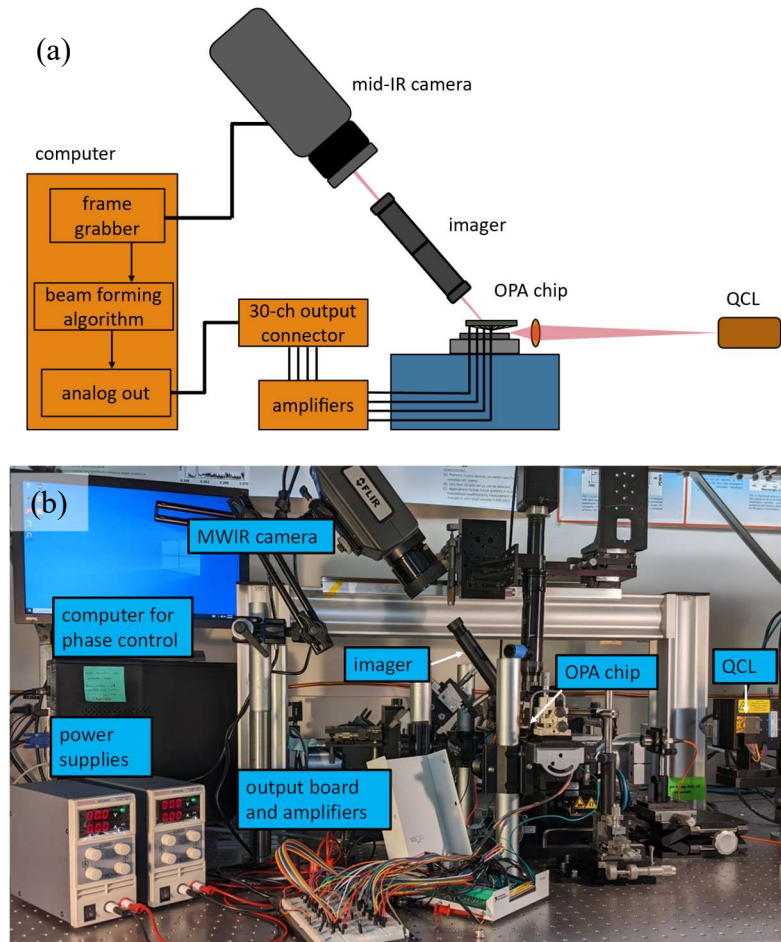


Figure 39: OPA test setup: (a) schematic layout of entire system, and (b) photograph of the actual setup.

The OPA gen1 device, following the power distribution tree, employed only straight waveguides of equal length. This made it possible (in the best cases) to maintain phase coherence along the optical paths, and phase calibration was unnecessary. The OPA generation 2 (gen2) device, on the other hand, possessed additional curved waveguides, leading to unequal path lengths. In an ideal device (with short path lengths and/or minimal sidewall roughness), the optical path length differences could be calculated and accounted for. However, in a real device (with optical lengths $\geq$ the phase coherence length) the curved waveguides permit increased interaction with sidewall roughness, and therefore a mixing of phases across channels is inevitable. Hence, phase calibration becomes critical [64–66]. Phase calibration is the process of adjusting each channel’s phase to bring all emitters into phase alignment, forming a well-defined beam. In theory, once this initial beam is formed, phase gradients can be applied to steer the beam. However, again dealing with non-idealities, it becomes more practical to carry out the phase calibration process for each steering point, recording the channel biases for each point and creating a lookup table for posterior beam steering.

The basic flow of the phase calibration process is shown in Figure 40. It consists of two nested loops—an outer loop that sweeps through each emitter channel and an inner loop that sweeps the phase from 0 to 2π . The optical intensities are measured after each phase adjustment, and the phase giving the maximum figure-of-merit (FOM) is applied following each phase sweep. Hence, the FOM is increased across an iteration. Multiple iterations may be carried out to further increase the FOM, until a (local or global) maximum is obtained. The FOM is the difference in intensity of the main lobe and the largest side lobe:

$$FOM = I_{main_lobe} - I_{largest_side_lobe} \quad . \quad (18)$$

The phase calibration routine is implemented with National Instruments LabVIEW. Details of the routine can be found in Appendix 1.

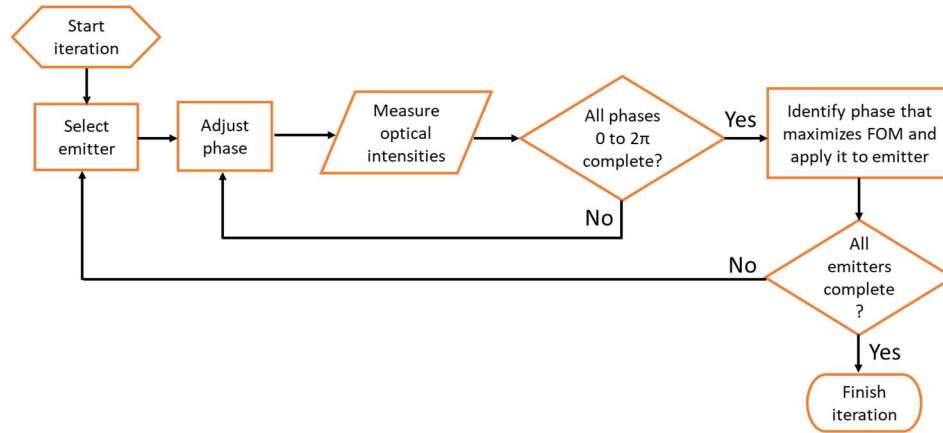


Figure 40: Phase calibration flow chart.

