Slow-light assisted and wavelength tunable TM waveguide on QCL/QCD compatible platform for mid-infrared lab-on-chip absorption spectroscopy

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Slow-light assisted and wavelength tunable TM waveguide on QCL/QCD compatible platform for mid-infrared lab-on-chip absorption spectroscopy

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ABSTRACT

The fundamental vibrational-rotational absorption signature of almost all the chemical compounds lies in the Mid-IR spectrum (λ=3-15μm) thus offering superior light-analyte interaction in this regime. In particular, the successful inscription of infrared-spectroscopy in a multi-pass cell has significantly boosted its use mainly in the gas-sensing application at the sub-ppm/ppb level. However, the requirement of bulky, alignment sensitive, and need of expertise-hands makes it inappropriate for many fields especially in portable applications like stand-alone environment monitoring, detection of chemical-warfare-agent in the battlefield, Astro-biological applications, etc. An external disruption-free handheld device (i.e., unaffected from any external vibration, physical stress, and thermal variations) with high specificity and selectivity are still prerequisites for such in-situ applications. The advancements in photonics have shown enormous possibilities to miniaturize all spectroscopic components to a single chip. In this context, the slow light-assisted engineered photonic structure on a QCL/QCD (quantum confined laser and detector) is most promising to replace bulky multi-pass cell optics. In principle, it slows down the light with several folds to enhance the light-analyte interaction and thus open an avenue for an on-chip sensing platform. Most efficient QCLs demonstration explored in the InP platform, also a selection of InP-InGaAs eliminates the requirement of the costly wafer-bonding process. In this paper, we consider slow-light assisted and wavelength-tunable periodic photonic structures. The device is designed such that it supports transverse-magnetically polarized mode directly emitted from QCLs. It eliminates the use of any additional polarization-rotator (conversion from TM to TE mode) which reduces fabrication complexity and additional space on the chip.

Keywords: Absorption spectroscopy, Sub-wavelength Grating waveguides, Mid-infrared, Quantum cascade lasers/detector, Indium gallium arsenide

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1. INTRODUCTION

Real-time in-situ identification and quantification of chemicals present in the atmosphere are important for a number of reasons including public health, security, industrial purpose, and environment monitoring [1-2]. Although a variety of techniques are currently being used for infield and laboratory chemical characterization, most generally involve the spectroscopy method. Spectroscopy technique relies on light-matter interaction across a wide range of wavelengths spectrum covering ultraviolet (UV) (λ ≈ 0.1-0.4μm), visible (λ ≈ 0.4-0.8μm), near-infrared (Near-IR) (λ ≈ 0.8-2.5μm) and Mid-IR (λ ≈ 2.5-20μm). Among all the chemical compounds, shows their fundamental vibration-rotational molecular absorptive nature in the Mid-IR region thus superior light-analyte interaction can be achieved [3-4]. For this reason, Mid-IR spectroscopy gain much attention among the scientific community especially after the evolution of efficient sources and detectors [5] i.e., quantum cascaded laser, and detector.

The efficient light-matter coupling in spectroscopy method for high sensitivity trace gas sensing application (typically in parts per million (ppm) and sometimes in parts per billion (ppb) level) requires long interaction length

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[6]. At the same time, other environmental fluctuations like thermal variation, vibration, and stress make the scenario worse as almost all-optical devices are highly dependent on these variables. It causes bulky and highly sensitive alignment setup on the optical bench thus constraining possibilities of chip-level detection essential for many portable applications where human intervention is difficult, for example, study of chemical-warfare-agent in the battlefield or monitoring of atmospheric gases in the high atmosphere.

