Development of fundamental buildings blocks needed for high spectral range integrated optics spectrometry: Active phase modulation to increase sampling efficiency in Fourier Transform Spectrometers

Guillermo Martin[a], Salma Baccar[a,b], Noémie Mestre[a,b], Myriam Bonduelle[a,b], Laurent Robert[c], Roland Salut[c], Nadege Courjal[c] and Alain Morand[b]

[a]Univ. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France

[b]Univ. Grenoble Alpes, CNRS, CROMA, 38000 Grenoble, France

[c]FEMTO-ST, Univ. Franche-Comté, 25030 Besançon, France

Further author information: guillermo.martin@univ-grenoble-alpes.fr

ABSTRACT

This paper focuses on the development of an essential building block needed to achieve high spectral etendue in integrated optical spectrometers based on Fourier Transform methods: the active phase modulation of the fringes to sample. The long term objectives of this project are to achieve high-resolution spectrometry in a large spectral range, using compact spectrometers based on the SWIFTS (Standing Wave Fourier Transform Spectrometer) approach. The primary applications in astronomy will be precise measurement of atmospheric compositions of detected exoplanets as well as other celestial bodies, such as the detection and analysis of specific gases like carbon dioxide (CO_2) and methane (CH_4) that are linked to life. The proposed on-chip Fourier transform spectrometer (SWIFTS) approach offers several advantages, including high spectral resolution, compact size, and a robust design. However, the principle of sampling in a simple, passive SWIFTS, implies to extract the signal with the spatial frequency of the detector's pixel pitch. As the pixels' pitch is typically 10 μm, the interferogram is strongly under-sampled, and the resulting spectral range without aliasing is small (typically tens of nm). The work presented in this paper is devoted to increasing the spectral range by temporal multiplexing, achieving on-chip phase modulation thanks to electro-optic properties of Lithium Niobate. By phase shifting the fringes under the sampling centers, we are able to reduce the effective distance between sampled values, therefore increasing the spectral etendue.

After a brief introduction on the SWIFTS principle, we will focus on the electro-optic modulation of the fringes, and show preliminary results that validate the temporal multiplexing approach and discuss further improvements and the range of application of this active phase spectrometer.

1. INTRODUCTION

SWIFTS is the acronym for Stationary Wave Integrated Fourier Transform Spectrometer [1]. In a Lippmann configuration, the spectrometer consists in a Ti:diffused channel waveguide having a mirror at the end of the waveguide, to ensure perfect backward reflection (Lipmann configuration), as shown in Figure 1. The forward propagating beam, coupled in the waveguide, is reflected on the mirror, and interference with the incoming beam results in a standing wave. Sampling this static interferogram, will allow to retrieve the spectrum of the source, by Fourier Transform methods. The principle is to sample the evanescent part of the optical field in the waveguide, using antennas placed at the surface of the waveguide. This scattered light is then detected using conventional optical detectors that are glued to the surface of the waveguides. Ideally, one antenna should illuminate one pixel. However, in the SWIR range, the active detection zone of typical InGaAs detectors is separated by a layer of InP (typ. 300 μm) that the light needs to cross, and that can induce crosstalk. Therefore, the antenna are not simple grooves but consist on a set of grooves acting as a small diffraction grating, to reduce angular divergence, avoid crosstalk and increase the signal-to-noise ratio [2,3].

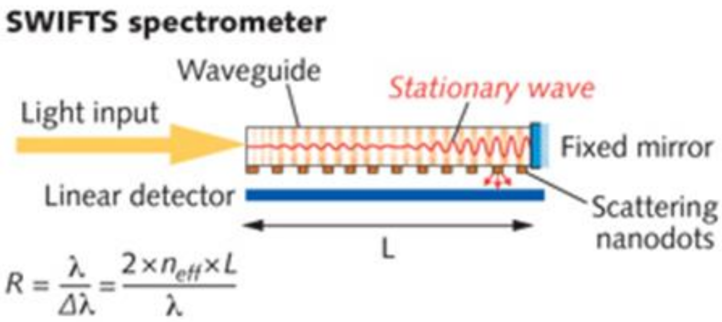


Figure 1. SWIFT Lippmann concept [4]: Light injected in a channel waveguide is reflected at the opposite face. The stationary wave obtained is sampled thanks to nano-scattering centers. The spectrum of the source is recovered after FT of the sampled signal.

In the SWIFTS configuration, the standing wave interferogram has a period of $\lambda/2n_{eff}$, with n_{eff} the refractive index of the fundamental guided mode, which means a sampling period that must be at least (maximum value) $\lambda/4n_{eff}$ to respect Shannon-Nyquist criteria. In the near IR (λ = 1500nm), this means that we should sample placing one antenna (under one pixel) every 175nm which is clearly not achievable using commercial detectors. Therefore, if we adapt to pixel pitch of commercial detectors, the signal will be undersampled.