Since the analog output signals from the computer provide only low currents—and therefore low powers—amplifiers are needed to provide the current necessary to power the OPA’s phase shifters. This amplification has been realized through use of a bipolar transistor in a “voltage buffer amplifier” configuration, shown in Figure 41 along with simulation characteristics of voltage and current. (We see that the amplifier V_{out} is offset from the V_{in} by the transistor Base-Emitter forward voltage ~ 0.7 V. Since we will be tuning each channel for optimum beam formation, the offset is irrelevant.) Importantly, it is seen that while the current drawn from the controller is very small (in the μA range), current through the load can readily increase (into the mA range).

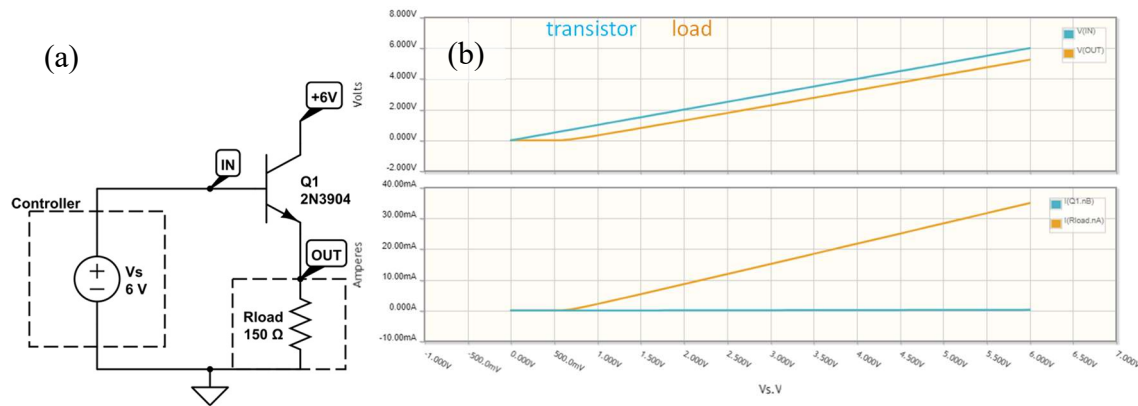


Figure 41: Amplifier. (a) circuit and (b) simulated voltage and current characteristics. The load is considered to be the metal strip heater of the phase shifter.

At first, it was attempted to view the emitted light on a screen and carry out the beam formation process from this vantage point. However, it was found that the light from the emitter aperture was overshadowed by background stray light—uncoupled light from the end-fire process, or light coupled to the semiconductor substrate and scattered therein. Figure 42 provides a MWIR near-field image of the situation, both prior and subsequent to application of the electrical probes to the chip. Although the effects of phase shifting were evidenced with the viewing screen, the background stray light prevented the beam formation algorithm from converging.

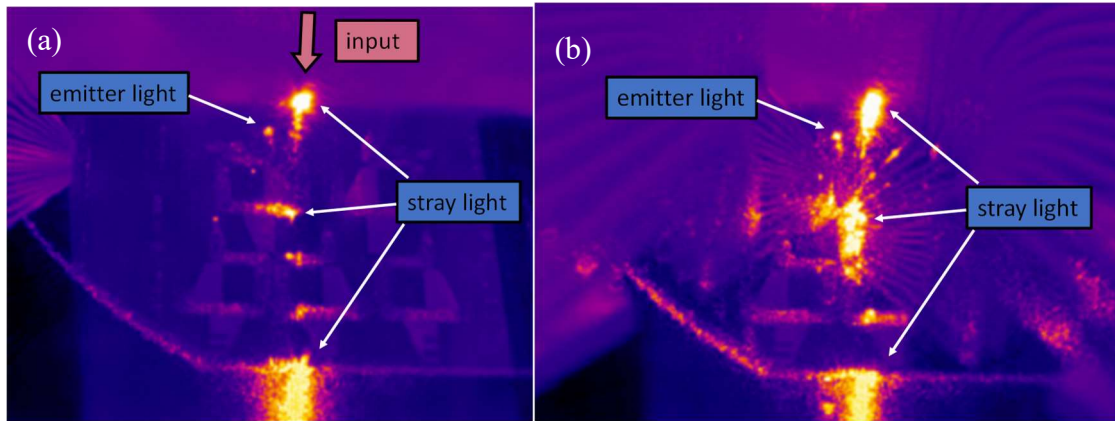


Figure 42: Mid-infrared images of light coupling to OPA chip: (a) bare chip, and (b) chip with connected electrical probes.