The monolithic integration of light sources with photodetectors and low-loss optical sensing waveguides can address all issues simultaneously, definitely, the choice of material is important for such integration. Silicon photonics is the most explored and matured in the last few decades, but despite it, unavailability of laser devices (due to indirect bandgap material) and high intrinsic optical loss in the mid-IR region after $\lambda > 6\mu m$ for Si and $\lambda > 3.7\mu m$ for SiO_2 makes it unsuitable for sensing application in this regime [7]. To date, the most efficient quantum cascade lasers (QCLs) operations are demonstrated in the InP platform. The lattice constant of $In_{0.53}Ga_{0.47}As$ matches well with InP materials and exhibit optically transparent characteristics for a wide range of spectrum in $\lambda \approx 3-15\mu m$ [8]. Most effectively InGaAs/InP is the best platform available that enables epitaxial growth of QCL/QCDs on the same wafer without the need for any expensive wafer/chip bonding process.

Absorption spectroscopy is a promising candidate in trace-gas sensing applications where optical radiation directly interacts with the targeted gas analyte. The Beer-Lambert law is fundamental for absorption-based spectroscopy techniques. As stated by this law, the transmitted intensity I can be represented mathematically as given below [9]:

$$I = I_0 \exp(-\gamma \alpha L) \tag{1}$$

where I_0 and L represent the incident intensity and interaction length respectively, α and γ are the absorption coefficient of the medium, and the medium-specific absorption factor which is based on dispersion enhanced light-matter interaction. In typical free-space optics, the typical value of γ is unity thus to get a highly sensitive measurement at ppm or ppb concentration level, interaction length must be large enough. However numerous schemes based on complex setup have been shown for enhancing absorption path lengths, Moreover, current state-of-the-art still struggles to accommodate such large-area devices for on-chip application.

In this work, we propose a slow light-assisted engineered photonic waveguide on InGaAs/InP QCL/QCD platform suited for trace-gas sensing application in the Mid-IR regime. The proposed waveguide is designed to support transverse magnetic (TM) mode which directly couple light from the QCL to avoid any additional polarization rotator on the chip. We also introduce a simple and efficient mechanism of thermo-optic tuning of optical group-index using a thermo-electric cooler to make the device operation robust and more reliable to any nano-fabrication error and thermal variations. It further can be used to detect multiple gas analytes that show vibrational-rotational molecular overtone in the tuning range of the device.

1. SLOW LIGHT ASSISTED PHOTONIC STRUCTURE

To address the needs of on-chip spectroscopy for highly sensitive trace-gas detection with improved size, weight, and power (SWaP), slow light-assisted photonic structure on the QCL/QCD platform plays a vital role. Periodic modulation of material refractive index in the engineered optical waveguide like sub-wavelength grating and photonic crystal waveguide results in slows down the light with several folds. For example, a heavy reduction in the physical length of even more than 100 times can be realized to achieve equivalent interaction of light with analyte as compared to free space optics [10]. It can be mathematically explained with the perturbation theory as given below

$$\gamma = f \times \frac{\left(\frac{c}{n}\right)}{v_g}, \quad f = \frac{\int_{analyte}^{3} \epsilon |E|^2 dr}{\int_{total}^{3} \epsilon |E|^2 dr} \tag{2}$$

