Laser written 3D 3T spectro-interferometer: Study and optimisation of the laser-written nano-antenna

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1- ABSTRACT

‣ Stationary Wave Integrated Fourier Transform Spectrometers (SWIFTS) are based on the sampling of a stationary wave using nano-sampling centres on the surface of a channel waveguide. Single nano-scale sampling centres above the waveguide surface will radiate the sampled signal with wide angular distribution, which is not compatible with the buried detection area of infrared detectors, resulting in crosstalk between pixels. An implementation of multiple diffraction nano-grooves (antenna) for each sampling center is proposed as an alternative solution to improve directivity towards the detector pixel by narrowing the scattering angle of the extracted light. Its efficiency is demonstrated from both simulated and measured far field radiative patterns exhibiting a promising method to be used for future integrated IR-SWIFTS.

‣ The implementation of the antennas will allow for a high resolution spectrometer in Infra-Red (here 1550nm) with no crosstalk problem (ref. [1]). These antennas, combined with the technology used (direct laser writing) will provide a robust, low-cost efficient tool that can be implemented as a 3D-3T spectro-interferometer (multi telescope beam-combiner), useful for astrophysics applications.

2.1 - ADVANTAGES

- High Resolution Integrated Spectrometers **(R>10000) :** **R = 2nL/λ**, L = sampled length of the waveguide
- Spectrometer on chip: SWIFTS (Stationary Wave FTS)
- Optimisation of the angular dependence of the sampled signal

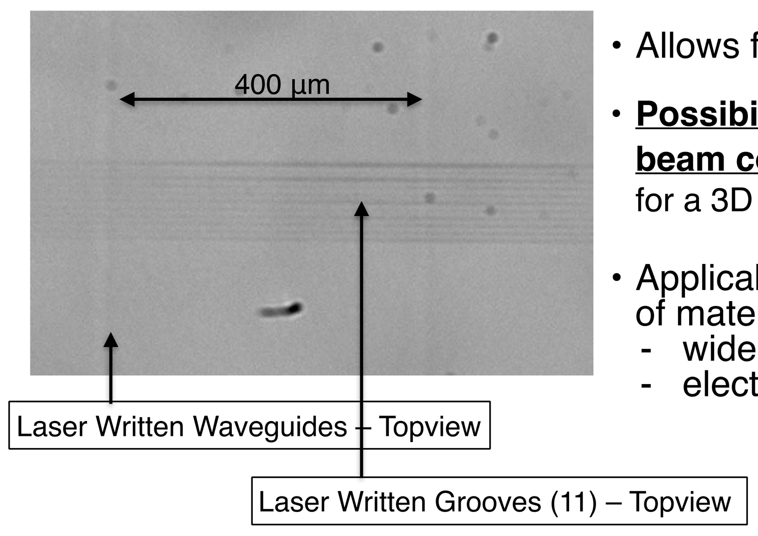
2.2 - CONSTRAINTS

- Sampling at **λ/4n** (needed to meet the Shannon-Nyquist criteria) means that for λ = 1,5 µm and n = 1,5 : pitch = 250 nm => very small and ill-adapted to the standard pixel pitch of detectors (around 10 µm)

3- INTEREST OF DIRECT LASER WRITING

Novelty concerning previous work [2] : waveguides and nano sampling centres fabricated using ultra-fast laser writing techniques :

- Waveguides : generated by **translating the sample during the laser irradiation**
- Nano sampling centres : high aspect ratio void structures whose diameter can be as small as 100 nm : structures that are generated by spatially shaping the laser
  - ➡ generation of non propagating beams (Bessel beams) which are not limited by diffraction, and can therefore easily reach wavelength focused waists and very high intensities [3]

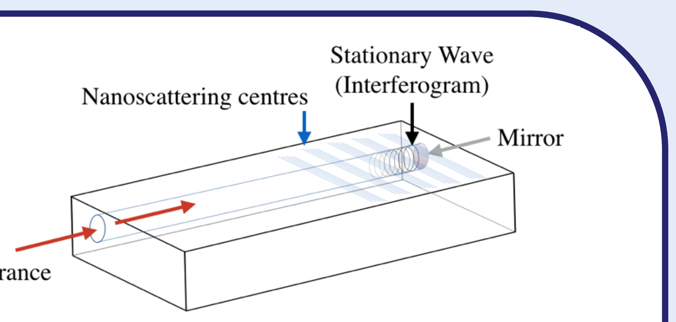


- Allows for **rapid** and **simple** fabrication
- **Possibility to design 3D waveguides : Multiple input beam combiners for phase-closure studies** (see ref. [1] for a 3D 3T example)
- Applicable to a wide variety of materials :
  - wide spectral range
  - electro-optic materials