To remedy the adverse effects of background stray light, an imaging system was designed to block this light from reaching the far-field region. The system uses a series of optical lenses and a spatial filter. The basic concept and design are shown in Figure 43. Lenses L1 and L2 constitute a $4f$ relay system that produce a $1\times$ image at the near-field plane, where a pinhole is used to view only the region of interest—i.e., our emitter aperture—and block light from all other regions. Lens L3, called the Fourier lens, produces the far-field pattern at the Fourier plane located at its focal length. The lenses are spaced at a distance $2f$ from one another. By adjusting our MWIR camera to focus on the Fourier plane, we can image the far-field directly.

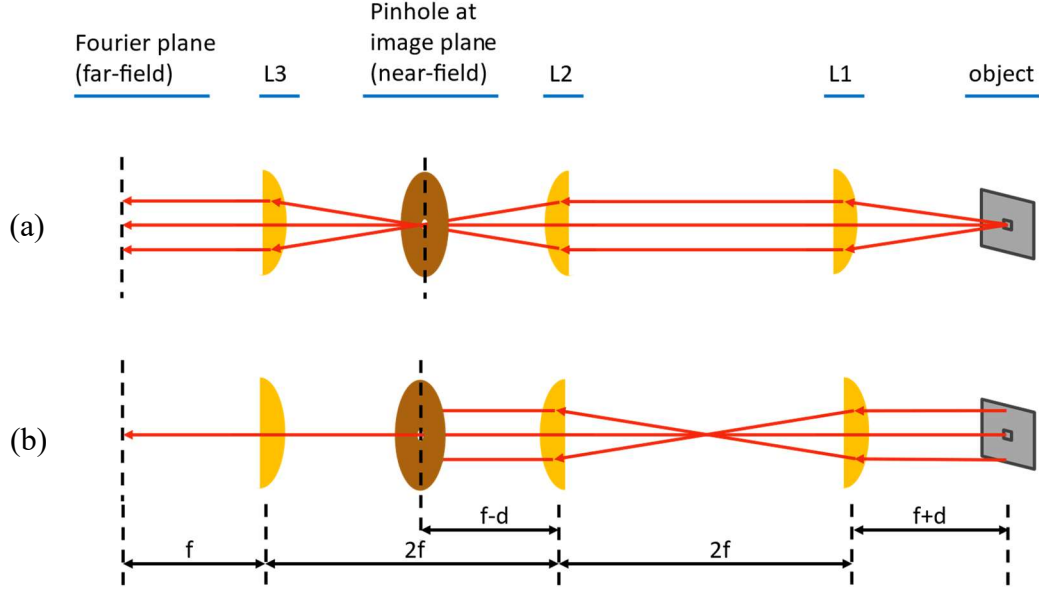


Figure 43: Far-field imaging concept and design: (a) oblique rays from emitting aperture pass through the pinhole at the image plane, and (b) rays from other locations are blocked.

All lenses are plano-convex CaF_2 with anti-reflective coating in the mid-IR. The lenses were purchased from those with immediate availability, opting for the largest diameter of 1 inch (for the largest field of view) and the shortest focal length of 42.9 mm (to save space in our already crowded experimental setup). However, it should be noted that the 1-inch-diameter lens, when placed at distance of 50 mm from the emitting aperture (which was found to be the distance needed to obtain a clear image at the image plane) provides a 23° -diameter field-of-view (FOV), which doesn't completely cover the device's theoretical beam steering FOV of 28° -diameter. A schematic representation of this difference is shown in Figure 44, along with a schematic view of the emitting aperture as seen through the pinhole.

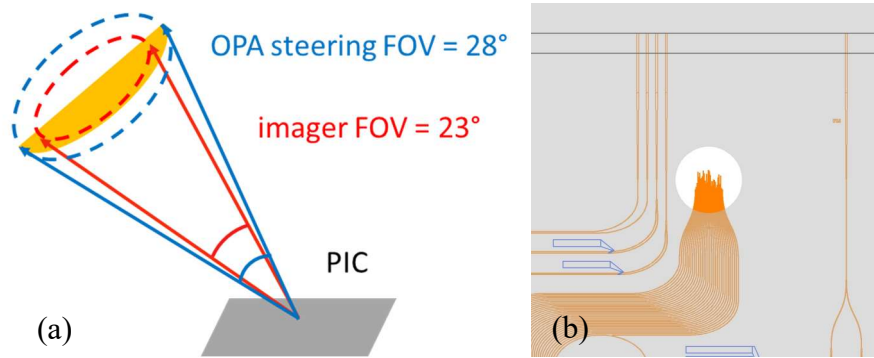


Figure 44: Aspects of the imaging system: (a) the imager FOV is smaller than the theoretical OPA steering FOV, and (b) a view of the emitter region from a 45° angle as seen through a 700- μm -diameter pinhole (with mask region semi-transparent for clarity).

