Extension to NIR and Visible ranges of high resolution relative spectral response measurement using Fourier Transform Infrared Spectrometer (FTIR) of CMOS FPAs

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ABSTRACT

The accurate knowledge of IR detectors specifications becomes of higher importance whatever the application. Among these specifications is the relative spectral response. Spectral response measurement of CMOS Focal Plane Arrays is now possible either thanks to a grating-based monochromator or through an FTIR spectrometer, this later solution easily leading to a 1 cm^{-1} spectral resolution whatever the wavelength. Through this method, the spectrum is calculated as the Fourier Transform of the signal of the detector. A Fast Fourier Transform algorithm (FFT) is then applied which requires a sampling frequency. Sampling points are selected at most at every zero-path difference of the interferogram of an internal He-Ne laser. Consequently, the analysis of signals with higher wavenumbers the He-Ne laser, i.e. in the visible is theoretically impossible. Our paper reminds the principle of the high resolution spectral response measurement through FTIR and presents the method to pass over the sampling limitation thus extending measurements over the visible for CMOS detectors. It also explains the drawbacks of this method: the existence of a blind range and the limitations toward UV range.

Keywords: CMOS detectors, focal plane arrays, Fourier Transform spectrometer (FTIR), infrared reference source, blackbody, relative spectral response, spectral resolution.

1. MEASURING PRINCIPLE OF HIGH RESOLUTION RELATIVE SPECTRAL RESPONSE OF CMOS DETECTORS THROUGH FTIR

1.1 Overview of the bench

The relative spectral response measurement method is part of the BIRD bench. This bench is a universal testing system of IR CMOS focal plane arrays (IRFPAs). It includes very low noise driving electronics of the IRFPA, opto-mechanical tools presenting accurate optical stimuli to the detector under test and video signal acquisition and processing system with accurate testing algorithms. The list of available measured parameters includes: temporal noise, fixed pattern noise, 3D-noise, responsivity, detectivity, dynamic range and linearity of the signal, quantum efficiency, NETD, bad pixel location, non-uniformity correction, MTF, pixel surface response, crosstalk, relative spectral response and G factor.

The very low noise electronics of the bench includes a bias voltage generation unit with output noise lower than 100 $nV/\sqrt{Hz}$ and a high frequency clock signal generator with slew rate higher than 1000V/µs. The multi-channel analog signal delivered by the IRFPA is digitized through an AD converter with 200 µV maximum input noise and multiplexed as up to a 320 MHz equivalent data flow in order to be transferred in GigE Vision to the acquisition unit. This bench is consequently able to test up to 4k x 4k detectors.

The opto-mechanical table is equipped with a highly stable (3 mK) low temperature extended area blackbody allowing an accurate measurement of noises, the detection of bad pixels and the calculation of the non-uniformity correction parameters. The spatial tests (MTF, crosstalk and pixel surface response) is made by focusing the image of a thin slit or pinhole on the detector surface through aberration free optics with f-number up to 1.

The principle of the relative spectral response measurement through an FTIR is made by the ratio of the response of the detector under test with the response of a reference detector which is supposed to be constant whatever the wavelength. The source is based on a broad band optical source passing through an FTIR. Depending on the selected analyzed spectral range, the optical source might be either a blackbody or a QTH lamp. With this configuration, the input source is considered as the sum of monochromatic sources and the interferogram received by the detector through the FTIR is the sum of monochromatic interference fringes and includes the information of the whole spectrum at the same time.

The principle of the FTIR based spectral response system is shown below:

