Mid-IR Thermo-Optic On-Chip Spectrometer on a III-V Semiconductor Platform

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***Abstract*- GaAs on InGaP is a very promising waveguide platform for the Mid-IR wavelength region due to its wideband transmission and low optical loss. We exploit this platform for the demonstration of a Mid-IR thermo-optic spectrometer. The device modelling results showed a temperature response time of a few seconds for a maximum power consumption of about 26 mW, for the required heater temperature rise needed to achieve a spectral resolution of 10 cm^{-1}.**

I. INTRODUCTION

Mid-Infrared (MIR) spectroscopy is a powerful bio-chemical analysis technique that can provide a wealth of qualitative and quantitative information about the sample studied. It finds application in many different fields such as production monitoring, materials science, biotechnology and medicine [1]. The MIR spectral region (2 - 20 µm) is of great interest due to the existence of the fingerprint absorptions of most biochemical molecules in this region. This intrinsic molecular selectivity can be exploited to realise a label free detection platform employing a spectrometer. An ultra-portable, cost effective and mass-manufacturable MIR spectrometer device has yet to be commercialised. With the immense advances in electronics and optoelectronics, the study of such devices became more intense recently, resulting in several designs [2, 3]. Most of the proposed designs were based on MEMS, offering high spectral resolution with a small device footprint. However, these devices suffered from many issues such as mechanical tilting and limitations introduced by the Talbot effect and thus have not been commercialised.

An alternative method suggested recently employs waveguide based tuneable interferometers exploiting either the electro-optic effect (EOE) or the thermo-optic effect (TOE) [3, 4]. Souza et al. [3] have presented a very promising miniature MIR thermo-optic device based on Silicon on Insulator (SOI) technology, which offers respectable resolution while still having small footprint. However, SOI suffers from intrinsic Si and SiO_2 absorption in the mid-IR. Other platforms based on $LiNbO_3$ utilising the EOE have also been demonstrated, however, such devices still suffer from MIR absorption beyond a wavelength of 5 µm.

In this work, we have studied the performance of III-V semiconductors (GaAs/InGaP); firstly as a waveguiding platform for operation in the MIR and secondly as thermo-optically active materials in a tunable interferometer. It has been shown that GaAs offers low propagation losses (less than 0.5 dB/cm) [5] with a transmission window spanning from 900 nm to 16 µm. The fabrication of GaAs based devices is well established using standardised microfabrication techniques. GaAs has been implemented in many tuneable integrated devices such as electro-optic modulators and thermo-optic switches [4], and therefore, lends itself to tunable MIR operation.

In this paper, we present the proposed design of a MIR spectrometer on chip based on a GaAs on InGaP platform, employing a tunable integrated Mach-Zehnder Interferometer (MZI) with metallic heaters. We also present and discuss the optical and thermal device modelling results of the proposed FTIR spectrometer on chip. To the best of our knowledge, this is the first proposal of a spectrometer on chip exploiting the TOE on a III-V semiconductor platform.

II. THEORY

The thermo-optic effect is an intrinsic physical property of a material when its temperature is altered, described as the refractive index change per degree K i.e. dn/dT (K^{-1}). While the electro-optic coefficients (EOC) of GaAs and InGaP are poor, their thermo-optic coefficients (TOC) are around 2×10^{-4} K^{-1} in the NIR-MIR, similar to that of Si. An important performance parameter of a spectrometer platform is its spectral resolution. The maximum Optical Path-length Difference (OPD) created by the change in the refractive index on one arm is proportional to the spectrometer resolution. As can be seen in Eq. (1), in order to increase the resolution, for a fixed available index change, the active length of the interferometer arm needs to be increased. That can be achieved, without significantly increasing the device footprint, by introducing waveguide spirals as shown in Fig.1 (b). The temperature rise needed for the required OPD/resolution is estimated using Eq. (2).

$$OPD = L\Delta n \tag{1}$$

$$\Delta T_{\pi} = \left(\frac{dn}{dT}\right)^{-1} \frac{\lambda}{2L} \tag{2}$$

III. DEVICE LAYOUT

Fig.1(a) shows the layer structure of the waveguide platform. The GaAs core layer is lattice-matched to the $In_{0.49}Ga_{0.51}P$ cladding layers. In other work [4] $Al_xGa_{1-x}As$ was used as a cladding for GaAs core, however, it has been shown that $In_{0.49}Ga_{0.51}P$ is superior as it offers many features such as low propagation velocity of dislocations, strong etch selectivity and unlike $Al_xGa_{1-x}As$, it does not incur oxidation during the deposition thus the resulting films are of better quality.