Need for a dedicated technology :
- Femtosecond Lasers
- High accuracy motorised axis
- Accurate control of energy

A- THEORETICAL BACKGROUND

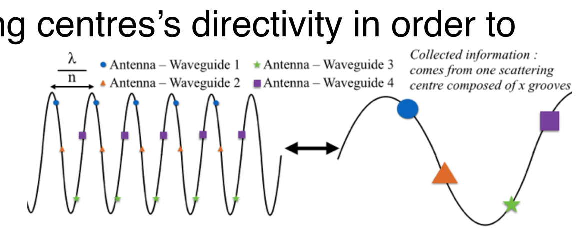
‣ Light enters a **buried single mode channel waveguide** and is directed towards a mirror : creation of a **stationary wave** interfering with itself [4]
Period : Λ = λ/2n ⇨ Evanescent field of the wave extracted with the grooves.



✦ N-IR Challenge°1: compensate subsampling (see 2.2) => **sampling with an offset** (spatial or temporal) ex: spatial offset : several parallel waveguides with shifted grooves

✦ N-IR Challenges °2 : **buried detection area** : requires the improvement of the sampling centres's directivity in order to **avoid crosstalk between adjacent pixels**

Antenna effect : grating to obtain an antenna radiating the signal vertically
‣ pitch between the grooves : **λ/n << pixel pitch : undersampling**
‣ pitch between the antenna groups : so that each group radiates on a different pixel

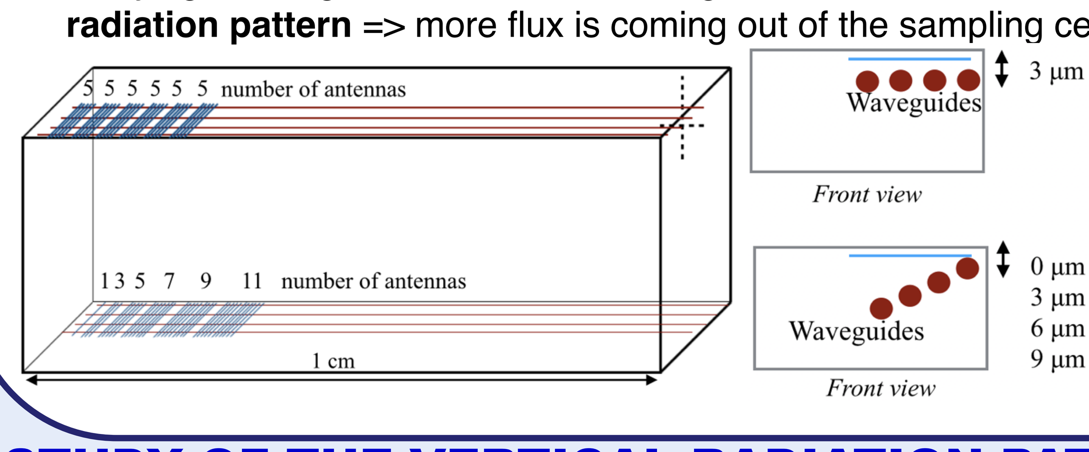


Using simulations, the grating law, Snell-Descartes's law : determine the optimal parameters : number of grooves, grating's pitch (between the grooves), refractive index…

B-GEOMETRY OF THE SAMPLE

➡ Different number of nanogrooves (=grooves) (1,3…11) : possibility to study the **optimal number of grooves** in order to **improve directivity.** Tech limitation : minimum pitch of 3* λ/n ≈ 3µm.

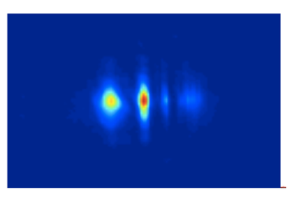
➡ Burying the single mode channel waveguides allows a **better distribution of the radiation pattern** => more flux is coming out of the sampling centres



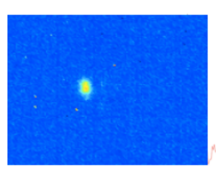
➡ Different depths between the grooves and the guides : study of the **extraction optimisation** depending on the **distance between the waveguides and the grooves**

C- OPTIMAL COMBINATION (number of grooves, distance guide / groove)

- The higher the number of grooves, the bigger the grating and the thinner the signal : optimal number of grooves = 11
- Far-field observations in order to study the signal extracted by each group (different number of grooves and different depths)
- But 5 or 7 grooves : FWHM constant and satisfying.



