Monolithic Integration of Quantum Cascade Laser, Quantum Cascade Detector and Slotted Photonic Crystal Waveguide for Absorbance Sensing from λ=3-15µm

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Abstract: We demonstrate monolithic integration of quantum cascade laser and detector and slotted photonic crystal waveguide on a single epitaxial heterostructure for on-chip slow light enhanced absorption sensing. Designs can cover λ=3-15µm wavelengths without wafer bonding.

Mid-infrared (Mid-IR) trace-gas sensing is a rapidly developing field with wide range of applications including detection of explosives and hazardous chemicals, control of industrial processes and emissions, performing breath analysis for medical diagnostics, and environmental and atmospheric monitoring. Mid-IR spectral range hosts fundamental vibrational-rotational transitions of virtually any chemical compound. Currently, most mid-infrared (mid-IR) trace gas sensing systems are developed around bulky gas cells and free-space optics based on cavity ring-down spectroscopy (CRDS) [1], tunable diode laser absorption spectroscopy (TDLAS) [2], Fourier transform infrared spectroscopy (FTIR)[3], or photo-acoustic spectroscopy (PAS) methods [4]. Although these systems can provide parts per billion (ppb) and in some cases, parts per trillion (ppt) sensitivities, these systems require bulky and expensive optical elements and, furthermore, are very sensitive to beam alignment and have significant size and weight that place constrains on their applications in the field, particularly for airborne or handheld platforms. Quantum cascade lasers (QCLs) have dramatically energized the field of trace-gas sensing by providing narrowband tunable continuous-wave room-temperature emission in the entire mid-IR spectral range from 3-11µm [5, 6]. Recently IRcell, a monolithic circular multipass gas cell intended for optical trace-gas sensing, was developed [7], however the free-space path lengths of 1-4m can only provide intermediate levels of sensitivity. Monolithic integration of light sources and detectors with a passive photonics platform is required to enable a compact trace gas sensing system that is robust to vibrations and physical stress.

Recently, we experimentally demonstrated that slotted photonic crystal waveguides (PCWs) can enable high sensitivity gas sensing on chip via absorption spectroscopy. The principle of slow light enhanced absorbance of gases on chip has been detailed previously. [8-11] We detected 3 parts per million (ppm) greenhouse gas carbon monoxide (CO) at λ=4.55µm with feasibility to detect down to sub-100 parts per billion (ppb) by nominal device modifications in a silicon-on-sapphire (SoS) platform [11]. We also detected the chemical warfare simulant triethylphosphate (TEP) down to 10ppm at λ=3.4µm also in a SoS platform [10]. While CO has maximum absorbance around λ=4.55µm where SoS can be used as a substrate with silicon core for low-loss waveguiding (~2dB/cm), silicon cannot be used at λ=9.5µm at the absorbance maxima of TEP. The available core-cladding choices such as Ge-GaAs, GaAs-AlGaAs, InGaAs-InP, all would need suspended membrane photonic crystal waveguide geometries. However, since most efficient quantum cascade lasers (QCLs) have been demonstrated in the InP platform, the choice of InGaAs-InP eliminates the need for wafer bonding versus other choices. In this paper, we demonstrate monolithic integration of QCL, quantum cascade detector (QCD) and suspended membrane slotted PCWs with polarization rotators on a single growth InGaAs/InP based epitaxial platform.

Fig. 1 shows a schematic epitaxial heterostructure, showing the monolithic epi of the passive undoped InGaAs waveguiding section (below) and the active QCL and QCD sections (above). Light is coupled in between active and passive regions via adiabatically tapered waveguide couplers. The monolithic growth eliminates expensive and low yield wafer/chip bonding processes in any other system, including GaAs/AlGaAs. It eliminates the need for intermediate adhesive layers such as SU8 (lossy at λ>5µm wavelength), silicon dioxide (lossy at λ>3.7µm) [12], silicon nitride (lossy at λ>5µm) [12] or complex surface activation strategies in direct wafer to wafer bonding [13]. InAs is nearly transparent over the entire wavelength range from λ=3.5-15µm [14]. Since GaAs is also practically transparent, lattice matched $In_{0.53}Ga_{0.47}As$ may be expected to be lossless as well. Initial designs and fabrication are at λ=6.15µm at an absorbance maxima of ammonia. The QCL section is a standard epi stack from Thorlabs. Fig. 2 shows the evolution of the fundamental transverse magnetic (TM) polarized mode, starting from the QCL ridge, traversing through an adiabatic linear taper and finally terminating in the passive InGaAs waveguide.