The objective of present work is to introduce a way to increase the sampling efficiency, reducing effective distance between two sampling centers, using temporal multiplexing [5]. The idea is to use the electro-optic properties of Lithium Niobate to introduce a temporal phase modulation that will shift the fringes under the sampling centers. The device developed in this work consists on a chip fabricated by Ti:diff in Lithium Niobate, with an integrated Mach-Zehnder (MZ) interferometer for electro-optical modulation at a first stage [6], followed by a channel waveguide along which the antennas are fabricated, and a mirror at the end of the waveguide to achieve SWIFTS Lippmann configuration. As the initial design is strictly symmetric, an external MZ is added to achieve large Optical Path Delay (OPD) scans using a translation stage, allowing us to set the center of the coherent wide band fringes under the desired antenna. The active phase modulation will then finely shift the fringes, by application of a voltage modulation ramp. A schematic drawing of the sample is shown in figure 2, and detailed explanation of the working principle is given in Section 3.

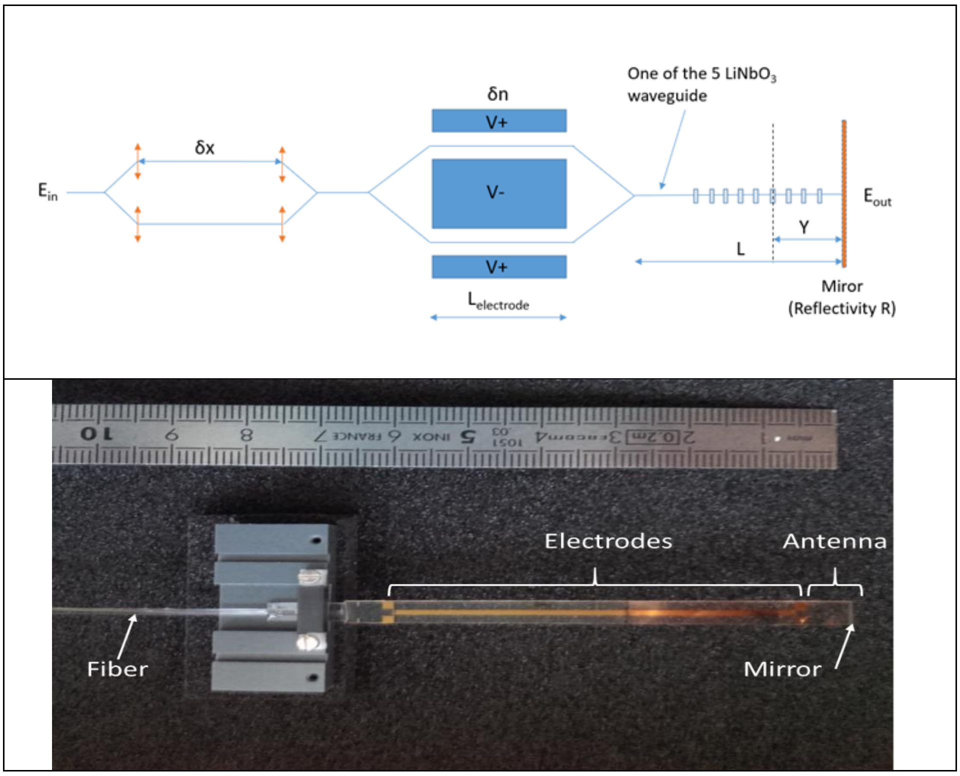


Fig. 2: Top: Scheme of the principle: A MZ modulator followed by a straight waveguide with a mirror at the end, and periodically sampled by the antenna, is the heart of the SWIFTS Lippmann spectrometer. As this first design is perfectly symmetric, an external OPD shift is obtained using a translation stage (δx). Bottom: Image of the sample

2. THEORETICAL BACKGROUND

The system described in figure 2 consists on a Static Lippmann SWIFTS (the single channel waveguide with the antennas and the mirror of reflectivity R at the end); an electro-optic active Mach-Zehnder phase modulator for scanning the fringes (which will allow fast but limited range OPD scan, typically a few tens of micrometers) and an external MZ modulator which will allow for slow but long range (typically mm) OPD scan, using translation stepper motors. The addition of this three stages will be studied in this section, in order to get a detailed view of the working principle. We will focus on the most interesting contribution, that is the relative phase between the optical forward beam passing through the upper part of the interferometer and the optical beam passing through the lower part of the interferometer and that, after reflection at the mirror, interacts with forward beam. The total phase of each path is given by:

Upper path forward propagating beam:

$$\phi_{tot} = \frac{2\pi}{\lambda_0}\delta x + \frac{2\pi}{\lambda_0}\delta n_{eo} + \frac{2\pi}{\lambda_0}n(L - Y) \qquad \text{eq (1)}$$

Lower path backward (after reflection) propagating beam:

$$\phi_{tot} = 0 - \frac{2\pi}{\lambda_0}\delta n_{eo} + \frac{2\pi}{\lambda_0}n(L + Y) \qquad \text{eq. (2)}$$

Where $\delta x = n_{ext}x$ is the external optical phase introduced by the translation stage x and $\delta n_{EO} = -\frac{1}{2}n^3 r_{33}\frac{V_{app}}{d_{elec}}L_{elec}$ is the internal phase introduced by the MZ electro-optic modulator.