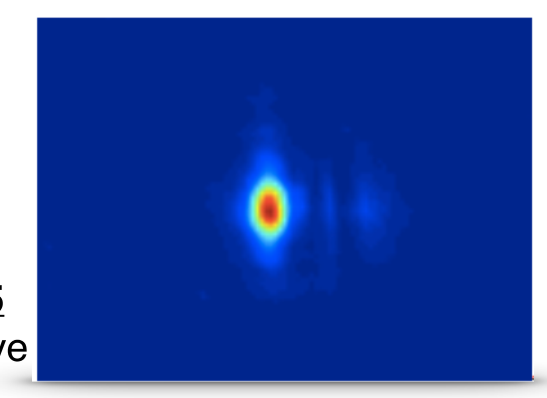
11 grooves — distance : 3µm



5 grooves — distance : 9µm

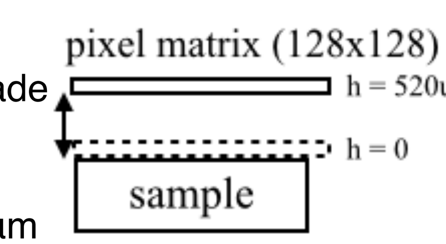
- Optimal burying depth : grooves too far away from the waveguides : weak evanescent field + insufficient extraction by the sampling centres
- Compromise between efficiency, directivity and reproducibility :
  - 11 grooves = more directive but reproducibility issues + takes more place !
  - 5 grooves : satisfying FWHM

➡ **CONCLUSION** : The **most advantageous combination** is **5 grooves**, for a **distance** between the waveguide and the groove of **3µm**



5 grooves — distance : 3µm

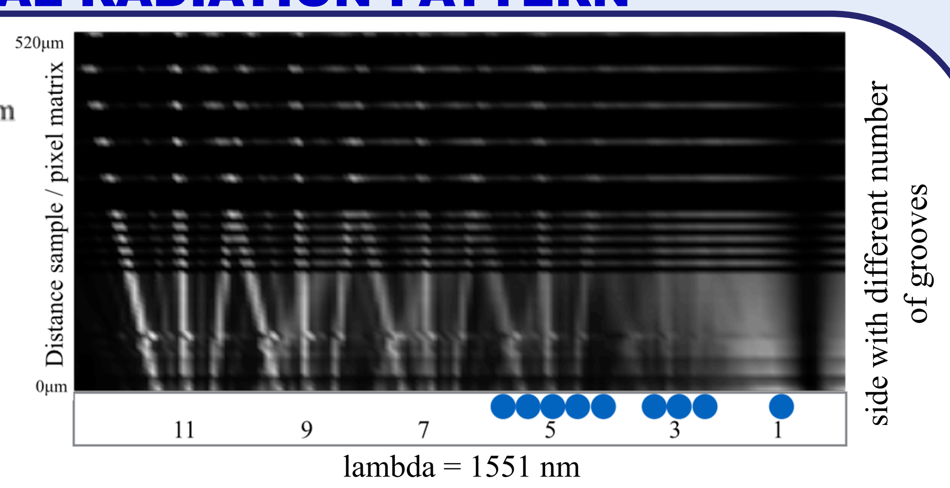
D- STUDY OF THE VERTICAL RADIATION PATTERN

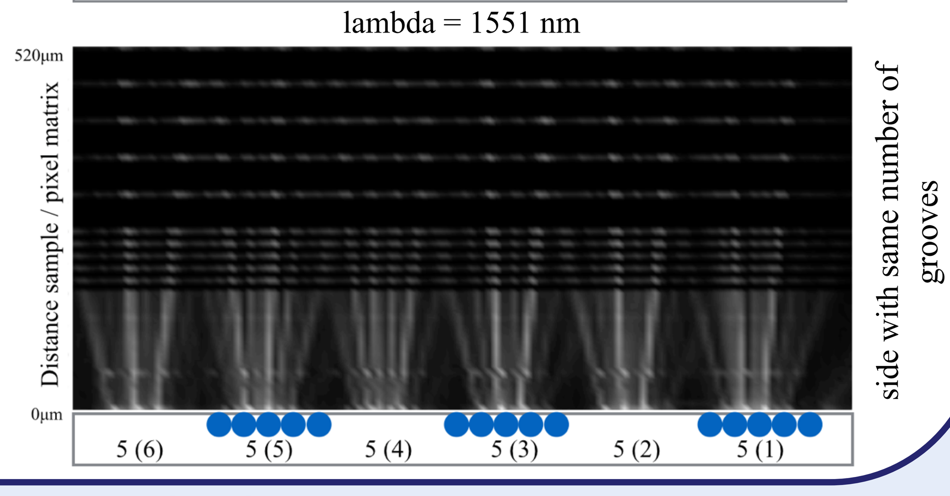


- The measurements are made for **different distances between the detector and the sample** : **0 µm** to 520 µm *(vertical sampling :10 µm, 20 and 50 µm).*