OPA DEVICE TESTING

Two chips were fabricated with 5 devices each. However, due to multiple issues, both in fabrication and initial testing, most were rendered faulty and inconsequential. Ultimately, just two devices were analyzed, and even these two were imperfect. The two devices originated from different chips, with different designs, resulting in different phase tuning characteristics, listed in Table 3. Notably, the 2π -phase-shift-power for device 2 is more than twice that of device 1. This difference is understood from the two main factors which affect phase tuning efficiency: the cross-sectional area for heat flow (recall Eq. (10)), and the trench etch depth. Device 2 has both a larger cross-sectional area for heat flow, and a shallower trench etch depth, both factors contributing to the device's larger 2π -phase-shift-power.

	Device 1	Device 2
# of operable phase shifters	20	26
waveguide width	$3.3 \pm 0.2 \mu\text{m}$	$4.3 \pm 0.2 \mu\text{m}$
waveguide height	$4.0 \pm 0.2 \mu\text{m}$	$3.4 \pm 0.2 \mu\text{m}$
trench depth	$11.5 \pm 2.5 \mu\text{m}$	$7.5 \pm 2.5 \mu\text{m}$
strip heater thickness	$170 \pm 20 \text{ nm}$	$240 \pm 20 \text{ nm}$
strip heater resistance	$155 \pm 15 \Omega$	$115 \pm 10 \Omega$
electrical power for 2π phase shift	$215 \pm 25 \text{ mW}$	$485 \pm 25 \text{ mW}$

Table 3: Tested devices' dimensions and phase tuning characteristics.

As alluded to above, prior to far-field beam calibration, a clear image of the device should be observed at the near field plane (without lens L3). Figure 45 shows a mid-IR near-field image of Device 1, both prior and subsequent to the introduction of the pinhole spatial filter.

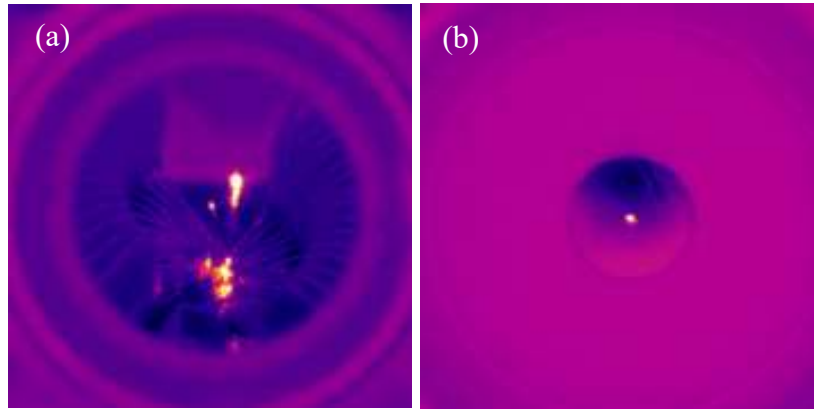


Figure 45: Mid-IR near-field images of an OPA device: (a) unmasked, and (b) masked by 500- μm -diameter pinhole. Note: the images have been spatially inverted, for clarity, from the observed images which are inverted from the object.

With the addition of the Fourier lens, the far-field pattern is observed at the Fourier plane, and the phase calibration procedure is carried out. An arbitrary area of the far-field (of dimensions $\sim 2^\circ \times 2^\circ$) is selected as the “signal” region-of-interest (ROI), and the remainder of the far-field FOV is taken as the background ROI. The calibration routine sweeps through the channels and phases calculating the FOM comparing the signal ROI to the background ROI. Figure 46 shows example far-field images during the calibration process.

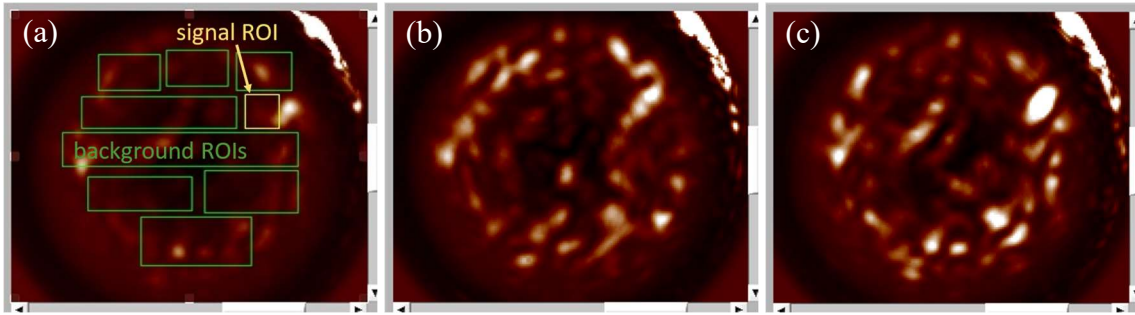


Figure 46: Far-field images during the phase calibration routine: (a) both signal and background ROIs indicated, (b) the uncalibrated pattern, and (c) the pattern following one calibration iteration, showing the formed beam in the upper right.

