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# Broadband mid-IR on-chip Fourier-transform Spectrometer

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**Abstract** — We present a new FTS approach that harnesses both spatial heterodyning and thermo-optical path tuning to overcome the resolution-bandwidth tradeoff in conventional counterparts. We experimentally demonstrate a mid-infrared SiGe FTS, with a resolution exceeding  $15 \text{ cm}^{-1}$  in a wide bandwidth of  $603 \text{ cm}^{-1}$ .

**Keywords** — Silicon photonics, Spectroscopy, mid-infrared

## I. INTRODUCTION

The mid-IR spectral range, and more specifically the wavelength region between 5 and 20  $\mu\text{m}$ , aroused a great interest in the Photonic Integration Circuit (PIC) community due to its great potential in spectroscopy and sensing [1, 2]. That is the reason why the development of photonic platforms dedicated to long MIR wavelengths has recently witnessed a burst of research activity [3]. Germanium-rich silicon-germanium (Ge-rich SiGe) has emerged as a promising integrated platform exhibiting a wide transparency range [4]. A linearly graded SiGe layer allows a smooth transition between pure silicon and Ge-rich material that minimizes the threading dislocation density due to lattice mismatch, while confining the optical mode in the upper part of the waveguide by refractive index gradient. The recent experimental demonstration of a MIR spectrometer in this platform [5] provides a promising departing point to develop new deep MIR spectroscopic systems. All these compelling features make the Ge-rich SiGe an excellent platform for developing mid-IR spectroscopy PICs.

In the last years, a myriad of integrated spectroscopic systems has been demonstrated [6-8]. Among them, on-chip Fourier-transform spectrometers (FTS) implement simple yet effective calibration algorithms that compensate phase and amplitude impairments, thereby providing a superior robustness against fabrication imperfections compared to dispersive counterparts. Within FTS, on-chip Spatial Heterodyne Spectroscopy (SHS) approach is based on an array of interferometers with linearly increasing optical path delay to achieve a remarkably resolution without any moving part. However, its operational bandwidth is limited by the minimum optical path difference between consecutive interferometers. The thermo-optic effect has also been used to scan the optical path delay of a single interferometer [9], but the resolution of these devices is limited by the maximum achievable optical delay.

In this work we propose and experimentally demonstrate a new FTS approach that gathers the advantages of spatial heterodyning and optical path tuning by thermo-optic effect to overcome the bandwidth-resolution tradeoff in conventional counterparts. This device is fabricated in a graded-index SiGe platform which has been demonstrated to have low propagation losses up to 8.5  $\mu\text{m}$  wavelength [4].

## II. WORKING PRINCIPLE AND EXAMPLE

The operation principle of integrated spatial heterodyne Fourier-transform spectrometers (SHFTS) has been previously reported in [10]. We propose here to achieve a broadband and high-resolution mid-IR spectrometer, by generating different path delays by both arm length difference and thermal scan sampling. For this purpose, the mathematical model of the MZI array is generalized to thermally-tuned MZI array. Then, the resolution and Free Spectral Range (FSR) of the thermally-tuned SHFTS are given by:

$$\delta\sigma = \frac{1}{\gamma_{max}} = \frac{1}{\Delta L_{max} n_{g+LH} \Delta n_{g,Tmax}} \quad (1)$$

$$FSR = \frac{1}{\Delta L_{max} n_{g+LH} \Delta n_{g,Tmax}} \frac{N_T N_L}{2} \quad (2)$$

where  $\gamma_{max}$  is the optical path delay difference,  $\Delta n_{g,Tmax}$  is the maximum group index change due to thermal difference,  $N_T$  is the different number of applied temperatures and  $N_L$  is the number of MZIs in the array.

To demonstrate the benefits and viability of the thermally-tuned FTS, we consider an array of 10 MZIs (9 unbalanced and 1 balanced MZI), with a path difference increase ( $\Delta L_{step}$ ) of 18.8  $\mu\text{m}$  between them. A 3 mm-long heater is located in the shortest arm of each MZI, too. As the optical mode is confined in Ge-rich SiGe materials, the thermo-optic coefficient of Ge is used and is also considered constant within the operational wavelength range with a value of  $4.1 \times 10^{-4} \text{ K}^{-1}$  [11].

In Fig. 1 is shown the simulated retrieval process of a monochromatic input (black arrow) in a  $551 \text{ cm}^{-1}$  bandwidth for different cases. The retrieved spectrum shown in Fig. 1(a) illustrate the classical SHS-based FTS without any thermal tuning. In Fig. 1(b) and 1(c) the thermal tuning is implemented using a uniform sampling of the optical path delay for 4 and 9 different applied temperatures, with a maximum thermal

increase of 54 K. In this figure is clearly seen the FSR enhancement when increasing the number of applied temperatures, and then reducing the minimum path delay difference between samples, without affecting the resolution performance.