The intensity distribution along the waveguide position Y, where Y is the distance to the mirror, is given then by:

$$I_{tot} = 1 + R - 2\sqrt{R}cos\left(\frac{2\pi}{\lambda_0}\left(\delta x + 2\left(-\frac{1}{2}n^3 r_{33}\frac{V_{app}}{d_{elec}}L_{elec}\right) + 2n_{eff}Y\right)\right) \qquad \text{eq. (3)}$$

Assuming R = 1, the intensity distribution is:

$$I_{tot} = 2 - 2cos\left(\frac{2\pi}{\lambda_0}\left(\delta x + 2\left(-\frac{1}{2}n^3 r_{33}\frac{V_{app}}{d_{elec}}L_{elec}\right) + 2n_{eff}Y\right)\right) \qquad \text{eq. (4)}$$

For a monochromatic source, at $\delta x = 0$ and $V_{app} = 0$, the fringes have an infinite coherence length, and contrast is preserved at any distance Y from the mirror. For a polychromatic source, the coherence length is given by $L_{coh}=(\lambda_0)^2/(2\cdot n_{eff}\cdot\Delta\lambda)$. Note that the SWIFTS configuration implies a factor 2 for the reflection and the effective refractive index of the guided mode, n_{eff}, in the calculation of the coherence length.

For a typical polychromatic spectrum to analyze, for example $\Delta\lambda$ = 100nm and λ_0 = 1.5 μm, the coherence length inside the waveguide is only L_{coh} = 5.6 μm. Therefore, using sampling centers that are spaced tens of microns will clearly not be adapted. The EO modulation can be then used to scan the fringes under the sampling centers. This phase shift introduced when $V_{app} \neq 0$ generates a dynamic system of fringes that will be increasingly far from the mirror, as the applied voltage increases. However, this dynamic fringe packet will be covered by the static, classical SWIFTS fringes, that are generated by each optical beam interacting with itself after mirror reflection. Besides, for a single optical beam that passes through the MZ modulator and recombines at the output, we will also obtain a global intensity modulation that will affect all the sampling centers at the same time, as long as the amplitude of the EO phase modulation is below the coherence length of the signal. This means that if we want to observe the dynamic fringes obtained from relative upper/lower path phase difference, and increase the sampling capabilities, we first need to strongly phase shift the center of the polychromatic wide band packet in order to place it far from the mirror, at a given sampling center, and achieve a modulation ramp with enough amplitude to scan the coherence length common to all the sampling centers, and still enough to make the dynamic packet be scanned under the sampling center.

Here appears the interest of the external phase modulation δx: This externally controlled MZ modulator, based on a set of two fibers on collimators, with one of them on a stepper motor, allows to introduce a large value (x = 3mm typically) and place the center of the interferogram given by eq. (4) on a sampling center at $Y_{offset} = x/2n_{eff}$ far from the mirror. Once this step is done, we can activate the phase modulation and scan the fringes. Note that in our case, as the antenna separation is Δz = 160 µm, the expected value to shift the center of the wide band fringes from one antenna to the next, assuming n_{eff} = 2.11 at 1.5 µm is around 700 µm, which corresponds to the experimental value Y_{offset} required to shift the fringe packet from one antenna to the following one.

For electro-optic modulation, we will apply a voltage using a triangular shape function and an offset voltage, in order to scan either centered at 0V, from $-V_{app,max}$ to $+V_{app,max}$, or shifted in order to scan from 0 to $+2V_{app,max}$. The last option will allow to go beyond the coherence length and scan the dynamic fringes over a larger voltage range (therefore phase), although limited to 150V with our current set-up.

3. DEVICE DESIGN AND EXPERIMENTAL SET-UP

The optical chip is 8.4 cm long and 4.5 mm large. Electrodes for the EO MZ modulator are L_{elec} = 5 cm long and have a gap d_{elec} = 8.6 µm. The sampling centers start at 400 µm from the mirror (to avoid edge effects, and be far from the static SWIFTS fringes) and consist on a set of 20 antenna 160 µm spaced, in order to ensure that diffracted signal will not introduce crosstalk. Each antenna consists on a set of 5 grooves, with a period of λ/n_{eff}, in order to obtain coherent interaction of the radiated field, therefore improving the directivity and extraction efficiency of the antenna.