Typically, the FOM improves with each iteration until it converges to a maximum. However, the realized maximum may not necessarily be the optimum solution, being a local maximum rather than a global maximum. Additionally, some factors may slow or even prevent progress to a maximum. Apart from the obvious handicap of inoperable phase shifters, there are two additional factors that complicate the optimization process. First, the pronounced intensity fluctuations of the quantum cascade laser, which exhibit a natural quasi-sinusoidal behavior, even at constant injection current. Since the calibration

process is based on intensity readings, these fluctuations inevitably add noise to the FOM. Second, the achievable resolution of our phase tuners, which is inherently determined by the resolution of the waveguide temperature control. In our experiments, we have found that partitioning 2π radians of phase shift into ~ 20 bias levels proves sufficient, with finer partitioning yielding little to no gain. However, it should be noted that this empirical tuning resolution may not correspond to the inherent resolution of the waveguide temperature control, being reduced by influence from the intensity fluctuations.

Various arbitrary steering points were calibrated for each device. For Device 1, the imager's axis was set to an elevation angle of 40° , yielding an elevation FOV from 28.5° to 51.5° . Figure 47 shows mid-IR images of four steering points of Device 1, along with corresponding 3D data plots. For Device 2, the imager's axis was adjusted to an elevation angle of 33° . Figure 48 shows mid-IR images of four steering points of Device 2, along with corresponding 3D data plots.

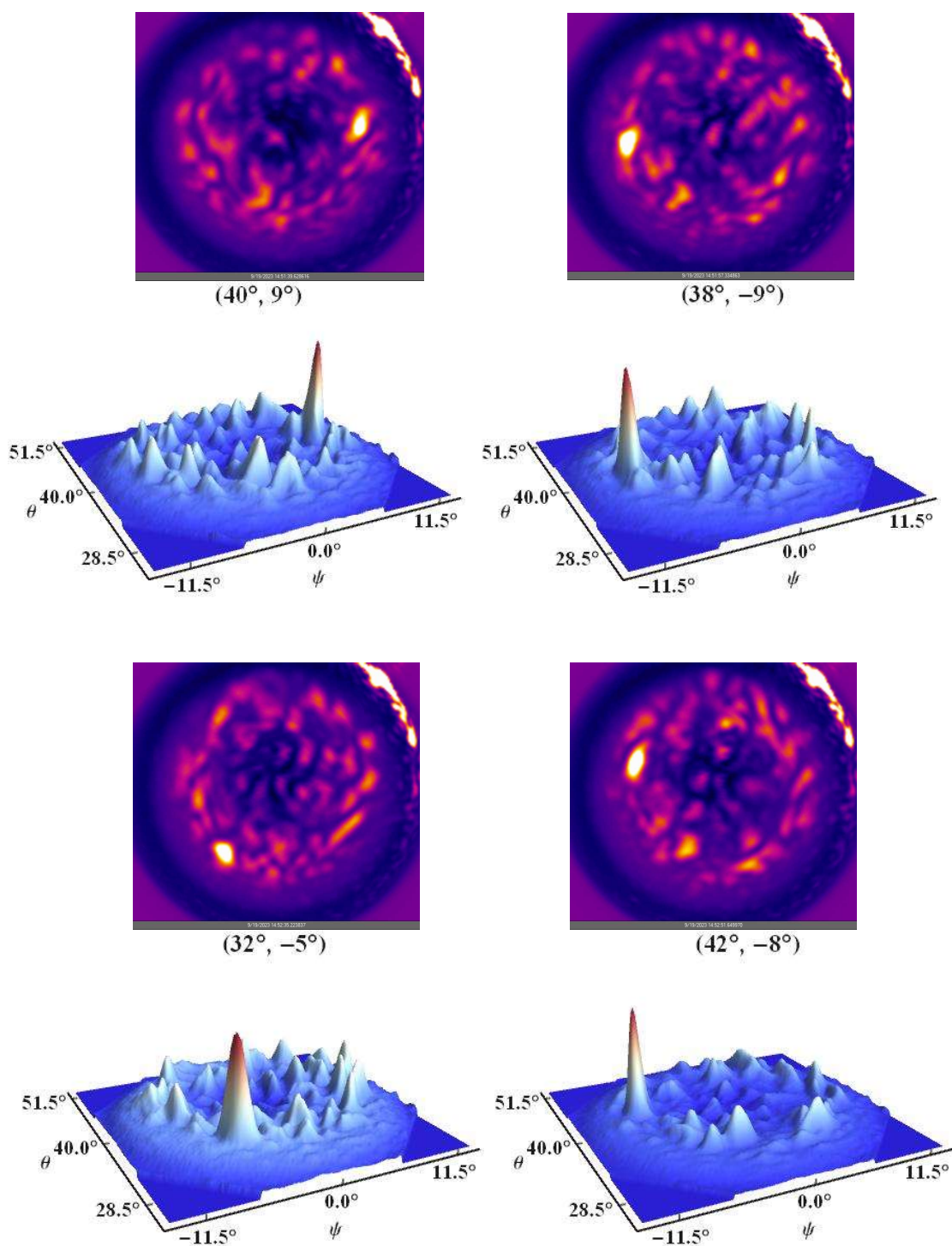


Figure 47: Device 1 steering points—mid-IR far-field images and corresponding 3D data plots.