‣ **No mirror => negligible wave reflection => no stationary wave**

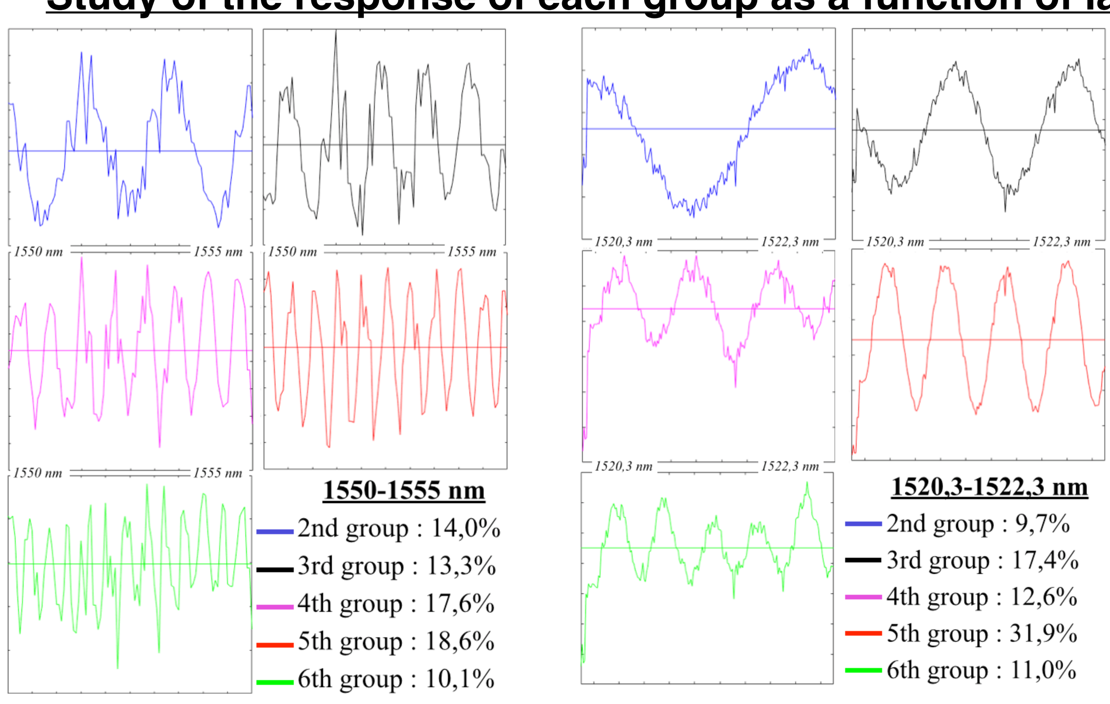
- **5 Bragg orders** (only 3 are clearly visible because of the glass/air interface) : grating law
- **Antenna effect** : different number of antenna = different radiation pattern
- Intensity : same for the groups with the same number of grooves (5) : no return wave (though a weak reflection can be seen because of an imperfect superposition)

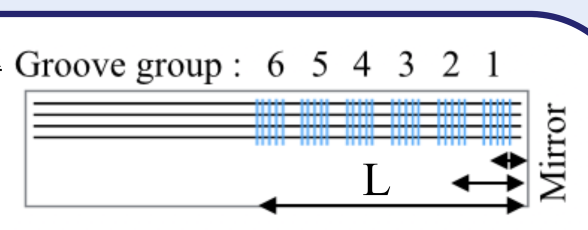




E- WITH THE MIRROR - SCANNING THE SWIFTS EFFECT

Study of the response of each group as a function of lambda



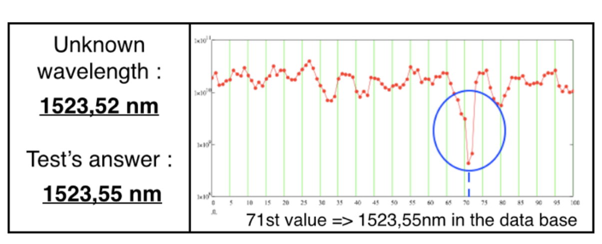


L : distance of the group to the mirror

- For all the measurements, the detector is on the sample (pixels on the sample)
- Contrast correct, better at 1520nm than 1550nm
- **Variation of the response of each group with the wavelength**
- ⇘ of the period with the ⇗ **of L** :