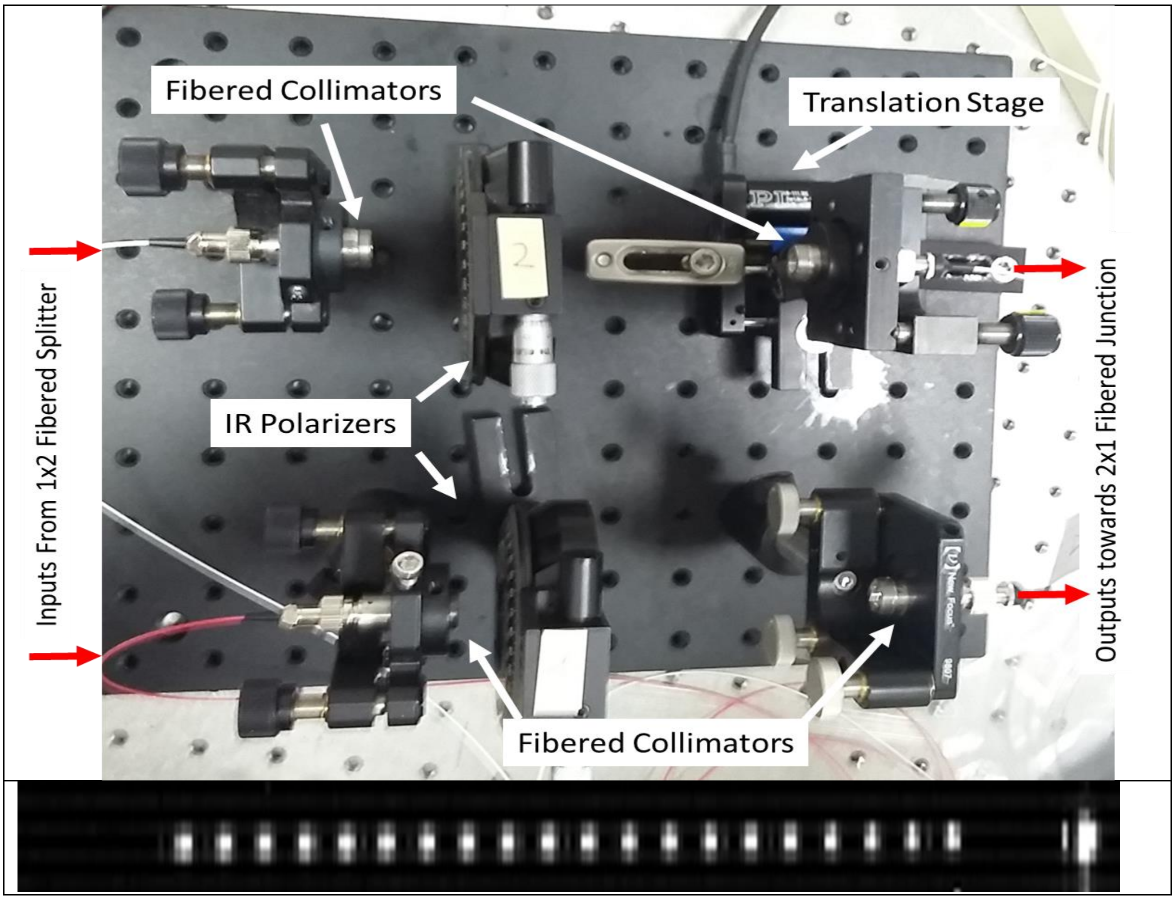


Fig. 3: Top: Detailed Image of the experimental set-up used to introduce the external modulation dx. Bottom: Image of the 20 antennas once illuminated, with the diffracted signal at the mirror edge also visible on the top right.

As shown in figure 3, the light source coming from the source via an optical fiber is split using a 1x2 fiber splitter. At the FC/PC connector, a fiber-collimator is positioned. One of paths is fixed while the other can be varied, using a translation stage. At the end (right part of the figure), the collimated light is again re-injected in a 2x1 reversed fiber-splitter using a second fiber collimator. This external MZ allows for the external relative Optical Path Delay δx. Finally, the recombined signal is injected on the SWIFTS integrated optical chip, giving the intensity distribution shown on the bottom part of fig. 3.

4. RESULTS

4.1 Monochromatic source

In the case of monochromatic light, a first EO modulation scan without any offset allows to get an idea of the fringes. In a pure MZ modulator, the contrast of the fringes will be constant all over the modulation ramp. However, as seen in figure 4, as the voltage increases from 0V, the contrast is reduced, due to the superimposition of the global modulation with the dynamic fringes that are shifted from the mirror. The signal observed in the figures below corresponds to the intensity of the 6th antenna counting from the mirror, as a function of time (i.e. as a function of the voltage applied).