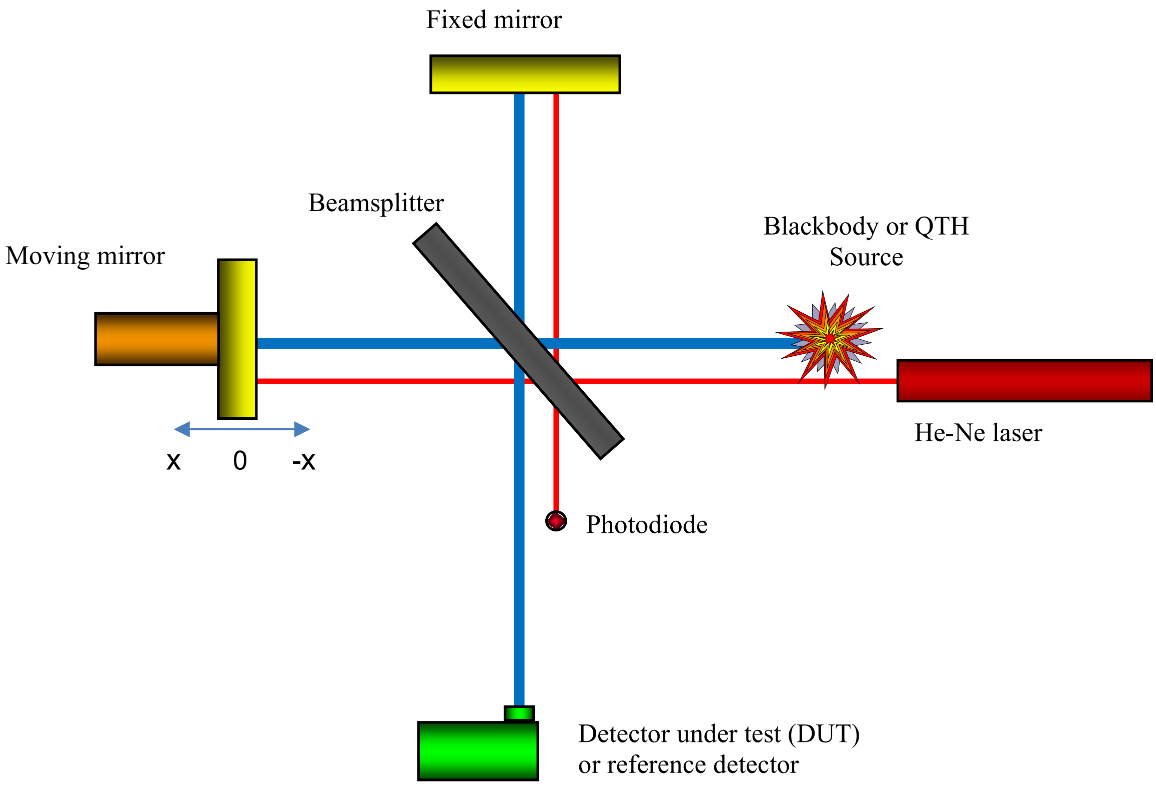


Figure 1 FTIR based spectral response principle

The Fourier Transform spectrometer is based on a Michelson interferometer. The high intensity, broad band source energy is projected into the interferometer. The interferometer consists in a beamsplitter which reflects half of the energy to a fixed mirror and half to a moving mirror. The moving mirror scans back and forth producing a path length difference with respect to the fixed mirror. This path length difference is sampled in time with respect to the internal HeNe laser - making also for internal/absolute calibration of the wavelength. The reflected beams then combine back at the beamsplitter to create a modulated signal. The detector measures the intensity of the modulated energy to produce an interferogram.

The shape of the interferogram depends on the source spectrum.

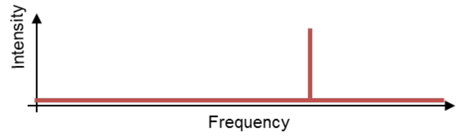
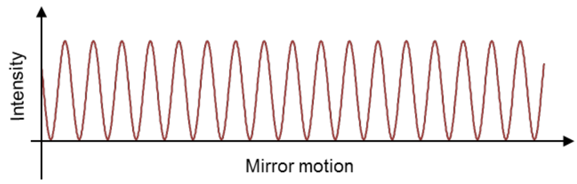
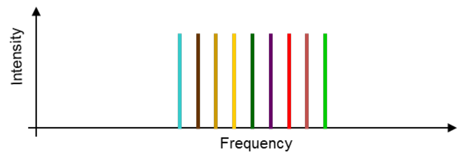
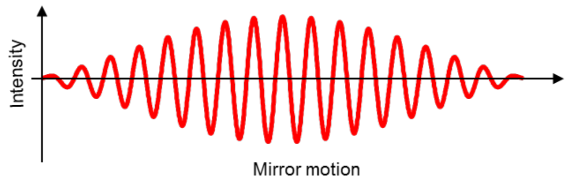
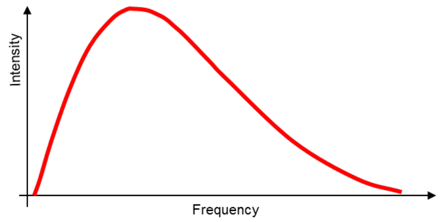
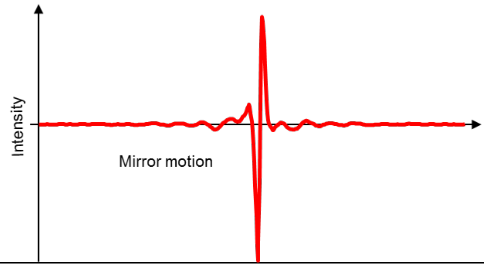
Source type		Modulated signal
Laser (monochromatic light source)		
Several single frequencies		
Broad band IR source		

Figure 2 Interferogram shape vs. source spectrum

The detector simultaneously receives all the frequencies and the interferogram is the sum of the contribution of all the frequencies at the same time. So using a Fast Fourier Transform calculation, the response of the detector to the optical source can be computed.