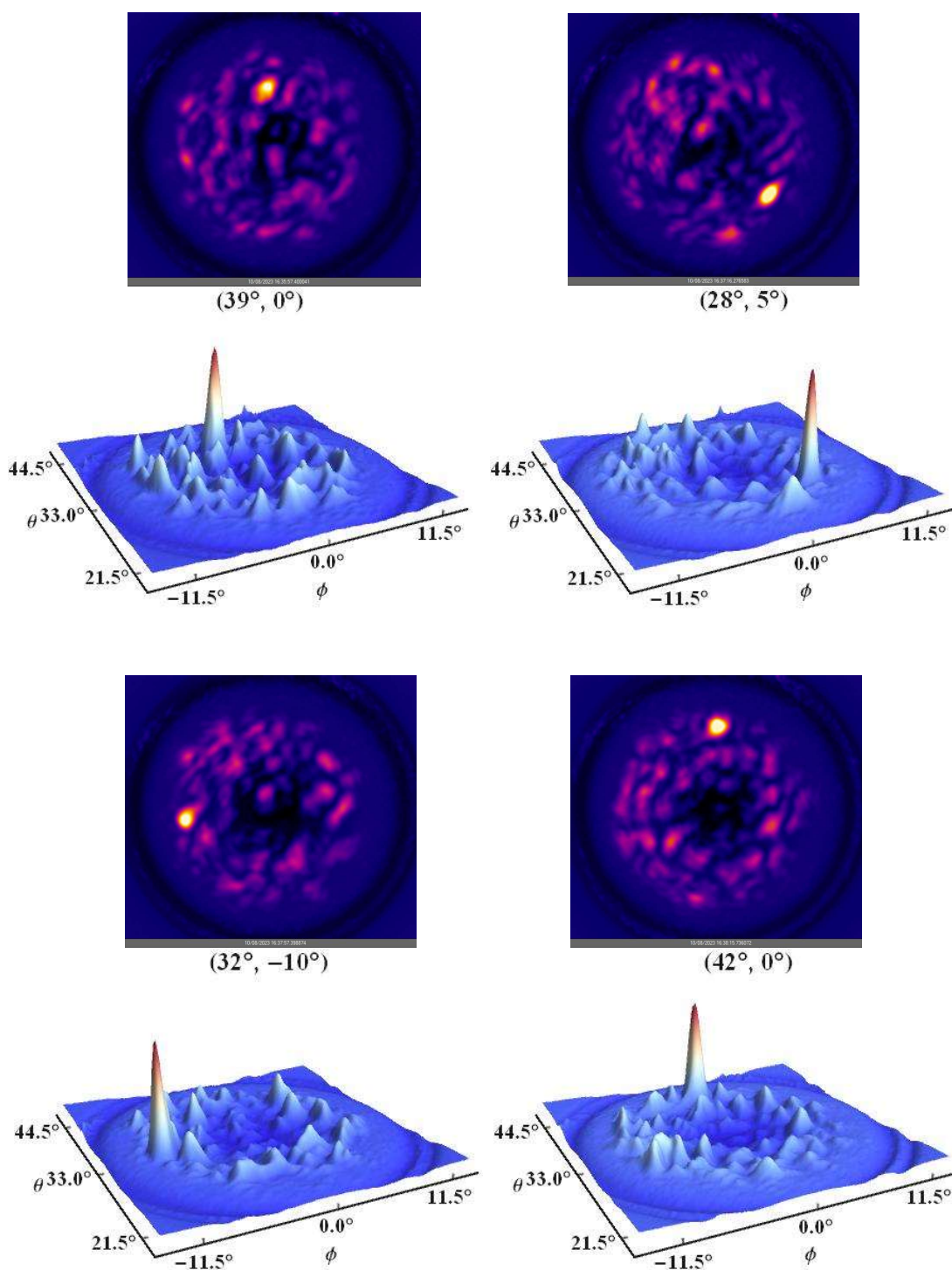


Figure 48: Device 2 steering points—mid-IR far-field images and corresponding 3D data plots.

Sid-lobe-level (SLL) and beam width (at FWHM) have been extracted from 11 calibrated beams from each device. Table 4 lists the data. As expected, in terms of SLL and beam width Device 2 clearly outperforms Device 1 (in contrast to the case of tuning efficiency, as described in Table 3): Device 2's average SLL is about 1 dB less than Device 1's average. The main reason for this is the higher number of operable phase shifters (26 vs. 20), i.e., more emitters are appropriately tuned to lower the power in the side lobes. In terms of the beam widths, the situation is different between θ and ψ . In ψ , there is no statistically significant difference between Device 1 and 2, whereas in θ there is. The likely main reason for the contrast in θ and not in ψ between the two devices is that the imager's axis in θ was different for the two devices, Device 2 being closer to the theoretical central elevation angle ($\sim 25^\circ$ per Table 2), yielding a smaller beam width in θ .