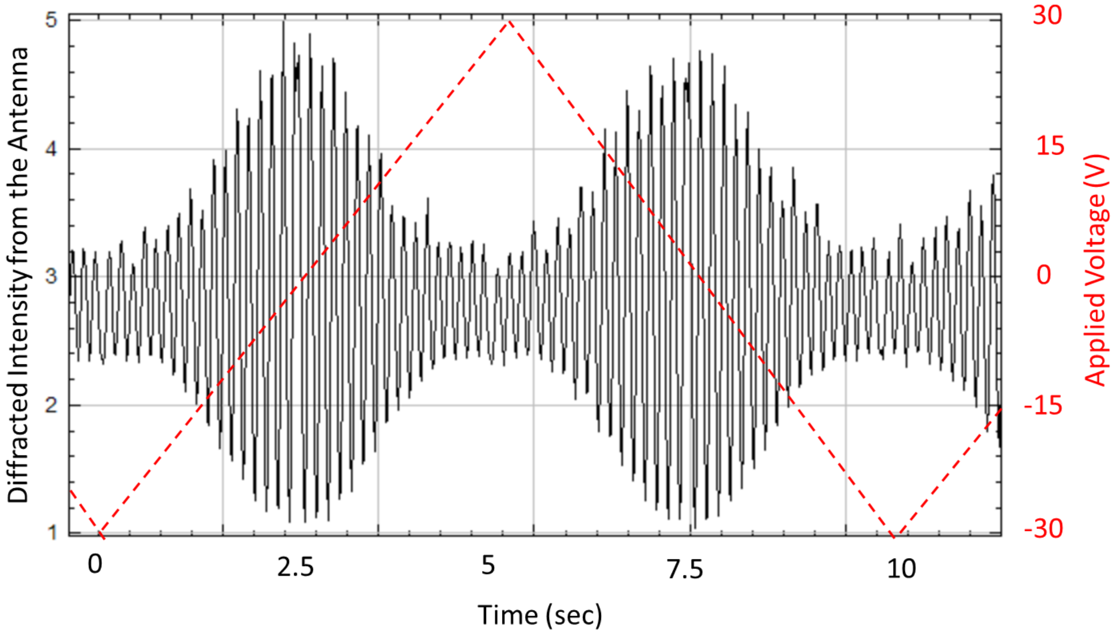


Fig. 4 : Fringes obtained on the 6th antenna, for an applied triangle modulation voltage with an Offset 0V, V_{app}= 60, V_{pp} and T = 10sec (5sec duration of one ramp).

In order to avoid this effect, a DC offset is applied. This will shift the dynamic fringes so far away from the observed antenna, that only the global modulation will be observed. This is due to the non-pure monochromaticity of the source, otherwise fringe overlapping will be observed independent of the DC offset.

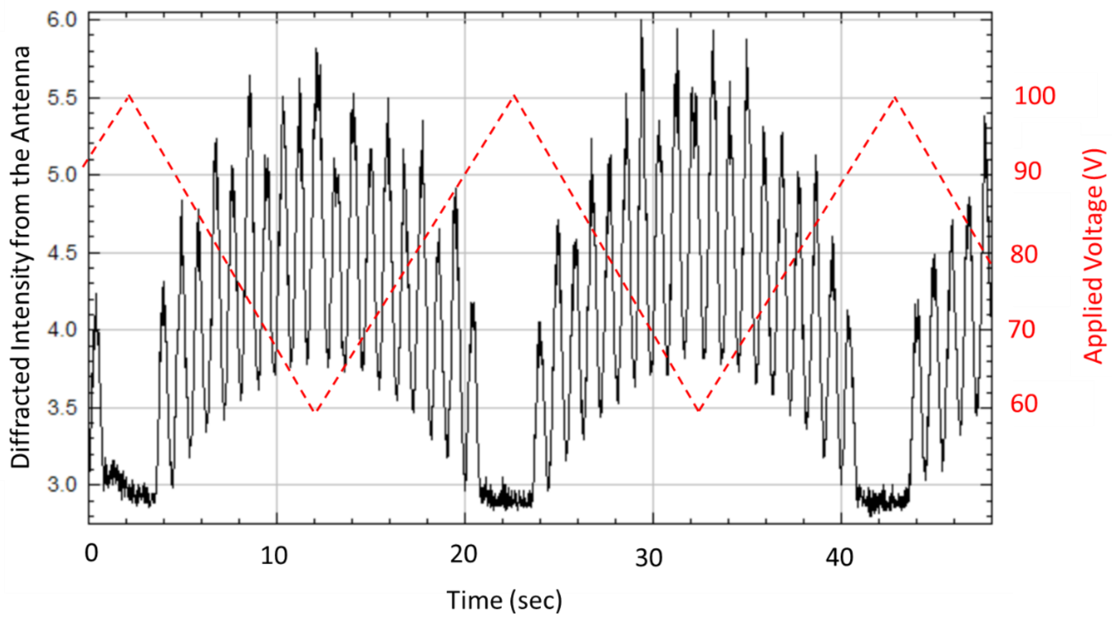


Fig 5: Offset 80V, V_{app}= $40V_{pp}$, T = 20sec of the triangle signal.