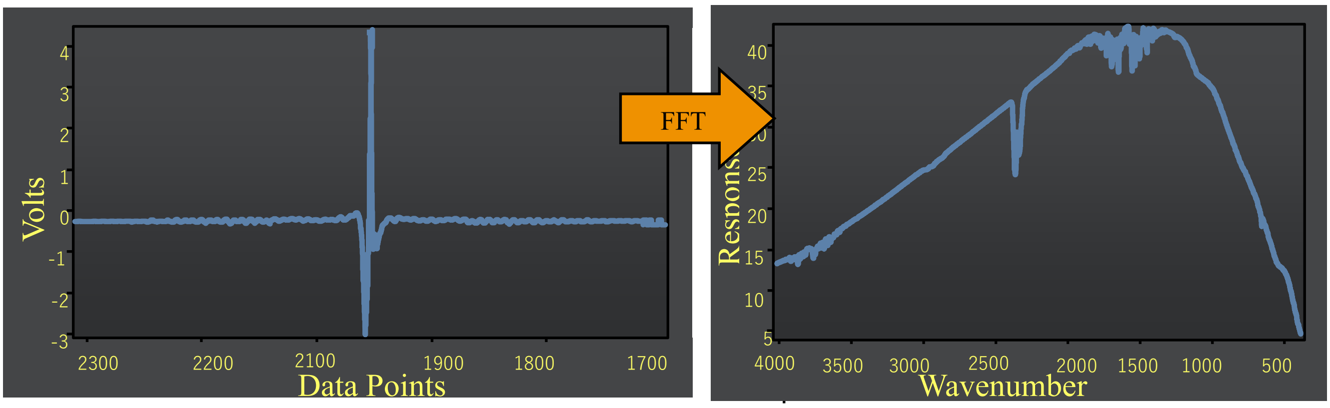


Figure 3 Response calculation through FFT algorithm

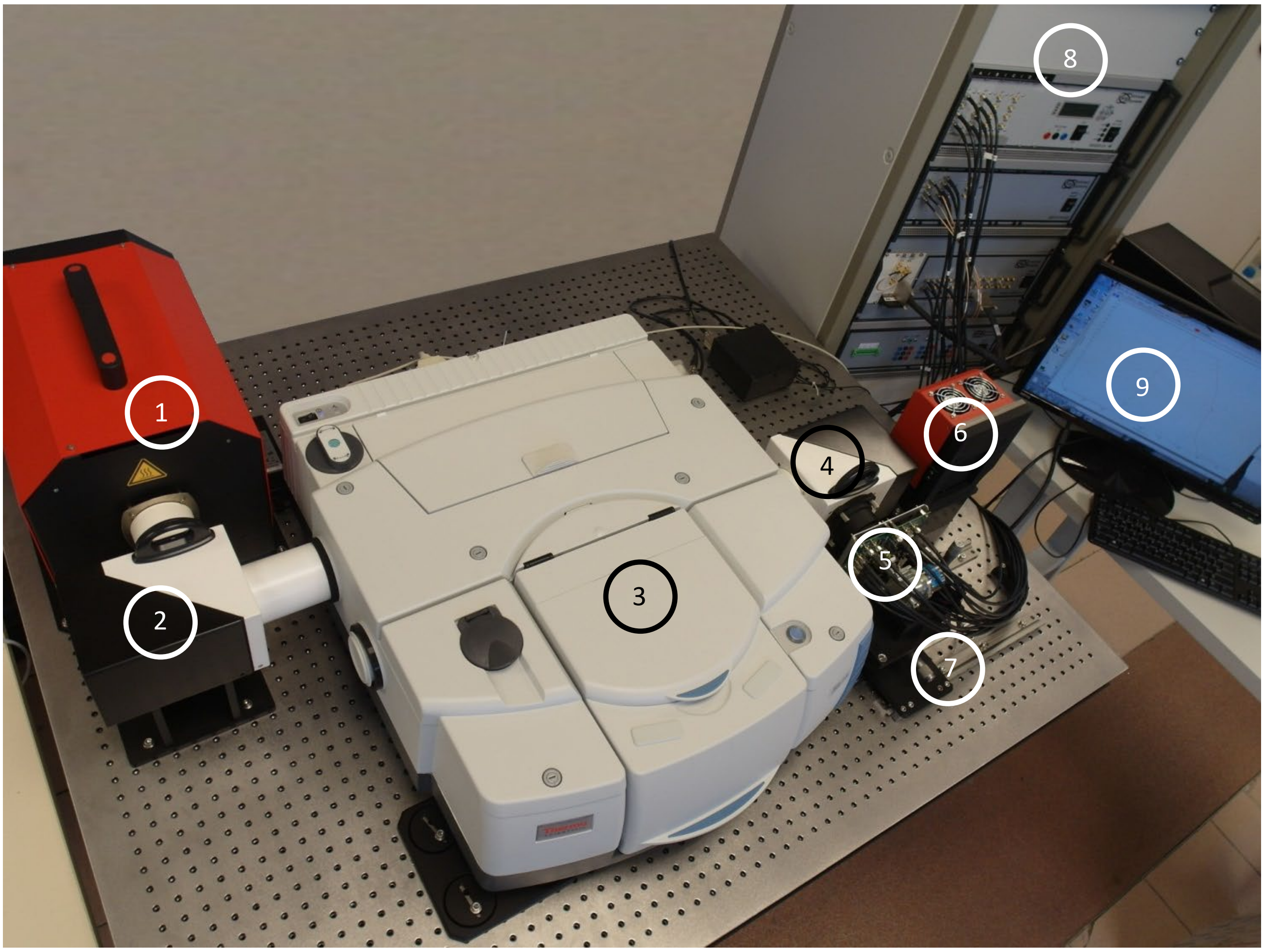


Figure 4 BIRD bench with FTIR based spectral response assembly

Figure 4 shows a view of the manufactured BIRD bench with FTIR spectrometer with:

1. Cavity blackbody
2. Input optics
3. FTIR spectrometer
4. Output optics
5. Detector under test
6. Extended area blackbody for noise test configuration
7. Trolley to switch from spectral response to noise test configuration
8. Electronic cabinet with clock signal and bias voltage generator and ADC converter
9. Acquisition and data processing computer

1.2 Sampling method

The spectrometer includes two sources: an infrared or visible source, and a He Ne laser source. The first is used for analyzing the DUT and the second is used only by the spectrometer, as a reference for sampling for the FFT algorithm.