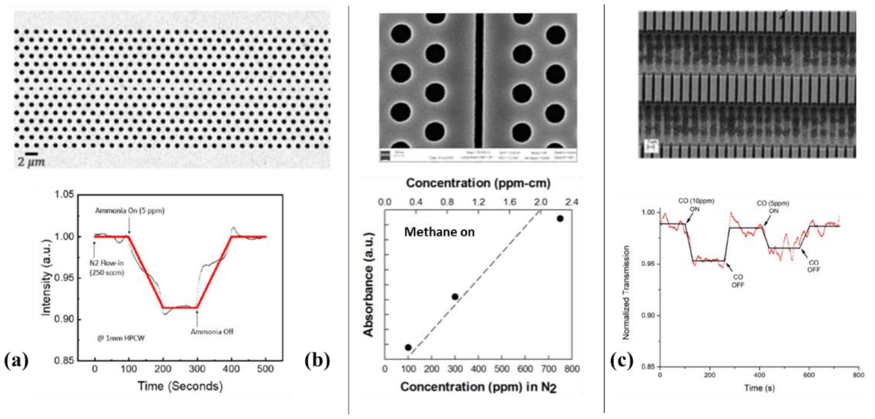

Fig. 1: Previously demonstrated trace gas detection in various material systems, (a) detection of ammonia using suspended InGaAs photonic crystal waveguide, (b) detection of methane at 100 parts per million (ppm) limits in SOI platform and (c) detection of carbon monoxide at 10 and 5 ppm detection limit using emission gratings on InGaAs platform.

where c represents the velocity of light in free space, v_g is the group velocity, n is the medium effective index and f is the filling factor. The current Mid-IR-spectroscopy based on free space bulk optics usually has $f \sim 100\%$ where v_g is the constant value governed by the analytes. It demands a large optical-analyte interaction length ranging from a few mm to several hundred cm (depending upon gas absorption coefficient) which is sometimes unrealistic for on-chip spectroscopy to accommodate such a long length. Fortunately, by taking the advantage of slow-light effect, optical-analyte interaction can be significantly increased even in a shorter length device. Eq. 2 shows that the low value of v_g (or high group index) drastically enhances the absorption thus creating the opportunity to reduce the physical length of the sensing waveguide while maintaining the appropriate interaction of optical signal with the analyte. Based on slow light-assisted structure, we have demonstrated several on-chip gas sensing devices for the detection of methane, carbon monoxide, carbon dioxide, ammonia, and triethyl-phosphate (TEP) [10-13]. Fig. 1 shows some of our previously demonstrated devices with the measured gas sensing characteristics in the various material platform.

2. QCL/QCD COMPATIBLE TM MODE GUIDED WAVEGUIDE

In designing of QCL/QCD monolithic integration on InGaAs/InP platform for sensing applications, some challenges are important to address: The first challenge is the coupling of QCL emitted TM mode to the slow light assisted structure whereas most of such photonic waveguides like PCW is designed to support TE mode. It certainly requires an additional polarization rotator to convert TM mode to TE mode for efficient coupling [14].

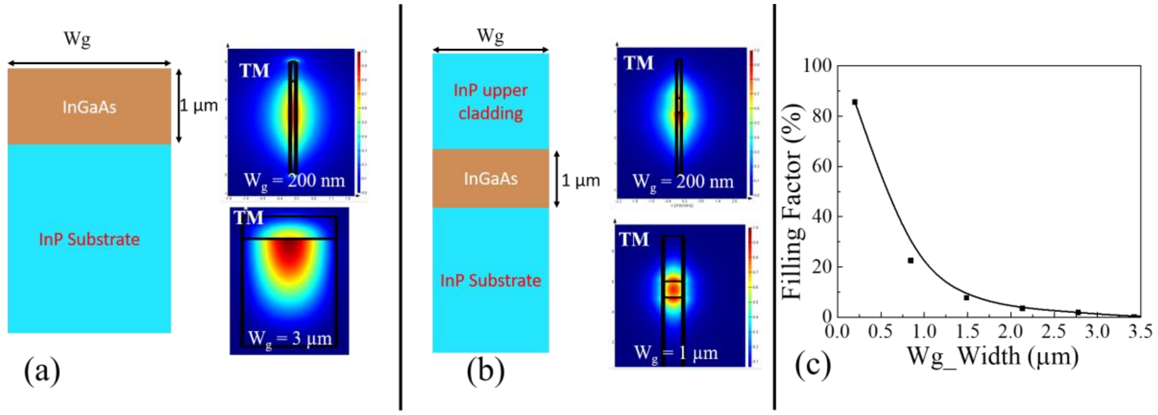

Fig. 2: Analysis of electric field distribution of fundamental mode with variable width combinations in (a) InP-InGaAs with top air cladding and (b) with InP upper cladding, (c) Filling factor as a function of waveguide width in InP-InGaAs waveguide with top InP cladding.

