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Mid-infrared optical phased array in an InP-based platform

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***Abstract*—We develop a 16-channel aperiodic optical phased array for beam steering in the mid-infrared spectral region in an InGaAs/InP platform. The device consists of an MMI light splitting tree, thermally isolated thermo-optic phase shifters, and power-balanced emission gratings.**

Keywords—mid-infrared, beam steering, optical phased array, aperiodic array, waveguide antenna, aperiodic array, indium phosphide

I. INTRODUCTION

Non-mechanical beam steering in the near-IR spectral region has undergone rapid progress in recent years, benefited by the maturity of the technology for telecommunications, and motivated strongly by lidar applications for sensing, mapping, and navigation. Over the course of this advancement optical phased arrays (OPAs) have emerged as a leading device technology for azimuthal steering, with performance optimizations (in e.g., steering range and resolution) coming to fruition. Extension to the mid-infrared, on the other hand, is just getting underway, motivated here primarily by the use of lidar and countermeasures in the atmospheric transmission window of 3–5 µm. Furthermore, these applications benefit from high-power robust modules. With InP-based quantum cascade lasers (QCLs) being the predominant semiconductor source in this range, monolithic integration of lasers and passive devices in a single material platform is considered the most promising approach to achieve the desired performance. With this in mind, we have chosen the low-index contrast InGaAs/InP waveguiding platform for our passive devices.

II. THEORY

The optical phased array is based on the principle of interference from multiple coherent sources. Adjusting the phases of the sources appropriately moves the locations of the interference maxima in the far-field, thus achieving "beam steering." For a uniform array of emitters, the steering angle of the main lobe ψ is easily determined as $\sin(\psi) = (\lambda/d)*\varphi/2\pi$, where λ is the free-space wavelength, d is the emitter spacing, and φ is the emitter-to-emitter phase increment. For $d > \lambda/2$, unambiguous steering of the main lobe is restricted by the presence of grating lobes. But the spacing of photonic waveguides is limited by the evanescent coupling between them. To achieve wide steering ranges while avoiding evanescent coupling, sparse aperiodic distributions of emitters are commonly employed to suppress the appearance of grating lobes, at the cost of an increased side-lob-level (SLL) [1].

III. CHIP ARCHITECTURE

Our previous work demonstrated the feasibility of an InGaAs/InP platform for beam steering in the mid infrared [2]. In our current work, we have redesigned our waveguiding structure for compatibility with integration of QCLs at a wavelength of 4.6 µm. The core thickness has been set to 850 nm, a nominal value which permits sufficient modal confinement in the gain section for lasing, while enabling a separate efficient coupling section [3]. Fig. 1(a) shows a cross-section with mode profile of our waveguide structure.

A schematic of our overall layout is show in Fig. 1(b). It consists of three main components: a series of cascaded 1x2 multi-mode interferometer (MMI) power splitters, thermo-optic phase shifters, and waveguide emitter antennas. The optical input is split into 16 channels by the MMI tree, each channel is independently tuned by its own phase shifter, and the antennas transmit the beam to the far-field. Advancing from our previous work, each component is redesigned for improved performance.

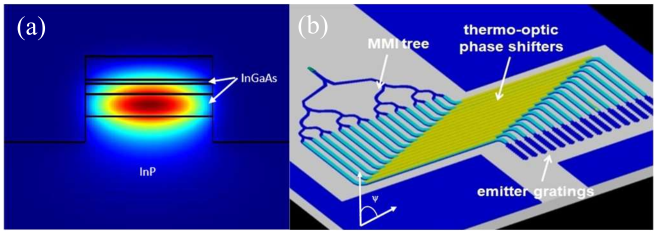

Fig. 1: (a) InGaAs/InP waveguide with the fundamental TM mode (width = 4.3 µm, height = 3.3 µm), (b) optical phased array schematic layout.

The MMIs possess a contour optimized for low loss in Ansys Lumerical. The design and electric field profile are shown in Fig. 2, along with a photo of a fabricated device.

The phase shifters are fanned out and separated by trenches to improve tuning efficiency, shown in Fig. 3. The trenches are formed with a bromine-based crystallographic wet etch which undercuts the waveguides [4]. To prevent collapse, non-etched

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supports are distributed across the length of the waveguides. An etched undercut duty cycle of up to 80% is being investigated.