Since the laser also goes through the interferometer, the output signal measured by the photodiode is a continuous perfect sine wave.

The signal received by the detector is then sampled at every zero-crossing of the interferogram of the laser. In order to have a correct sampling of the signal on the DUT, the approximate frequency of this signal must be lower than the frequency of the laser interferogram.

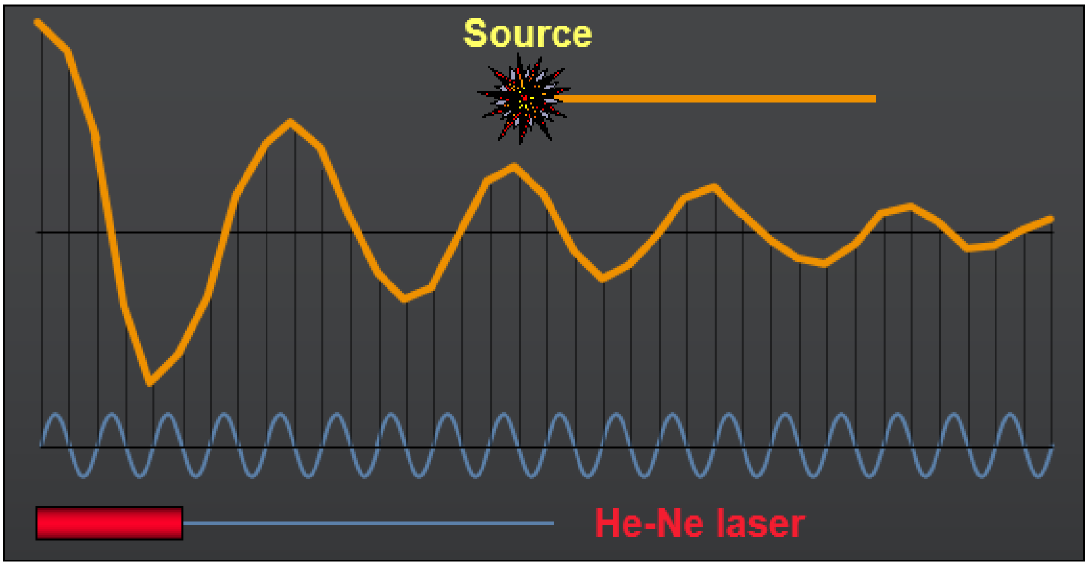


Figure 5: Sampling principle of an interferogram

The sample spacing parameter or SSP defines how many zero-crossings have to be considered for sampling the signal of the DUT. A SSP=1 gives a sample at each zero-crossing. A SSP= 2 gives a sample every 2 zero-crossing, etc.

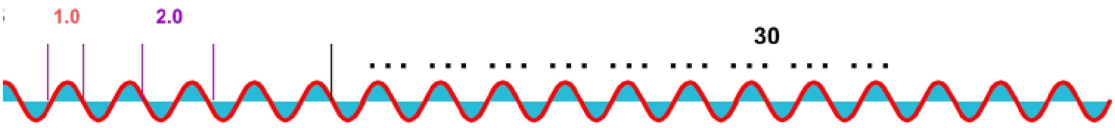


Figure 6: Signification of the SSP parameter

The choice of the SSP is very important because it also defines the covered spectral range.

The He-Ne laser wavelength is 632.8nm, which is equivalent to a wavenumber of 10^8/632.8nm ≅ 15800cm^{-1}. For an SSP=1, the maximum measurable frequency is then 15800cm^{-1}, and for an SSP=2, it is 7900cm^{-1} (i.e. 1.27 µm). For an SSP=10, the maximum measurable frequency is 1580 cm^{-1} (i.e. 6.3 µm). The recommended SSP values depending on the usual IR spectral ranges are given in the below table.

Usual IR range	Recommended SSP value
LWIR	10
MWIR	4
SWIR	2
NIR	1

Table 1: Recommended SSP values

This table shows the analysis over the visible range is theoretically not reachable. In addition, the signal to noise ratio is lower for lower wavelengths since the accuracy on the measurements of the He-Ne laser zero crossing matters more than for higher wavelengths.

In addition, since the laser also goes through the interferometer, the laser illumination also falls on the detector under test. Due to its intense radiation, it may saturate it and must be removed using optical filter such as notch filters which precisely remove the laser frequency and nothing else.