In figure 5 we observe the "monochromatic" fringes of the global modulation, that can be used to calibrate the modulator. Note that the high frequency oscillation are modulated by a sort of triangle ramp, that is linked to the EO modulation at low frequency (here T = 20sec). By taking the Fourier Transform, we clearly obtain a single peak that corresponds to the frequency (wavelength) of the source, therefore allowing for the accurate determination of the correlation between voltage and displacement with λ = 1.55µm. A rapid inspection of the fringes shows that for 30V, we obtain 8.5 fringes (i.e. an equivalent scan of 13.17 µm).

4.2 Polychromatic source

By using a SLED source at 1620 nm, with a coherence length of ca. 80 µm, we apply a triangle modulation signal from -50V to +50V, at a frequency of 40 mHz. The external shift δx has been used to place the center of the fringes on the 5th antenna. The intensity of different antenna is shown in figure 6.

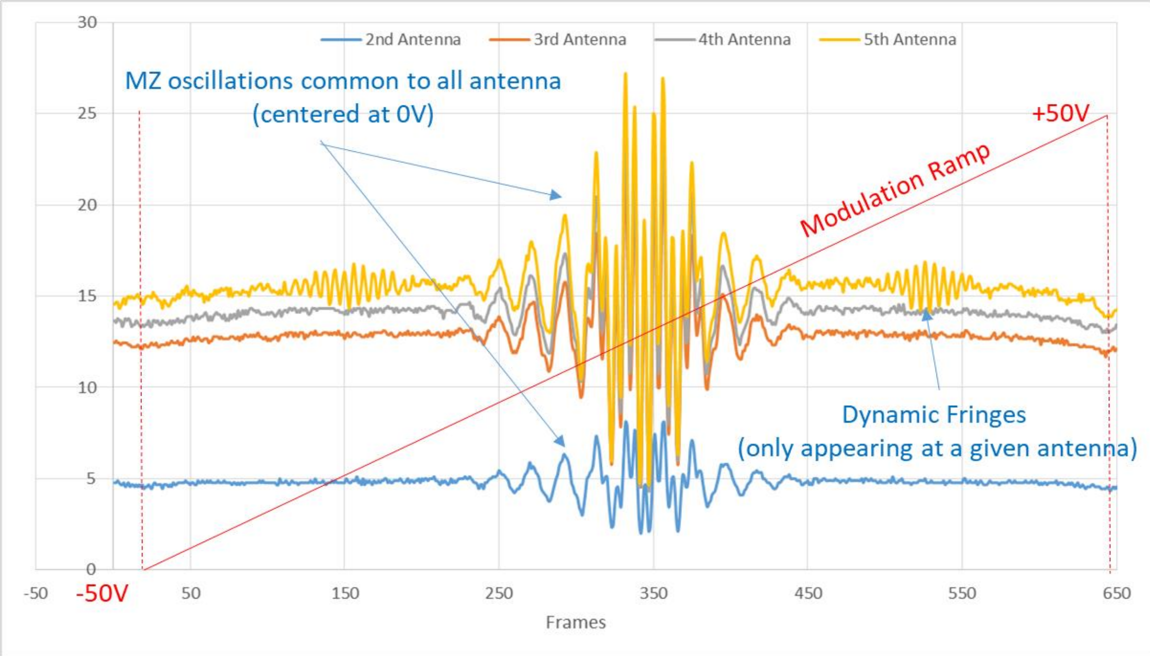


Fig.6: Signal observed when setting the center on the 5th antenna.

We can observe, close to 0V, the common oscillation for all the antennas, due to the MZ modulator while scanning the coherence length. Then, at higher voltage (and depending on the value of the δx externally set) we can observe the dynamic fringes making a unique antenna blink, while the others are just showing a constant (but not null) flux. Note that using the external phase shifter, we can move the center of the dynamic wideband fringes to any desired antenna, as shown in figure 7 below, where the dynamic packet has been placed on the 3rd antenna:

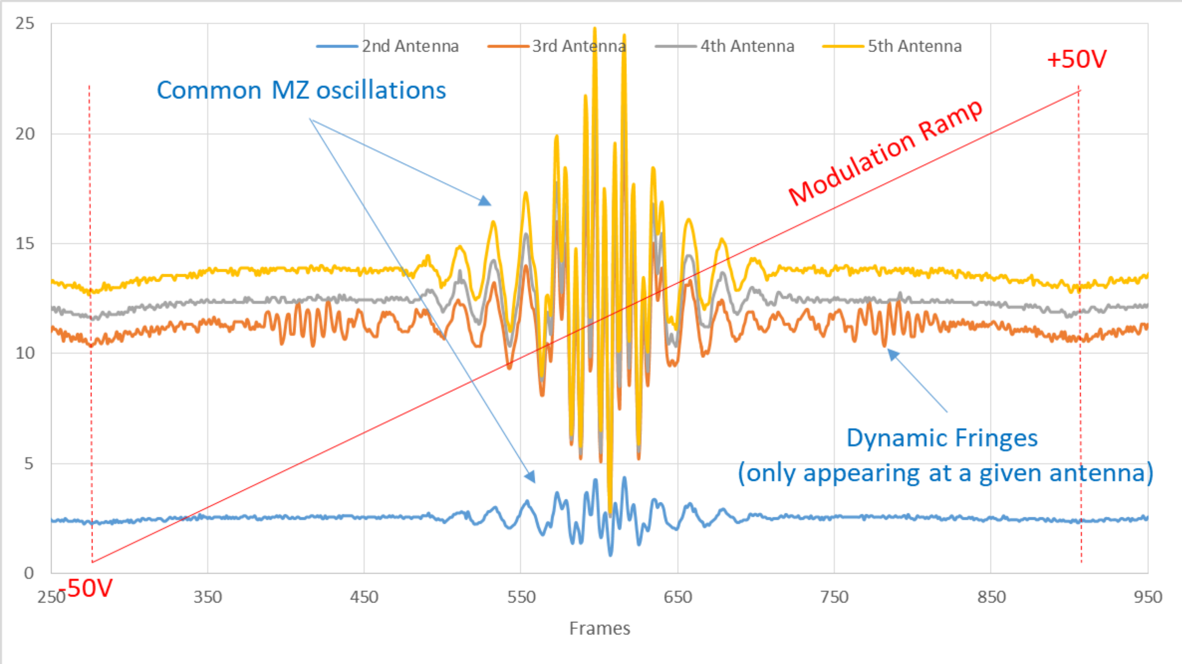
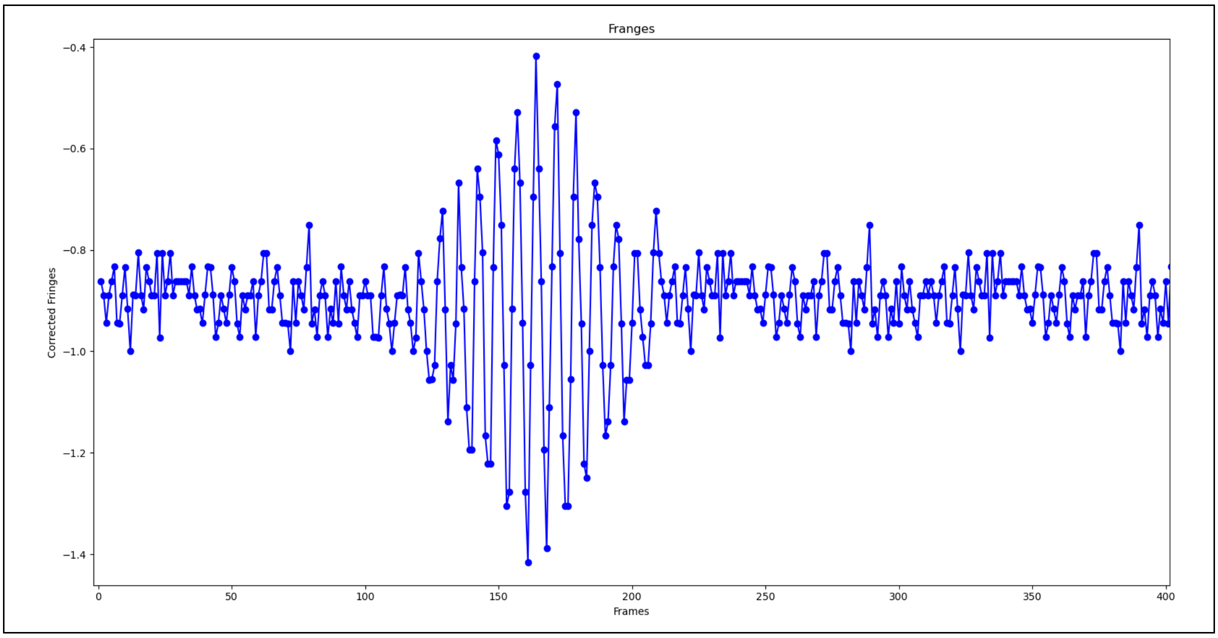


Fig.7: Same modulation, but with an external shift setting the wideband fringes on the 3rd antenna.