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$In_{0.49}Ga_{0.51}P$ also offers a wide transmission window extending from λ≈650 nm to λ≈24 µm. The metallic heater material was chosen to be Nickel (Ni) for fabrication convenience. The proof of principle device has been designed to operate between λ=3 µm and 4 µm, and the design specifications (requirements) are summarised in Table 1.

IV. MODELLING RESULTS AND DISCUSSION

In an FTIR interferometric spectrometer, the power spectrum is retrieved from the observed output interferogram. For correct and clear interpretation of the interference patterns created during thermal tuning, single-mode light propagation is essential. A multi-mode waveguide platform would produce unwanted beating between the available modes and would lead to a distorted interferogram. The optical device modelling was performed using Lumerical's Finite Difference Eigenmode (FDE) solver. The first optical modelling task was to optimise the waveguide dimensions such that only one mode is supported at λ=3 µm. This ensured single mode operation throughout the spectral region of interest (currently 3-4 µm). Next, the losses experienced by the mode were estimated. Two major sources of loss in our platform were the heater/substrate absorption and the bend loss introduced by the small radius bends within the spiral arms. For the proof of principle device, the MZI splitter and combiner were designed in such way that they have negligible loss at the cost of wafer space, thus there was no optimisation modelling step for these components at this stage. The heater/substrate loss and the bend loss were estimated to be ~0.05dB/cm and ~0.07dB/bend (200 µm radius), respectively.

TABLE 1

Specifications and critical parameters of the spectrometer

Desired Spectral Resolution	10 cm^{-1}
OPD required	1 mm
MZI arm active length	60 mm
ΔT required for π-shift (ΔTπ)	0.167 K (λ=4 µm)
Total ΔT required ~ 500π-shifts (10cm^{-1} resolution)	83.33 K

The heat transport was modelled using Lumerical's HEAT solver and COMSOL, whereas the thermo-optic performance of the device was evaluated using the Lumerical's FDE method. The value of total temperature rise at the waveguide centre needed to produce the required OPD is numerically found to be about 2 K less than the analytically calculated value seen on Table 1. This is because the analytical calculation does not consider the varying temperature gradient (temperature dependent thermal properties) as in the case of numerical modelling (Fig. 1(c). From Fig.1 (d), we deduce the power required for a π-shift to be ~52 µW for our design. Hence the total power needed is ~26 mW with a temperature response time of a few seconds. These values were estimated using a convective air vertically bounded model. The device can be tailored to attain the required waveguide core temperature at much higher speeds (of the order of few hundred microseconds) at the cost of higher power consumption.

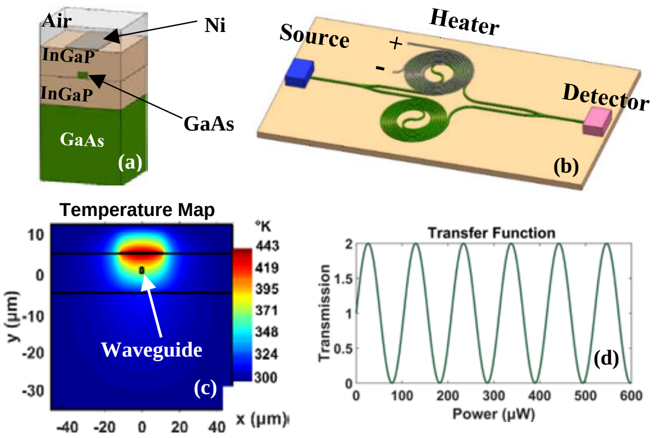

Fig.1 (a) Layer Structure, (b) MZI design layout, (c) Temperature map, (d) MZI thermo-optic transfer function (λ=4 µm)

V. CONCLUSION

A thermo-optically tunable on-chip spectrometer based on GaAs/InGaP has been designed and the optical and thermo-optic behaviours were studied by numerical modelling. The modelling results have shown that the proposed device design combined with excellent physical properties of the materials, can provide a platform for very efficient thermal tuning, achieving a resolution of 10 cm^{-1} at the cost of about 26 mW of power with a small device footprint. Due to the adequately fast temperature response, the total power consumption per scan is expected to be extremely low, thus making the device practically viable and portable. Fabrication of the proposed device is underway.

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