2. CONSIDERATIONS ABOUT THE FFT CALCULATION PROPERTIES

The main calculation to retrieve a spectral response from an interferogram is a Fourier transform computed through a Fast Fourier Transform (FFT) algorithm. The domain of the measured data is the temporal or spatial domain. The Fourier Transformed domain is the frequency or spectral domain and the computed Spectrum is in the frequency domain, or wavenumber $\sigma(cm^{-1})$ domain.

Spatial/temporal domain	Frequency /Spectral domain
Interferogram	Response
Mirror position (cm)	Wave number (cm^{-1})
Sampling frequency (Hz)	Spectral range (cm^{-1})
Optical path difference (cm)	Spectral resolution (cm^{-1})

Table 2: Corresponding parameters

For instance, the optical path difference between the 2 beams of the interferometer is given by:

$$\delta = 2d \tag{1}$$

where d is the travel distance of the moving mirror. A 0.5 cm travelling distance leads to a 1 cm optical path difference. In the Fourier domain, a 1 cm optical path difference is equivalent to a 1 cm^{-1} spectral resolution.

The delivered results from an FFT calculation shows both the spectrum and its replica about the sampling frequency. As an example, Figure 7 shows the result of the computation of a spectrum located exclusively in the NIR range, i.e. with no wavenumber below the 15800 cm^{-1} sampling frequency, i.e. with no higher frequencies than the sampling frequency selected here by SSP = 1. The replica of this spectrum (left) is also delivered.

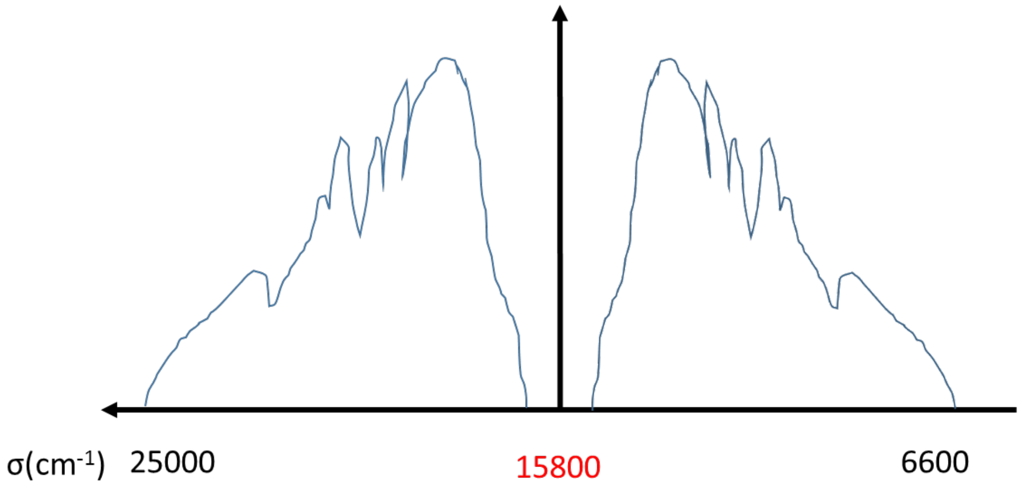


Figure 7: Example of a NIR calculated spectrum with SSP=1

However, it commonly happens that the signal contains frequencies higher than the sampling frequency meaning the detector under test is sensitive both in visible and NIR range, i.e. below and above 633nm.

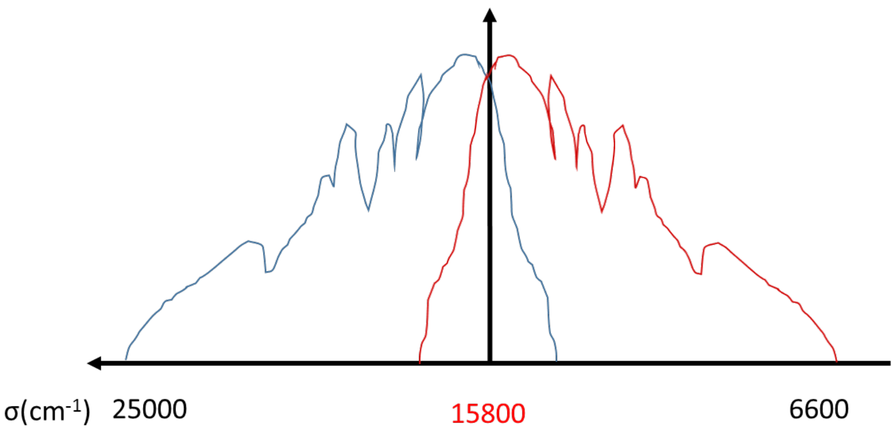


Figure 8: Aliasing in FTIR spectrometry

Figure 8 shows an example of this situation: data in the "red" domain, i.e. above 633nm (or below 15800 cm^{-1}) are affected by the overlapping of the symmetrical spectral response leading to an aliasing phenomenon. The computed spectrum at the 700nm wavelength for instance also contains information from its replica about 633 nm, i.e. from 633 – (700 -633) = 566 nm!

The first obvious solution to the above issue is to increase the sampling frequency by implementing a blue laser into the FTIR. This solution leads to an extremely expensive system and is hardly implemented by FTIR manufacturers. Our solution consists in using anti-aliasing filters.