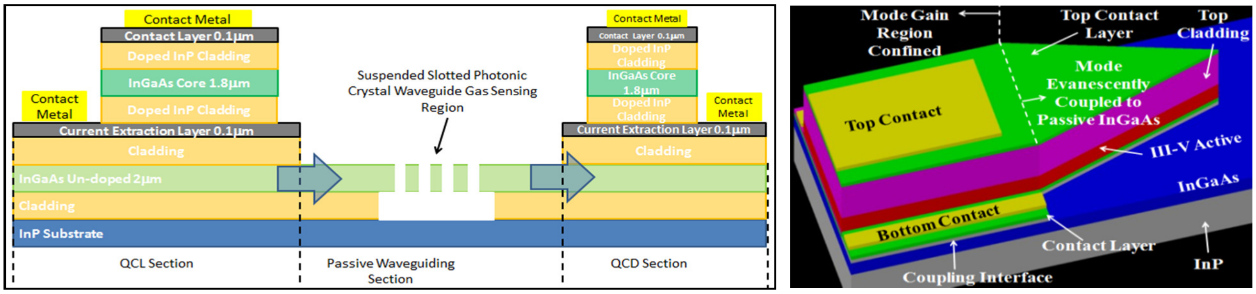


Fig. 1: (a) Schematic of the device structure with QCL and QCD and suspended membrane $In_{0.53}Ga_{0.47}As$ waveguides in a monolithically epitaxial heterostructure on InP substrate. (b) Structure for evanescent coupling of light between III-V gain and GaAs waveguiding region, maximizing the confinements in each necessary region.

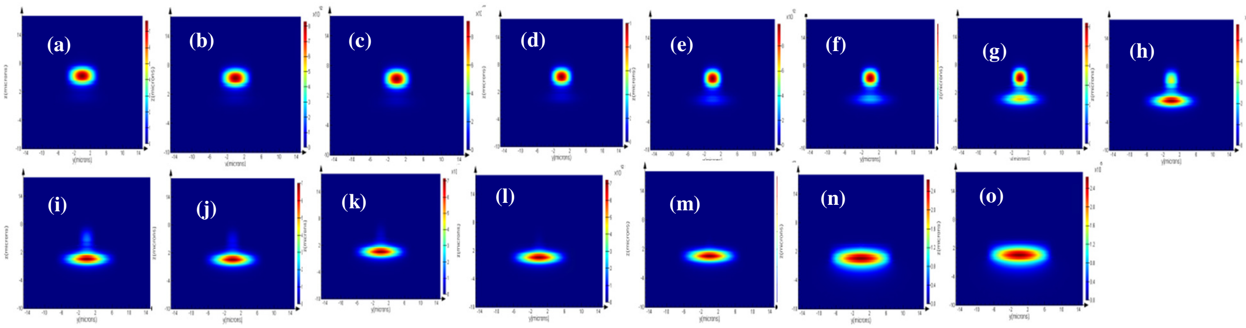
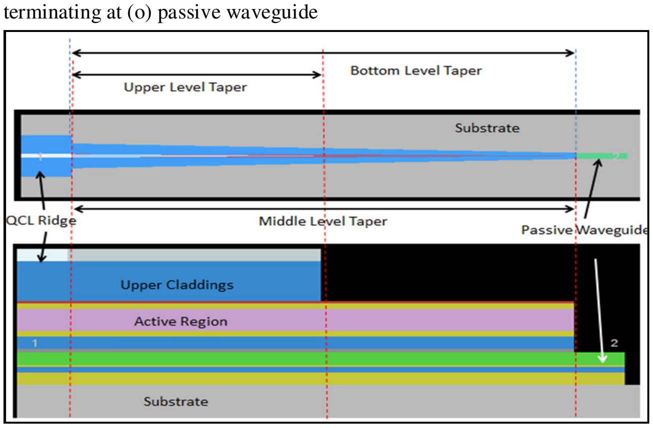


Fig. 2: Evolution of the fundamental TM mode along the length of the adiabatic starting at (a) QCL region, through different taper distances and terminating at (o) passive waveguide



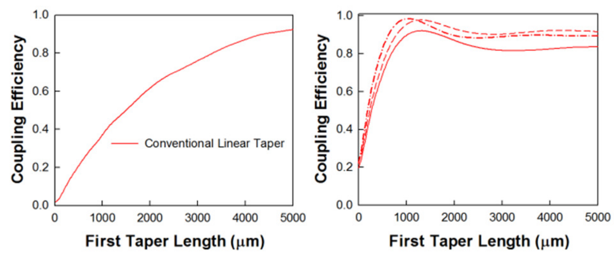


Fig. 3: (a) Schematic top view and side view of the 3-level taper to couple light efficiently from QCL to the passive waveguide (b) Coupling efficiency from QCL to underlying passive waveguide using (b) conventional linear taper and (c) designed 3-level taper on the exact same heterostructure for different parameters.

Since the cost of a QCL epi is dependent on the growth thickness, and since a significant portion of the epi would be etched away in the passive waveguiding section, it is necessary to build compact integrated photonic components, including the adiabatic taper and the polarization rotator [15]. In Fig. 3, we show that while a conventional linear taper needs to be ~5mm long to achieve 90% coupling efficiency from the QCL into the underlying passive waveguide, the 3-level taper that we have designed can achieve 99% coupling efficiency over a total length of 1.5mm (1mm for the first taper and 0.5mm for the second taper). A distributed feedback (DFB) QCL array integrated with slotted PCWs will enable absorption spectroscopy over the gain bandwidth of the QCL. Device fabrication is in progress. Measurement results will be presented. The research is supported by Army (ARO) SBIR Contract #W911NF-17-P-0056. The content of the information does not necessarily reflect the position or the policy of the Government, and no official endorsement should be inferred. The authors thank Mikhail Belkin at the University of Texas, Austin for useful discussions.

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