Wavelength Tunable Group delay in InGaAs Subwavelength Grating Waveguide for Mid-Infrared Absorption Spectroscopy

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Abstract: An engineered structure based on InGaAs-InP subwavelength grating waveguide is proposed on QCL/QCD platform for sensing application. The proposed structure attribute slow light effect with fine group index tuning capability of 0.48nm/K using thermo-optic effect.

1. Introduction

A wide variety of optical sensing platforms, including fourier transform infrared spectroscopy (FTIR) [1], tunable diode laser absorption spectroscopy (TDLAS) [2], cavity ring-down spectroscopy (CRDS) [3], and many others [4-5] have been demonstrated for trace gas detections. In particular, fundamental vibrational-rotational transitions in the mid-infrared (Mid-IR) region are 10-1000 times stronger than in the near-IR region [6]. Due to this strong molecular absorptive nature in this regime, extremely high sensitivity of parts per billion (ppb) or even sometimes in parts per trillion (ppt) are achievable. However, all the mentioned spectroscopic techniques rely on a bulky and costly experimental setup, which is also highly sensitive to any environmental perturbations due to the need for very precise experimental alignment and thus inappropriate for many in-situ sensing measurements, especially in remote areas where human intervention is not feasible. It raises the need for a portable sensing system that can be easily mounted on a mobile platform like a UAV (unmanned aerial vehicle) and can perform highly sensitive measurements.

Ideally, sensors capable of high sensitivity and specificity are also desired to be compact, easily portable, as well as less affected by any unwanted disturbances like physical stress, thermal variations, and vibrations. The on-chip integration of light sources and photodetectors with an optically transparent sensing waveguide on a monolithic platform is essential to achieve such a portable biochemical sensing system that is highly robust to vibrations and free from any sensitive alignment. Most essentially, In0.53Ga0.47As/InP is the best combination available to date that allows epitaxial growth of quantum cascade lasers/detector (QCL/QCD) on a monolithic platform thus, no expensive wafer/chip bonding process is required. The lattice constant of In0.53Ga0.47As matches well with InP materials and exhibits optically transparent characteristics for a broad spectrum range in $\lambda \approx 3-15\mu m$. It opens up the opportunity to implement monolithically integrated absorption spectroscopy on-the chip without using any sophisticated alignment and heavy equipment like an optical spectrum analyzer.

The absorption spectroscopy principle relies on Beer-Lambert law [7]. It states that the optical intensity in the medium decays exponentially as a function of the absorption coefficient of that medium (α), medium-specific absorption factor (γ), and interaction length of optical signal with medium (L) as given by $I=I0\exp(-\gamma\alpha L)$. In general, to achieve a sensitivity of trace gas measurement in sub-ppm or sub-ppb level, L can vary from a few millimeters to hundreds of centimeters. Such long interaction length is challenging to accommodate on the chip. With the benefit of engineered photonic structures like subwavelength grating and photonic crystal waveguides, a low value of group velocity can be obtained for a band of wavelengths to realize the enhancement in the interaction of optical signal with the analyte in a shorter device length. This is promising for reducing physical length; 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 compared to free space optics [8].

In this work, we propose the unique design of the novel gas sensor using monolithic integration of the engineered slow light-assisted photonic waveguide on a QCL/QCD platform in the Mid-IR regime. Since a typical QCL offers to gain only in transverse magnetic (TM) mode. Considering that fact, the waveguide proposed herewith is designed directly to couple TM mode emitting from the laser, thus eliminating the use of any additional polarization converter. Furthermore, a novel mechanism of thermo-optic tuning of group-index is theoretically proposed that makes the device more reliable and robust to any fabrication error and thermal variations. It can also be utilized to scan a range of wavelengths for multiple detections of those trace gas species whose absorption overtone lies in the tuning range.