3. HIGH RESOLUTION SPECTRAL RESPONSE MEASUREMENT OVER VISIBLE AND VNIR RANGES

Because of aliasing, spectral ranges above 633nm and below 633nm must be measured separately. This can only be done using optical anti-aliasing filters, i.e. sharp edge low-pass and high-pass filters. These filters simultaneously keep the intense radiation of the He-Ne laser from saturating the detector under test. The low-pass filter will only keep the signal below 633nm, while the high-pass filter removes any wavelength below 633nm. The filters are implemented at the exit of the output optics (item 4 of Figure 4).

For the following, it is assumed that the DUT has the spectral response shown in Figure 7.

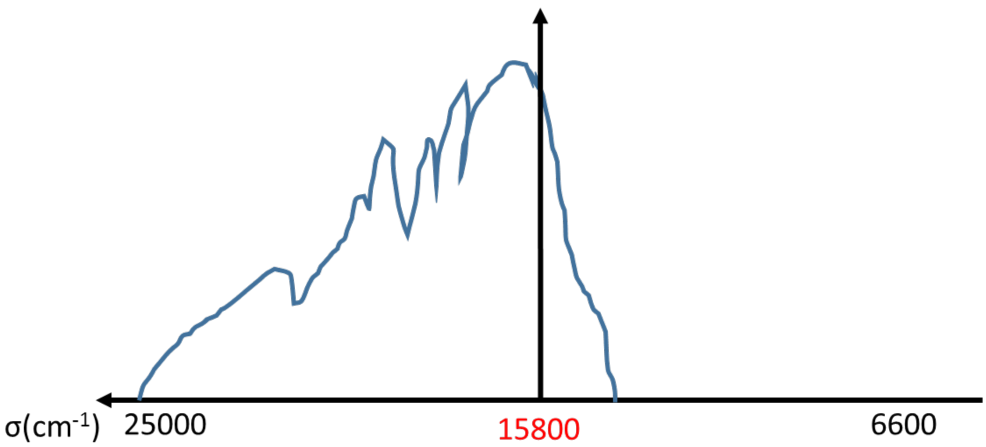


Figure 9: Example of spectral response curve

3.1 Red and VNIR part of the spectrum measurement

In order to measure the spectrum above 633nm or below wavenumbers lower than 15800cm^{-1}, the aliasing of the signal at lower wavelengths must be removed. A high pass filter is inserted into the optical path thus transmitting only the low wavenumbers.

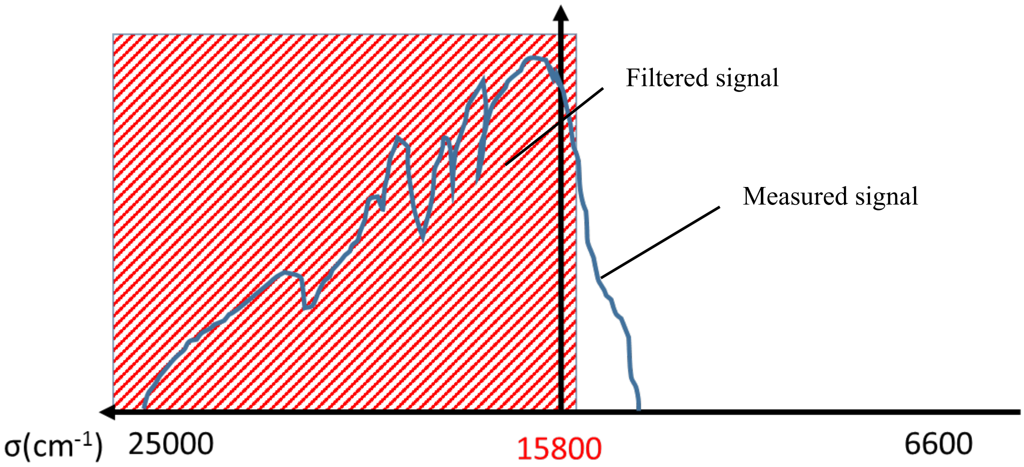


Figure 10: Spectral range filtered for Red and VNIR measurement

3.2 Measurement of the blue part of the spectrum

As for the Red measurement, the signal from wavelengths above 633nm should be removed using a sharp low pass filter in order to measure the response for wavelengths between 400nm and 633nm.