This additional on-chip component does not only take extra space on the chip but also accounts for a further penalty in form of additional insertion loss. To avoid the use of a polarization converter, our group has already proposed TM polarized SWG in InGaAs material using a suspended waveguide structure [12]. However, fabrication of such suspended waveguide structure on low index contrast of InGaAs/InP platform is another challenge.

In this section, we discuss the fundamental mode distribution and related filling factor in two different structures on InGaAs/InP platform as shown in Fig. 2(a) and 2(b). Since there is insufficient index contrast between the InGaAs and InP to accommodate the fundamental TM mode in the high index InGaAs region with a high confinement factor. It causes leaky confinement nature of the optical mode in a region of the most available effective refractive index in the waveguide. In Fig. 2(a), the top and bottom mode profiles show the mode confinement in the InP substrate due to low index contrast and insufficient width of the InGaAs to retain the required optical mode in the InGaAs region. By tailoring the width of the waveguide, optical mode confinement can be easily tuned. Such mode profile can offer good overlap between light with analyte medium for sensing application but from a monolithic integration perspective, it certainly creates some issues, where the main issue is collecting optical signals at the QCD. It is because, QCD can only detect the optical signal when light is confined in the waveguiding region (InGaAs in this case), not in the substrate.

The issue of mode leakage in the substrate region can be solved by placing upper cladding on top of the InGaAs waveguide as shown in Fig. 2(b). The top and bottom mode profiles show the mode is now residing in the high index InGaAs region whereas its confinement factor mainly relies on the width of the waveguide. Fig. 2(c) shows the dependency of optical mode confinement to the width of the waveguide. It should be noted that there is always a tradeoff between optical mode confinement, optical loss, and group index value which should be known for the best optimizing device design for sensing applications.

3. THERMO-OPTICALLY TUNABLE GROUP INDEX IN PERIODICALLY ARRANGED PHOTONIC WAVEGUIDE

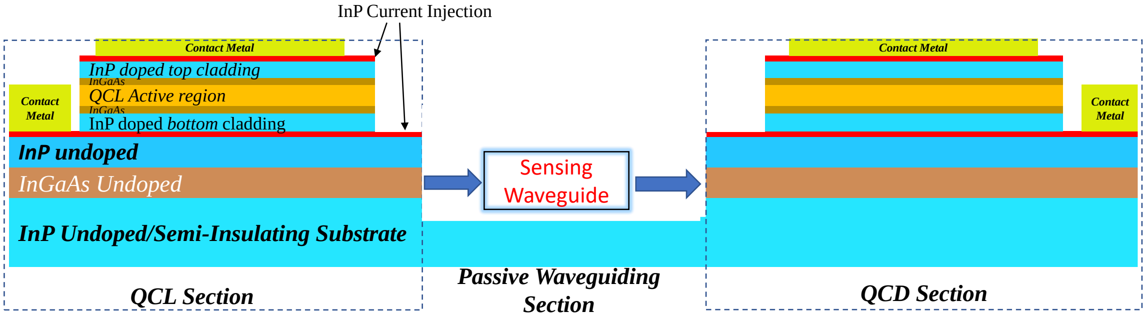

Fig: 3: Schematic of the monolithically integrated device structure including QCL/QCD and sensing waveguide in a epitaxial heterostructure on InP substrate.