Device 1 Steering Point	SLL (dB)	Beam width	
		θ ($^\circ$)	ψ ($^\circ$)
"00"	-2.4	0.85	0.64
"02"	-2.0	1.01	0.88
"03"	-3.0	1.21	0.74
"04"	-2.7	1.25	0.72
"06"	-2.8	1.14	0.77
"07"	-4.2	1.05	0.70
"08"	-2.4	1.01	1.01
"09"	-2.1	1.07	0.90
"10"	-1.7	1.12	1.03
"11"	-1.8	1.16	0.94
"13"	-1.8	0.92	0.88
Average	-2.5	1.07	0.84
Std. dev.	0.7	0.12	0.13

Device 2 Steering Point	SLL (dB)	Beam width	
		θ ($^\circ$)	ψ ($^\circ$)
"00"	-3.8	0.89	0.80
"01"	-2.9	0.91	0.86
"02"	-3.3	0.89	0.80
"03"	-2.8	0.87	0.70
"04"	-3.3	0.74	0.84
"05"	-4.1	0.80	0.72
"06"	-2.8	0.97	0.78
"07"	-4.3	0.93	0.65
"08"	-4.8	0.84	0.80
"09"	-3.3	0.82	0.93
"10"	-3.2	0.80	0.72
Average	-3.5	0.86	0.78
Std. dev.	0.6	0.07	0.08

Table 4: Side-lobe-level and beam width for each of 11 calibrated beams for both tested devices

Table 5 provides a comparison of the experimental performance of our aperiodic OPA with a theoretically ideal one, as well as with a periodic one. It is noteworthy that, regardless of the existence of 4 inoperable channels, the experimental beam size ($0.9^\circ \times 0.8^\circ$) is still not too far off from the theoretical value ($0.6^\circ \times 0.6^\circ$), remaining much smaller than the value for the periodic array ($3.7^\circ \times 4.5^\circ$). The contrast with the periodic array of course arises from the $\sim 6\times$ larger emitting aperture dimensions. Dividing the steering range by the beam size gives the number of resolvable points. Theoretically, the aperiodic array should provide $\sim 2177/47 = 46$ times more resolvable points compared to the periodic array. Experimentally, we observed ~ 577 resolvable points. However, this value was impaired by the imager-limited FOV (as illustrated in Figure 44). Considering a device-limited FOV ($\pm 14^\circ \times \pm 14^\circ$), we should observe ~ 1088 resolvable points.

	Periodic OPA Theory	Aperiodic OPA Theory (ideal)	Aperiodic OPA Experiment
Number of channels:	30	30	(26 working)
Spacing	$2\lambda = 9.2 \mu\text{m}$	$\geq 2\lambda = 9.2 \mu\text{m}$	
Emitting aperture area:	$46 \mu\text{m} \times 39 \mu\text{m}$	$300 \mu\text{m} \times 266 \mu\text{m}$	
Steering range ($\Delta\theta \times \Delta\psi$):	$\pm 14^\circ \times \pm 14^\circ$	$\pm 14^\circ \times \pm 14^\circ$	$\pi (11.5^\circ)^2$
Beam width ($d\theta \times d\psi$):	$3.7^\circ \times 4.5^\circ$	$0.6^\circ \times 0.6^\circ$	$0.9^\circ \times 0.8^\circ$
Number of resolvable points:	≈ 47	≈ 2177	≈ 577
Side-lobe-level:	-28 dB	-17 dB	-4.8 db (best) -3.5 dB (avg)

Table 5: Comparison of experimental aperiodic OPA with theory, as well as with a periodic one.

The best side-lobe level (SLL) for one steering point (within the imager-limited FOV) was found to be -4.8 dB, while the average across all steering points was -3.5 dB.

These values are quite a bit larger (worse) than the theoretical SSL of -17 dB but expected considering the various non-ideal factors in play. First, the anomalies in the device itself—the (chance) inoperability of 4 phase tuners and the (inherent) imperfect power distribution across the emitters—anomalies which render perfect phase tuning impossible. Second, the imprecision of the test system, most notably the laser power fluctuations, which hamper the effectivity of the feedback routine. Also, the mediocre resolution of phase tuning, related to the precision of heat addition and removal from the chip. Each of these detriments can be mitigated or eliminated to improve system performance. In terms of the device, for example, the waveguides can be rerouted to provide a more balanced distribution of power (having been limited in our current case by the arrangement of our test setup). In terms of the setup, the laser power can be stabilized through the use of detector feedback to the laser controller.

To gain a better understanding of the dependence of the SLL and beam width on the non-idealities, we can incorporate the non-idealities into our theoretical models.

Chapter 4: Conclusion and Perspective

The OPAs developed in this work—in the mid-IR spectral region and on the InP-based platform—are “initial demonstration” devices. They indicate the plausibility of on-chip non-mechanical beam steering for future applications that will benefit from the high-transmission, low-solar-noise spectral range.

For OPAs operating in the near-IR spectral range, over a decade of research has led to the current inflection point of commercial viability. Though many lessons can be gained from this learning process to augment the device development in the mid-IR, the difference in material platforms, sources, and detectors will continue to be repressing factors, so that overall a similar rate of progress is expected.