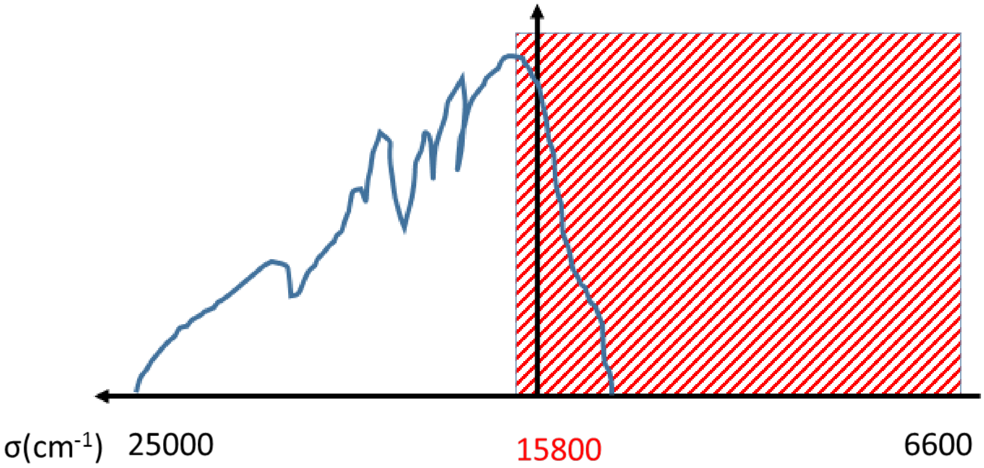


Figure 11: Spectral range to be filtered for Blue measurement

However, due to the low sensitivity of reference detector over the visible range, the low level of input source signal and the limitation due to the sampling frequency, the signal between 400nm and 633nm is extremely noisy and hardly exploitable. The visible part of the curve i.e. between 25000cm^{-1} and 15800cm^{-1} is rather obtained as the symmetrical curve of its replica.

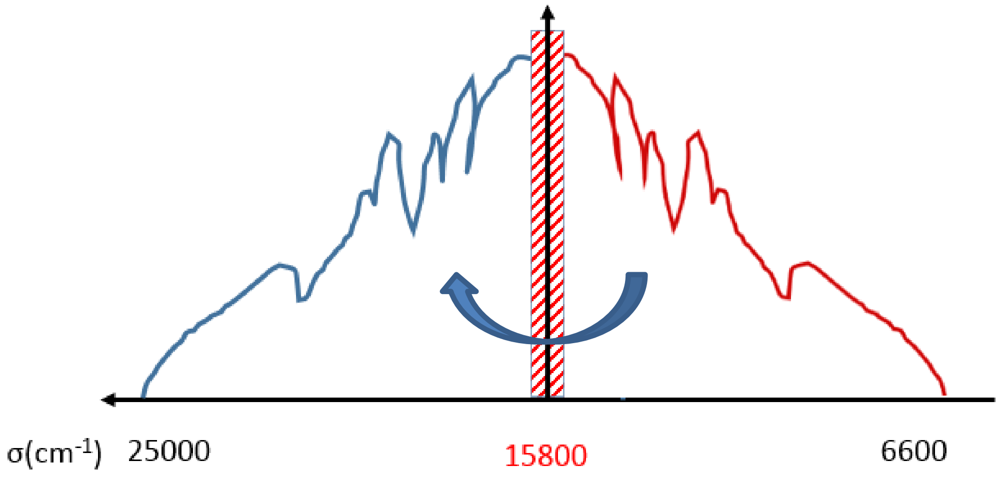


Figure 12: Folding of the NIR replica to the Blue range

The replica is then folded back in the high wavenumber domain and the final spectrum is the combination of the two parts as shown in Figure 13.

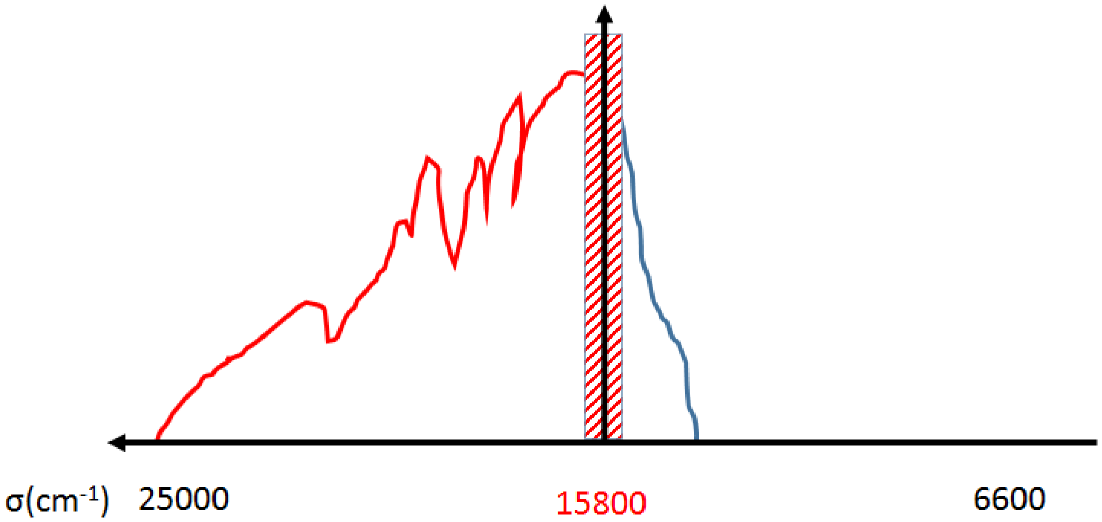


Figure 13: Recombination of the two parts of the spectrum

3.3 Blind range

The selected high pass anti-aliasing filter has edge as sharp as possible but a blind range always remains around the He-Ne laser wavelength as shown on Figure 13.

