Mid-infrared 2-D Aperiodic Optical Phased Array in an InP-based Platform

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Abstract: We fabricate a 2-D aperiodic high-resolution optical phased array, which includes a multi-mode interferometer light-splitting tree, thermally isolated thermo-optic phase shifters, and total internal reflection mirror emitters in an InGaAs/InP platform for 2-D beam steering.

With the progression of light detection and ranging (LiDAR) and optical communications technologies, the development of a robust and agile beam formation and steering technology has seen great strides. The optical phased array (OPA) has become a promising candidate for this purpose, due to its compact chip-scale form factor and non-mechanical mechanism. In recent years, visible and near-infrared OPAs have been widely studied and demonstrated in silicon-based platforms. However, in comparison to operation in the near-infrared, LiDAR and communications in the mid-infrared have the potential for longer distance and greater security, owing to lower background solar noise and lack of widespread use of this spectral range. Furthermore, mid-infrared OPAs can be integrated with high-power robust modules such as InP-based quantum cascade lasers (QCLs), which are the predominant semiconductor sources in mid-infrared spectral region. With the low-index contrast InGaAs/InP waveguiding platform, the monolithic integration of lasers and OPAs in a single chip is considered the most promising approach to achieve the desired performance.

In this work, the waveguides are designed considering the future integration with InP-based QCLs at the wavelength of 4.6 µm. Based on the low-index contrast InGaAs/InP system, the core and cladding thicknesses have been set to 850 nm and 1450 nm, respectively—values which will not impair lasing of the adjacent QCL, while still generating efficient coupling [2]. The device architecture consists of three main sections: (1) a 1x32 multi-mode interferometer light-splitting tree, (2) a set of 30 thermally isolated thermo-optic phase shifters, which are connected to metal contact pads for biasing, and (3) an 2-D aperiodic sparse array of small-area emitters. Fig. 1(a) shows a cross-section with mode profile of our waveguide structure, and Fig. 1(b) shows the whole layout of the proposed device.

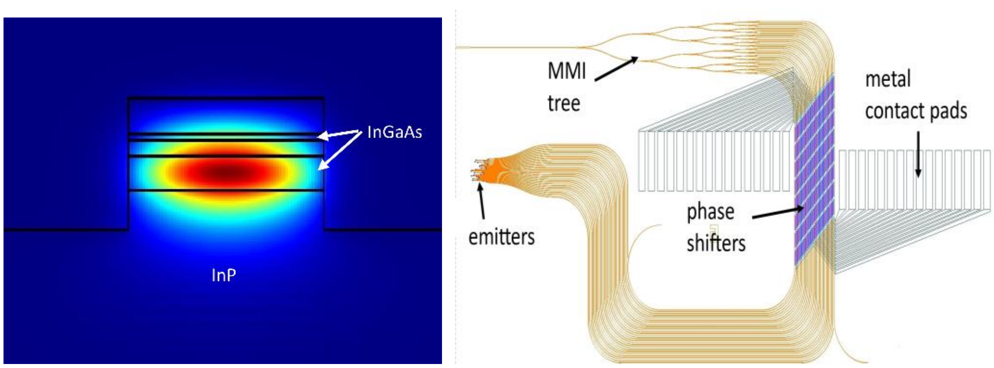

Fig. 1: (a) InGaAs/InP waveguide with fundamental TM mode (cross-section area = 3.3 x 3.3 µm²), (b) optical phased array schematic layout.

As shown in Fig. 2, suspended thermal phase shifters are adopted in the proposed OPA. With a bromine-methanol wet-etch process, the reverse mesa-shaped trenches are produced due to the preferential etching property of (110) plane of the InP substrate. Thus, the thermal phase shifters are nearly undercut by left and right trenches, so suspended thermo-optic phase shifters with great thermal confinement are fabricated.