2. Sensor design and thermo-optically tunable group index

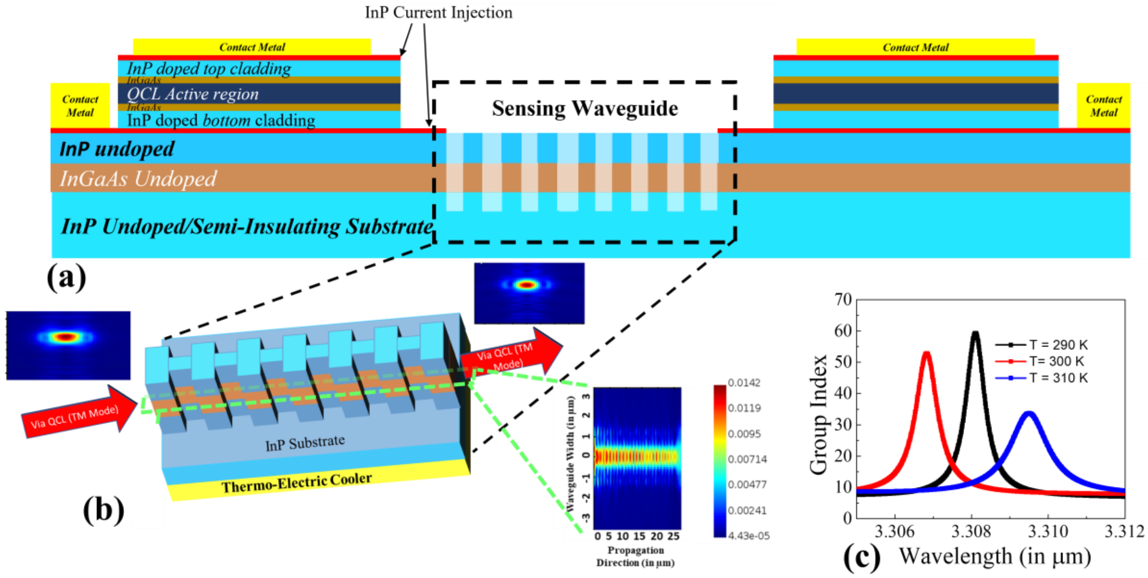

Fig.1 (a) Schematic of the device structure with QCL and QCD and SWG $In_{0.53}Ga_{0.47}As$ waveguides in a monolithically epitaxial heterostructure on InP substrate. (b) 3D view of proposed SWG where inset in green box shows optical propagation in direction of periodicity, thermo-electric cooler is placed beneath the sensing waveguide to enable thermally induced index puturbation . (c) Group Index as a function of wavelength for varying temperature from 290K-310K.

Fig. 1(a) illustrates monolithic integration of QCL, sensing waveguide, and detector on an InGaAs/InP epitaxial heterostructure. The undoped InGaAs waveguiding layer offers low propagation loss characteristics necessary to provide maximum optical intensity at the QCD thus better sensitivity can be achieved. The 3D schematic of the proposed waveguide is shown in Fig. 1(b) with electric field distribution of optical TM mode profile at input and output end of the sensing waveguide at λ = 3.3µm. Unlike the high contrast SOI platform, InGaAs/InP doesn't have sufficient index contrast and for this reason placement of upper cladding of InP plays a crucial role in confining optical mode into InGaAs waveguide. Previously, we have been demonstrated that the SWG waveguide could have a propagation loss as low as 4.1 dB/cm for TM mode in the InP-InGaAs platform with a group index of 15 [9]. However, the propagation loss for a subwavelength waveguide with larger n_g remains undetermined. The calculation of the optical group index and its thermo-optic tuning is shown in Fig. 1(c). It can be seen that a high group index is obtained near λ=3.3µm in a shorter device length of only 80µm. With the application of proposed thermo-optic tuning, redshift in the resonance peak is observed for the given temperature range of 290K to 310K which shows the capability of fine resonance tuning of 0.48 nm/K. With the benefit of the proposed thermo-optic tuning mechanism, device performance can be made robust to any uncontrolled variations like thermal fluctuations and nano-fabrication error that bring shift the resonance peak and it can be recentered to its original value.

3. References

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