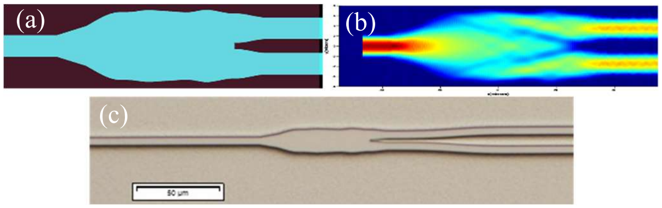

Fig. 2: Multi-mode interferometer: (a) in-plane layout (overall dimensions between waveguides = 60 x 12 μm^2), (b) TM electric field profile, (c) microscope photo fabricated device.

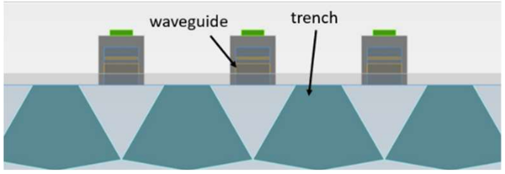

Fig. 3: Waveguide thermo-optic phase shifter, undercut with 55° crystallographic etch.

A single emission grating is shown in Fig. 4. Taking advantage of the low-index contrast nature of waveguide, which causes a significant portion of the fundamental mode to reside in the cladding, we create the grating in the cladding only. Our waveguiding structure incorporates an InGaAs etch stop layer within the top InP cladding (seen as the second layer from the top in Fig. 1), permitting the formation of a 400 nm InP overlay without the need for a delicate shallow etch. The grating is adjusted in duty cycle and width to provide more uniform emission, which decreases the spot size in far field [5].

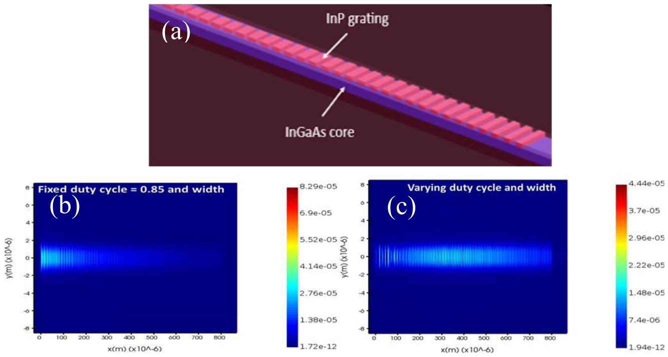

Fig. 4: Emission gratings. (a) Schematic of uniform emission grating waveguide, and upper emission performance of (b) fixed duty cycle emission grating and (c) custom emission grating.

As mentioned, the distribution of emitters significantly affects the OPA characteristics such as steering range, beam width, and side-lobe-level. We have used a particle swarm optimization to determine the distribution of emitters in our aperiodic OPA [6]. Through the iterative procedure, we have designed a 16-antenna OPA which can achieve an azimuthal beam steering range up to ±35° with the worst SLL being -7.20 dB, as shown in Fig. 5.

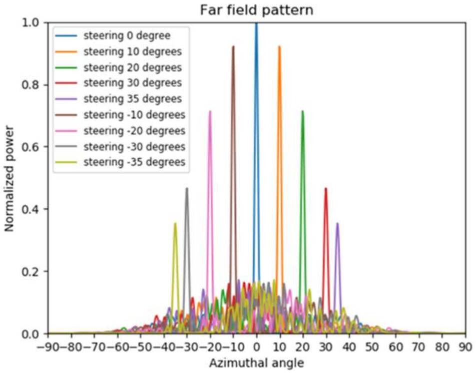

Fig. 5: Far-field simulation of 16-antenna aperiodic array along azimuthal direction.

IV. SUMMARY AND NEXT STEPS

We are developing an InP-based OPA suitable for chip-scale monolithic integration with QCLs. Compared to our previous work, both the power splitters and the phase shifters are more efficient, and the emitter gratings produce more uniform emission. Additionally, we are implementing an aperiodic array to suppress grating lobes and enable a wider steering range.

This device layout and fabrication are being developed at the time of this writing (Q1 2022) with expected completion in Q2 2022. Characterization results of both the independent components and the full OPA will be presented.

ACKNOWLEDGMENT

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