The interest of this configuration is that the signal from an antenna, other than the one where the dynamic packet has been set, can be used as a reference and improve the quality of the interferogram under study. Following this idea, if we substract the signal from the 4th antenna to the signal from the 5th antenna in figure 6, we obtain the interferogram shown in the upper part of figure 8:



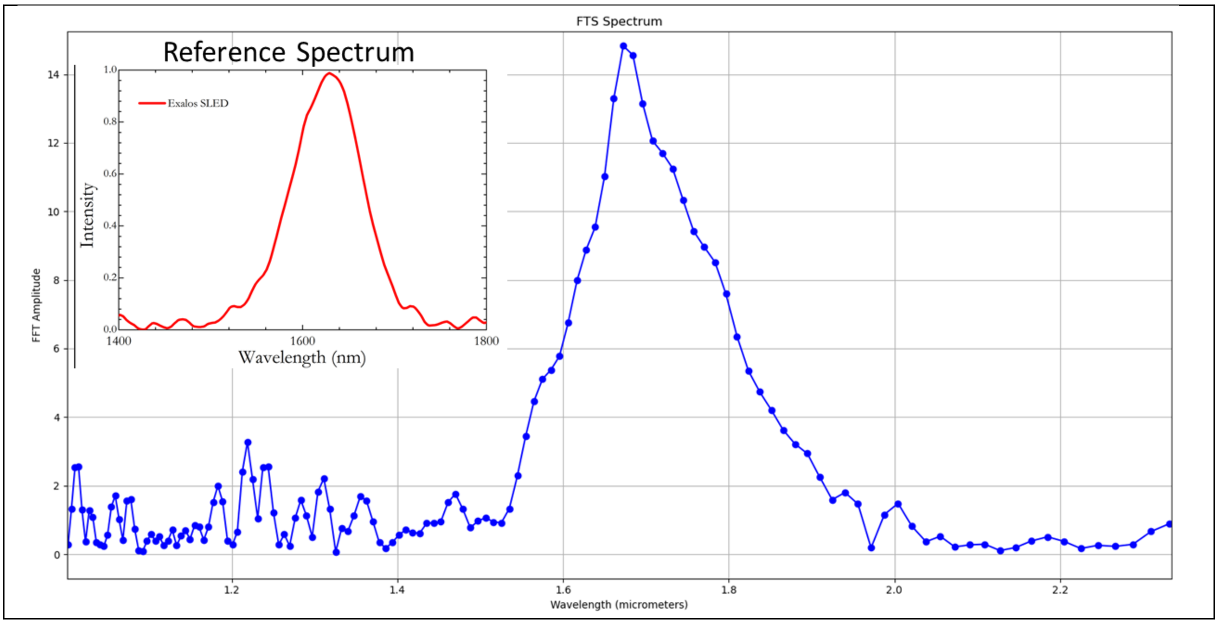


Fig. 8: Top: Fringes obtained after substraction of the reference interferogram to the one obtained at the antenna of interest. Bottom: FT of the fringes, after zero-padding up to 1024 data values. In the inset, the reference spectrum given on the datasheet of the SLED source.

As shown in this last figure, we are able to recover with good accuracy the spectrum of the SLED, by Fourier Transform of the coherence length of the fringes under a single antenna. Although this result would be similar by looking directly at the output of a simple MZ modulator, the idea is to reduce the applied voltage needed to scan the whole coherence length by using several antenna (with closer distance between each other) and patching the signal extracted from each of them. Besides, whereas a low coherence signal can be easily scanned using a classical MZ modulator in transmission, when looking for applications in high coherent sources, where hundreds of fringes must be scanned, a classical MZ modulator with a single output will not be adapted. Therefore, for SWIFTS applications, but also for sampling an interferogram over long distances with a distributed system of antenna along the waveguide surface, this temporal multiplexing approach seems well adapted.

5. CONCLUSION

We have conceived, fabricated and tested an optical chip devoted to SWIFTS spectrometry, that contains a first stage of electro-optic phase shifting thanks to a MZ modulator and a second stage with periodically spaced antenna, in order to sample an interferogram obtained by making interfere a direct beam with a mirror-reflected beam. However, due to the complexity of the system, several other interference systems appear, in particular the standard intensity modulation of an optical beam after passing through a MZ modulator. Therefore, it was needed to introduce an external OPD shifter, in order to shift the SWIFTS dynamic fringes far from the mirror, and use a low coherence SLED source in order to be able to discriminate the common oscillations from the signal of interest.

We showed that the antenna were all functional, and that the principle of EO phase shifting was working, allowing for reconstruction of the spectrum using two antennas (one for the dynamic signal, the second to get a common interference signal, to use as a reference). However, this needed an external static shift of several mm, and high modulation voltages to be able to scan the whole system of fringes. Future work will be devoted to fabricate unbalanced MZ modulators in $LiNbO_3$, in order to directly introduce “on chip” a static shift, and reduce the distance between consecutive antenna, in order to reduce the voltage needed to shift the wideband packet from one antenna to the following one, which will allow for reconstruction of a high coherence length interferograms and recover the spectrum of the source, using FFT methods.

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