Actually, the high pass filter used into our test cannot cut the laser wavelength more sharply than 10nm away from this wavelength. Therefore, the FTIR spectrometer is blind between approximately 620nm and 645nm.

3.4 Minimum wavelength toward UV

Using the “folding of the replica curve” method described in paragraph 3.2, the signal of the replica at 6600 cm^{-1} is imaged at 25000cm^{-1}.

However, this high performance blue filter does not filter wavelengths higher than 1.250µm (i.e. with wavenumber lower than 8000 cm^{-1}) efficiently, as shown on its curve of transmission (Figure 14):

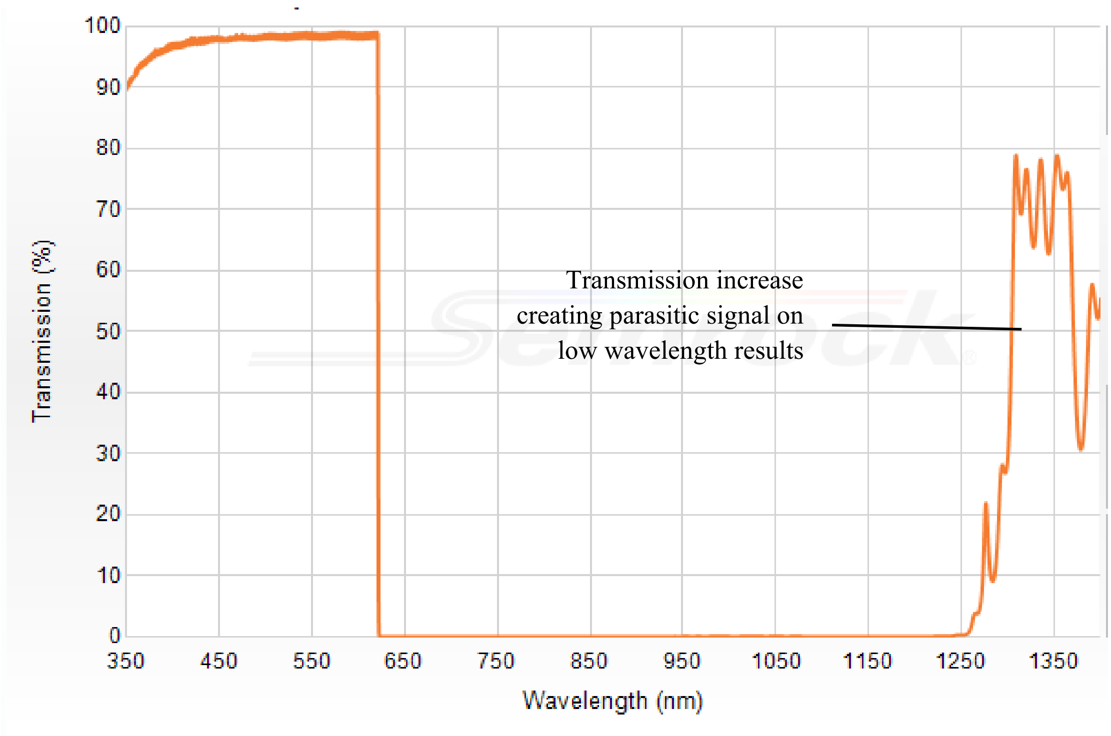


Figure 14: Transmission spectrum of the high performance blue filter

Signal with wavelengths higher than 1.250µm (or lower than 8000 cm-1) is transmitted and added to the replica of the visible curve. Since the symmetrical wavenumber to 8000cm^{-1} is 23600cm^{-1} i.e. 423nm, some parasitic signal appears for wavelengths below 423 nm.

The measurement must be then limited to a minimal wavenumber symmetrical to 8000cm^{-1}, i.e. 423 nm, about the laser wavenumber.

3.5 Potential solutions

A potential solution is to use a reference detector and a detector under test with no sensitivity at wavelength above 1.250µm. Silicon detectors, for example, cannot detect wavelengths higher than 1100nm. They also have a much higher detectivity in the visible range. However, this solution keeps us from running a continuous measurement from 0.4 µm to 2.5µm.

Another potential solution is to use an additional filter to remove any signal above 1.250µm while measuring the replica spectrum. However, this type of filter would also reduce the already low signal measured at wavelengths smaller than 633nm.

4. CONCLUSION

High resolution relative spectral response using FTIR spectrometer is particularly suitable for IR CMOS detectors as the highest sampling frequency given by the internal He-Ne laser is higher than the frequencies defining the IR spectrum. Extending this method to the visible range seems impossible at the first sight since the sampling frequency is lower than the frequencies defining the visible range. However, using the property of the FFT calculation providing both the spectrum and its replica about the He-Ne wavelength, we managed to combine measurements over and below the He-Ne wavelength to provide a continuous spectral response curve over visible and VNIR range, with the limitation of the existence of a blind zone around the He-Ne wavelength and inaccurate results close to the UV wavelengths due to aliasing and sharp-edged filters properties. At least, the continuous spectral response of a detector covering the 0.4 to 2.5 µm range can be computed.

5. REFERENCES

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