$$I \propto \cos(2\pi * 2nL/\lambda)$$

- Specific signature as a function of L and lambda : spectrometer



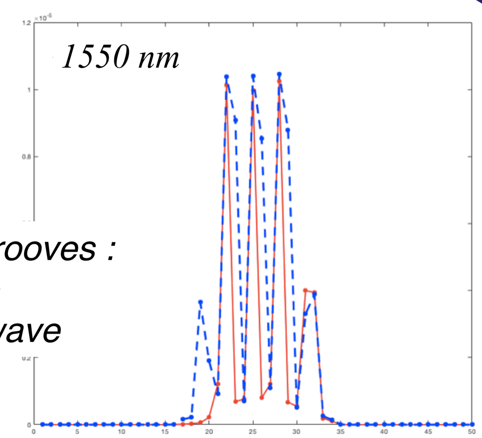
- **Possibility to determine an unknown wavelength in a data base with an accuracy of 25 pm**
- Test repeated for several unknown wavelength : always conclusive

F- SIMULATIONS

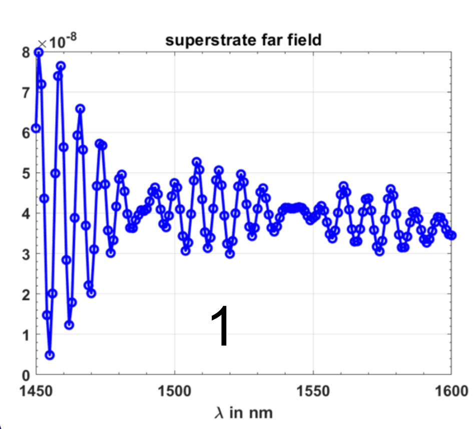
Contrast : not optimal & better at 1520nm than at 1550nm :
‣ multiple Bragg orders (grating law)
‣ asymmetry neff(glass) = 1,44 at 1,55nm

- The superposition between the wave and its reflection is bad : multiple asymmetric thin Bragg orders

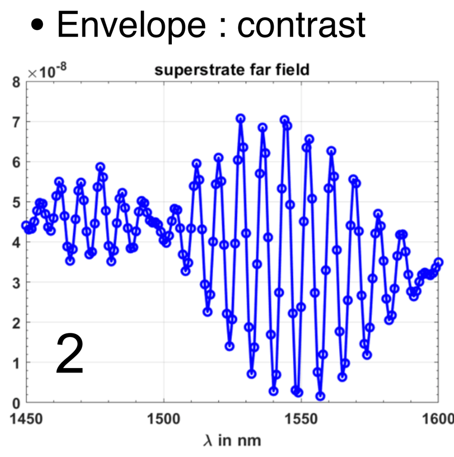
Radiation of 1 group with 5 grooves :
red = only the incoming wave
blue = incoming + returning wave



Simulation of the variation with λ of the response for a 5 grooves antenna
- Internal oscillations : interferences wave / wave's reflection
- Envelope : contrast



antenna pitch: 3µm



antenna pitch : 3,22µm= 3*λ/n

1• Best contrast at 1450 nm (neff (glass) = 1.444) => at 1450, the grating is synced with the grooves
Actual situation

2• Best contrast at 1550 nm : **antenna pitch perfectly adapted to λ and neff**
Optimal situation : antenna pitch = 3,22µm guarantees an even better contrast

G.1-CONCLUSION

- Conception of a design allowing a correct sampling of a wave in N-IR using the SWIFTS technology while studying the antenna effect
- Fabrication of the sample using laser photo-inscription (buried waveguides & possibility to have 3D waveguides)
- Predictions for the correction of the encountered difficulties : improve the contrast

➡**Obtention of a spectral signature on a 5 nm window with an acceptable contrast even though the configuration is not optimal, room for improvement (simulations) with only a slight change in the antenna pitch**
➡**Possibility to determine an unknown wavelength with high accuracy**

G.2-PERSPECTIVES

- Spatial multiplexing using parallel shifted antennas
- Electro-optical material material (KTP, Lithium Niobate) :
  - ‣ higher refractive index
  - ‣ temporal modulation for a better sampling
  - ‣ allows for the sampling of a larger spectral band

4-ACKNOWLEDGEMENT

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5-REFERENCES

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