The aperiodic array developed herein has proven superiority to that of the prior periodic array by way of its $\sim 20\times$ number of resolvable points. I believe the concept will be fundamental in future higher-number-of-emitters OPAs, where more advanced algorithms will be used to determine the emitters’ positions. The TIR mirror emitters are a noteworthy departure from the more common grating emitters. However, it remains to be seen which one will be able to balance more optimally fabrication ease, envelope size, and directionality. Finally, though the thermo-optic phase shifting surely has room for further improvement, it is likely that other approaches, e.g., electro-optic, will be developed for more efficient faster tuning.

In parallel with the continued advances in the passive components, monolithic integration techniques with quantum cascade devices are expected to progress in a timely fashion. Advances in waveguides, feedback and isolation structures, and active-to-passive coupling will soon permit the first demonstrations of fully integrated devices. Moreover,

innovative architectures facilitating simpler or more coordinated lasing and steering processes can be expected.

Appendix: LabVIEW beam formation routine

The full beam formation (phase calibration) program consists of two major routines which run in parallel: the main channel biasing sweep and the imaging routine. The imaging routine continuously calculates the FOM, which is relayed to the main routine following each applied bias. Simplified versions of the two routines are provided here.

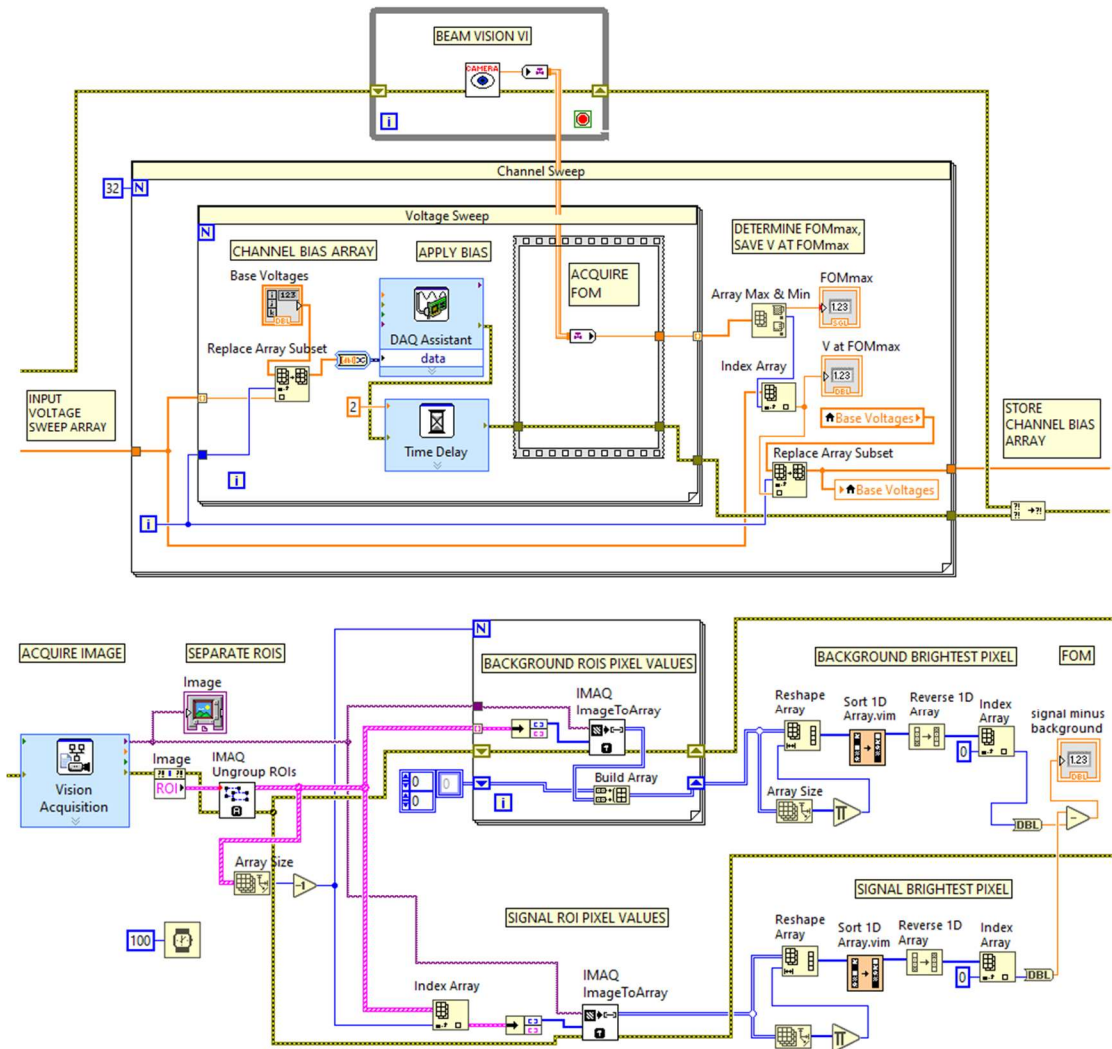


Figure 49: LabVIEW beam formation routine. (a) main channel and voltage sweeps and (b) imaging and FOM calculation routine.

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