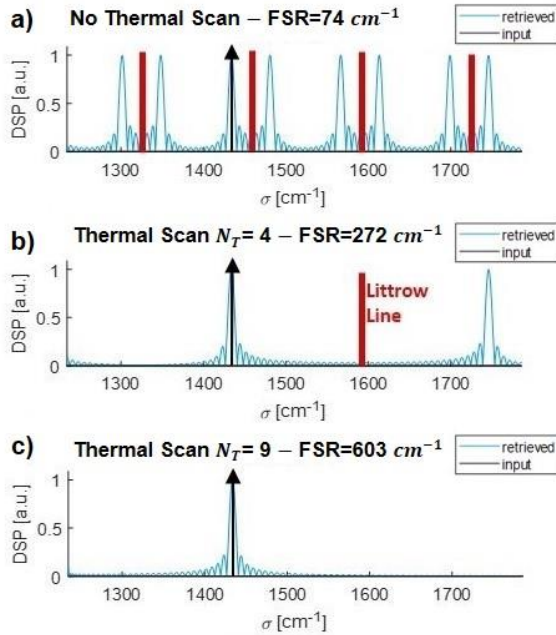


Fig. 1. Retrieval process of a monochromatic input centered at  $1434 \text{ cm}^{-1}$  for different cases. (a) Non thermal tuning. (b) 4 different applied temperatures with linear path delay sampling. (c) 9 different applied temperatures with linear path delay sampling. Littrow lines are reported in red.

### III. EXPERIMENTAL DEMONSTRATION

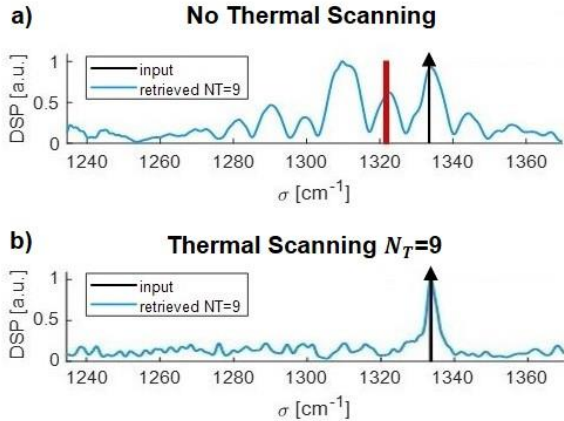


Fig. 2. Experimental retrieval process in a wavelength range from 7.3 to 8.1  $\mu\text{m}$ . (a) Retrieved spectrum with non-thermal tuning. (b) Retrieved spectrum with  $N_T = 9$  and a maximum applied temperature increase of 54 K.

The thermally-tuned FTS has been evaluated experimentally using a 10 MZI array with an  $\Delta L_{step}$  of 18.8  $\mu\text{m}$ . The theoretical resolution and FSR of such array without any thermal-tuning are  $14.6 \text{ cm}^{-1}$  and  $74 \text{ cm}^{-1}$  respectively. Heaters have been added in the shortest arm of each MZI. A maximum temperature variation of 3 K has been applied on each MZI, which is much smaller than  $\Delta T_{max} = 54 \text{ K}$  to have a uniform sampling of the optical path delay. Interestingly, the thermally-tuned FTS is also

working in this case, where the gamma sampling is not uniform. Indeed, we can see in Fig. 2(a) that a FSR of  $74 \text{ cm}^{-1}$  is not enough to properly retrieve the input a monochromatic signal in a  $132 \text{ cm}^{-1}$  bandwidth range. In comparison, the use of the thermal tuning allows to increase the FSR up to  $603 \text{ cm}^{-1}$ , which is much larger than the measurement window and thus a good signal retrieval is obtained.

### IV. CONCLUSION

This work shows that it is possible to harness the thermo-optic effect to enhance the performance of on-chip FTS. This effect can be used to increase the FTS performance, to reduce the number of MZI in the array to achieve given specifications, thus reducing the device footprint, or even both at the same time. These results provide to the best of our knowledge, the first experimental demonstration of on-chip MIR Ge-based FTS exploiting both spatial heterodyning and temperature tuning. On-chip integration of sensing circuits with the FT spectrometer could pave the way for future demonstration of robust, high-resolution, and cost-effective multi-target spectrometers covering an ultrawideband of the fingerprint wavelength range.

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