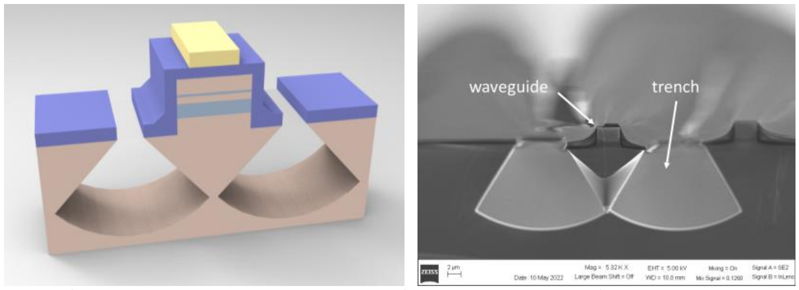

Fig. 2: (a) schematic of the suspended thermo-optic phase shifters. (b) SEM image of cross-section through waveguide and trenches.

The small area emitters are facilitated by total internal reflection (TIR) mirrors and enable 2-D beam steering in far-field, as shown in Fig. 3. Similar to the wet-etching for trenches, we make use of the 55° angle of the (110) plane formed by the preferential etch of a bromine-methanol solution. In this case, the etch extends through the waveguide, creating an undercut facet that is the TIR mirror. Also, the facet is covered by an SiO_2 layer to improve the emission efficiency further. With the high index contrast of InP/InGaAs to SiO_2, the 55° angle permits TIR.

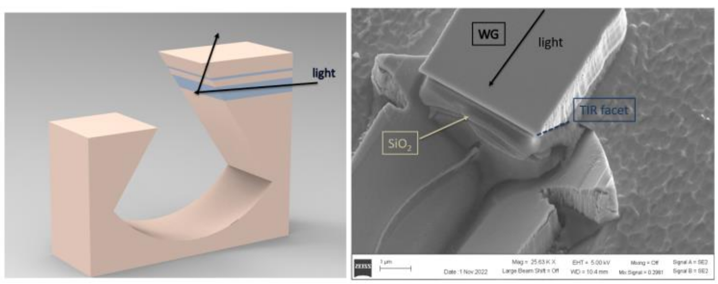

Fig. 3: (a) schematic of the TIR emitters. (b) SEM image of TIR emitters.

Eventually, we used a particle swarm optimization (PSO) to position the emitters and produce an OPA with a narrow half-power-beam-width [3]. This is an iterative procedure, and the aperiodic array produced was similar to a Costas array, that is that the displacement vector between any two emitter elements is unique [4]. As shown in Fig. 4, the proposed 30-element OPA provides a beam steering range of ±14° in both the longitudinal and azimuthal directions in the far-field with up to 2413 resolvable points.

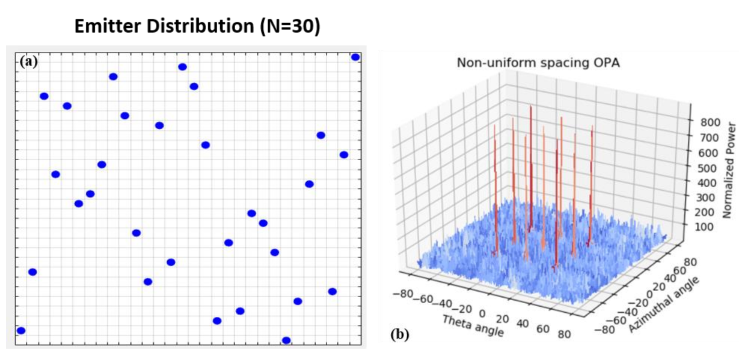

Fig. 4: Our proposed OPA. (a) Layout of the OPA, where each spot represents an emitter location, (b) far-field patterns in the longitudinal and azimuthal directions, respectively.

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[3] T. Dong et al., "Hybrid design approach of optical phased array with wide beam steering range and low side-lobe level," Opt. Lett. **47**, 4 (2022).
[4] T. Fukui et al., "Non-redundant optical phased array," Optica **8**, 10 (2021).