Slow light-assisted photonic structure plays a key role in absorption-based spectroscopy. To obtain the slow-light effect on the QCL/QCD platform, the waveguide proposed in Fig. 2(b) can be periodically arranged such that a higher group index for a certain band of wavelengths can be obtained. The proposed does not only support the fundamental TM mode directly coming out of QCL but also slows down the light to have better interaction of the optical signal with the analyte in a compact device area. Figure 3 illustrates the epitaxial heterostructure of the proposed lab on-chip gas sensor where light from the QCL active region will be first sent down to underlying undoped InGaAs waveguide using a multi-level taper structure as reported in our previous research [15]. The optical propagation in the undoped InGaAs waveguide region is beneficial for low propagation loss characteristics so that maximum optical intensity at the detector can be achieved to ensure better sensitivity. The analysis of the slow light effect can be done using calculation of group index (n_g) which principally reveals the slowdown factor of light to the speed of light in the air using the following equation given below:

$$\tau_g = \frac{1}{v_g} = \frac{d\beta}{d\omega} = \frac{1}{c}\frac{d\beta}{dk}, \qquad n_g = \frac{c}{v_g} \tag{3}$$

where τ_g is the group delay, β is the phase propagation constant, k, and c represent wavevector and speed of light, respectively. In our previous research, we have demonstrated a suspended InGaAs SWG waveguide on InP substrate that has propagation loss of 4.1 dB/cm for TM mode with an optical group index of 15 [12]. As we know larger n_g will result in enhanced light-material interaction but higher propagation loss as the light stays more in the periodic photonic structure. However, in practice it is observed that resonance peak is highly sensitive to many external influences including pressure, temperature, strain, fabrication error, bending, and material refractive index (RI). To counter these unwanted shifts in the resonance peak, we propose thermo-optic tuning of group index in periodic photonic structure which makes our device robust to any external fluctuations thus reliable sensing operations can be achieved. It can be simply done by placing a thermoelectric cooler (TEC) beneath the sensing waveguide structure that can recompensate undesired peak shifts. The calculation of the optical group index and its thermo-optic tuning is shown in Fig. 4. It can be seen that a high group index of ≈100 with a 1nm wide resonance peak is obtained near λ = 4.25μm in a shorter device length of only 100μm. With the application of proposed thermo-optic tuning, we find that the resonance peak is nearly a linear function of thermal variations in the given temperature range of 290K to 330K with the capability of fine resonance tuning of ≈ 0.125 nm/K as shown in the inset of Fig. 4. The obtained values of the group index are important for the realization of the carbon dioxide (CO_2) sensor as its absorption peak(s) centered around this wavelength range. Moreover, to obtain a slow-light effect to some other wavelength, the group index can be further tuned simply by optimizing the grating parameters.

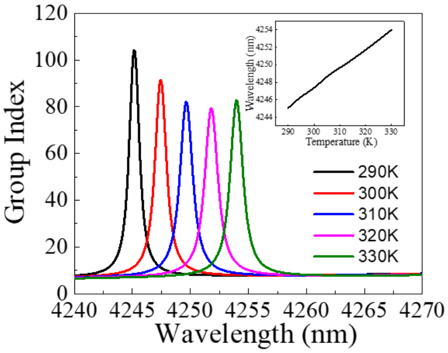

Fig. 4: Group Index as a function of wavelength for varying temperature from 290K-330K. Inset shows the trace of peak resonance wavelength as a function of temperature.

4. CONCLUSION

In conclusion, we proposed a slow-light assisted and wavelength-tunable periodic photonic structure on QCL/QCD platform. The proposed structure is simple to fabricate and showed the great capability to couple TM polarized mode directly emitting from QCLs thus eliminating any use of additional on-chip polarization rotator. We also calculated the slow-light effect in that structure with the capability of proposed thermo-optic tuning that enables the device robust to any nano-fabrication error and uncontrolled environmental variations of temperature, and mechanical stress. The proposed integration of all spectroscopic components on a single chip is an ideal candidate for portable sensing applications.

REFERENCES

[1] Tan, X., Zhang, H., Li, J., Wan, H., Guo, Q., Zhu, H., Liu, H., and Yi, F., “Non-dispersive infrared multi-gas sensing via nanoantenna integrated narrowband detectors,” Nature communications 11(1), 1–9 (2020).

[2] Jain, S., Srivastava, S., Rajput, S., Singh, L., Tiwari, P., Srivastava, A. K., and Kumar, M., “Thermally stable optical filtering using silicon-based comb-like asymmetric grating for sensing applications,” IEEE Sensors Journal 20(7), 3529–3535 (2019).

[3] Picqu´e, N. and H¨ansch, T. W., "Mid-ir spectroscopic sensing," Optics and Photonics News 30(6), 26–33 (2019).

[4] Lochbaum, A., Fedoryshyn, Y., Dorodnyy, A., Koch, U., Hafner, C., and Leuthold, J., "On-chip narrowband thermal emitter for mid-ir optical gas sensing," ACS photonics 4(6), 1371–1380 (2017).

[5] Yao, Y., Hoffman, A. J., and Gmachl, C. F., "Mid-infrared quantum cascade lasers," Nature Photonics 6(7), 432–439 (2012).

[6] Zou, Y., Chakravarty, S., Chung, C.-J., Xu, X., and Chen, R. T., "Mid-infrared silicon photonic waveguides and devices," Photonics Research 6(4), 254–276 (2018).

[7] Lin, H., Luo, Z., Gu, T., Kimerling, L. C., Wada, K., Agarwal, A., and Hu, J., "Mid-infrared integrated photonics on silicon: a perspective," Nanophotonics 7(2), 393–420 (2018).

[8] Chakravarty, S., Midkiff, J., Yoo, K., Rostamian, A., and Chen, R. T., "Monolithic integration of quantum cascade laser, quantum cascade detector, and subwavelength waveguides for mid-infrared integrated gas sensing," in [Quantum Sensing and Nano Electronics and Photonics XVI], 10926, 109261V, International Society for Optics and Photonics (2019).

[9] Mortensen, N. A. and Xiao, S., "Slow-light enhancement of beer-lambert-bouguer absorption," Applied Physics Letters 90(14), 141108 (2007).

[10] Lai, W.-C., Chakravarty, S., Wang, X., Lin, C., and Chen, R. T., "On-chip methane sensing by Near-IR absorption signatures in a photonic crystal slot waveguide," Optics letters 36(6), 984–986 (2011).

[11] Rostamian, A., Midkiff, J., Yoo, K. M., Dalir, H., and Chen, R. T., "Parts-per-million level detection of carbon monoxide using grating array waveguides in InP/InGaAs at [lambda]= 4.6 μm," in [Quantum Sensing and Nano Electronics and Photonics XVII], 11288, 112882G, International Society for Optics and Photonics (2020).

[12] Yoo, K. M., Midkiff, J., Rostamian, A., Chung, C.-j., Dalir, H., and Chen, R. T., "InGaAs membrane waveguide: a promising platform for monolithic integrated mid-infrared optical gas sensor," ACS sensors 5(3), 861–869 (2020).

[13] Chakravarty, S., Midkiff, J., Yoo, K., Rostamian, A., and Chen, R. T., "Monolithic integration of quantum cascade laser, quantum cascade detector, and subwavelength waveguides for mid-infrared integrated gas sensing," in [Quantum Sensing and Nano Electronics and Photonics XVI], 10926, 109261V, International Society for Optics and Photonics (2019).

[14] Chung, C.-J., Midkiff, J., Yoo, K. M., Rostamian, A., Guo, J., Chen, R. T., and Chakravarty, S., "InP-based polarization rotator-splitter for mid-infrared photonic integration circuits," AIP Advances 9(1), 015303 (2019).

[15] Chakravarty, S., Midkiff, J., Rostamian, A., Guo, J., and Chen, R. T., "Monolithic integration of quantum cascade laser, quantum cascade detector and slotted photonic crystal waveguide for absorbance sensing from λ= 3-15 μm," in [2018 Conference on Lasers and Electro-Optics (CLEO)], 1–2, IEEE (2018).