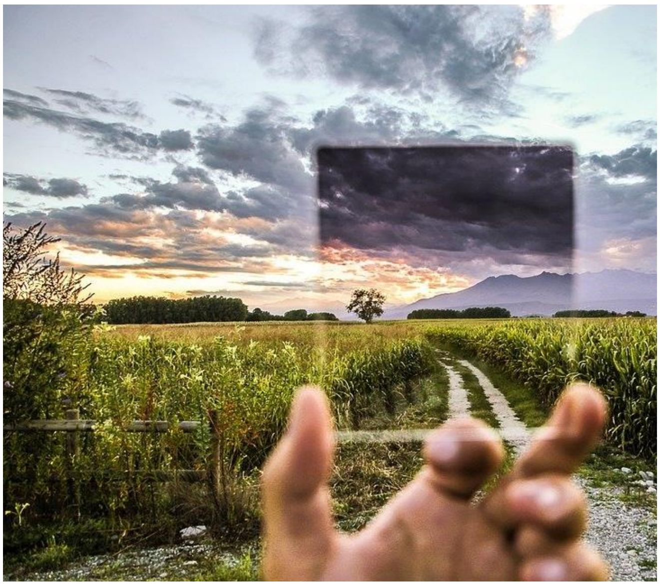
AN0137 Application Note: Infrared optical filter choice considerations for NDIR gas detection systems

1. Introduction



Pyreos is a world leading manufacturer of pyroelectric detectors. The company is utilising a proprietary manufacturing technology to create a truly unique thin film pyroelectric chip found nowhere else in the world.

Some of the main applications in which our detectors are used are:

- Gas detection and analysis
- Fire/Flame detection
- Materials Analysis
- Motion detection and gesture recognition

Each one of these applications require a carefully chosen filter attached to the detector. The main reason to do so is to limit the spectral range of wavelengths input on the thin film PZT (Lead Zirconate Titanate) film. Choosing a correct optical filter is often a non-trivial exercise and needs to be carefully thought through by a system/module designer.

At Pyreos, we offer a variety of filter options. An extensive list of wavelengths available from our standard range can be viewed on our website: https://pyreos.com/infrared-sensing-by-wavelength/.

We also welcome custom filter requirements and can support rapid prototyping.

This application note will describe some of the most important parameters to consider while choosing a correct filter to be integrated into a PZT IR detector, i.e. spectral profile, bandwidth, substrate material, incident angle, ambient temperature. A Nondispersive Infrared (NDIR) gas detection method will be used as an example.

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2. Nondispersive Infrared (NDIR) gas detection

Pyreos infrared detectors based on pyroelectric material are particularly well suited for gas detection with the NDIR spectroscopy method. High responsivity (200,000 V/W) and the ability to detect infrared radiation over a wavelength range of 2-20µm makes Pyreos detectors suitable for most gas sensing applications.

2.1 General overview describing a typical NDIR system

NDIR spectroscopy is based on a simple yet effective principle of absorption of a wide spectral source by a chosen gas and monitoring detector signal changes at a particular detection wavelength, which correlate to the gas absorption characteristics. A simplified sketch of such system can be found in the Figure 1 below.

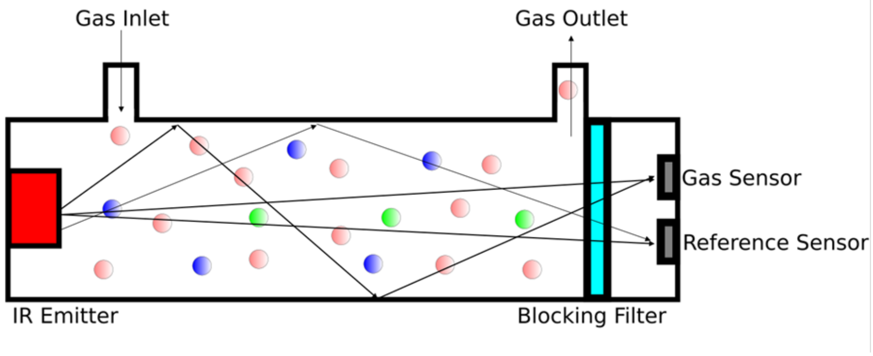

Figure 1 Simplified sketch of an NDIR spectroscopy system

IR emitter (usually a bulb or a MEMS based device) is used to fill the gas tube with a broad range of wavelengths corresponding to the blackbody radiation. Some of these wavelengths will become absorbed by the gas, e.g. CO_2 absorbs well around ~4.26 µm. If such broad spectrum interacted directly with a detector, it would not be possible to measure changes at the gas absorption band. A narrowband filter is required to block everything but the gas absorption band. For example 4.26/90 (CWL/FWHM) in case of CO_2.

2.2 Non-standard filters

Certain NDIR spectroscopy applications require filters which are not typical for most common applications and must poses bespoke spectral characteristics. Reasons for a new type of filter are usually:

- detection of a novel type of gas or gas mixtures (e.g. a new refrigerant),
- spectral variations in the gas detection module
- spectral shift to a non-saturated region

Pyreos works with a network of qualified filter suppliers. Pyreos is able to provide infrared detectors with the appropriate narrowband filter to suit a customer's requirement. A standard and off-the-shelf list of such filters can be found on some of our datasheets or on the Pyreos website: https://pyreos.com/infrared-sensing-by-wavelength/

Bespoke filter wavelengths and bandwidths are available upon request.

3. Filter parameters

3.1 Filter definition

In order to source an IR detector with the required filter characteristic a few basic parameters need to be defined. Below is a list of the most crucial ones:

- Transmission: peak transmission, T_{peak} (see Figure 2) (also minimum transmission spec is used, e.g. ≥75%)
- Central wavelength, CWL (Figure 2)
- Bandwidth, often in Full Width at Half Maximum – FWHM (Figure 2)
- Out of band blocking, for example: UV - band & band - 10µm, at average ≤0.1%, peak ≤1%
- Manufacturing tolerances on the above parameters

Typically, a filter with CWL of 5.30µm and FWHM of 180nm will be described as 5.30/180, see figure below.

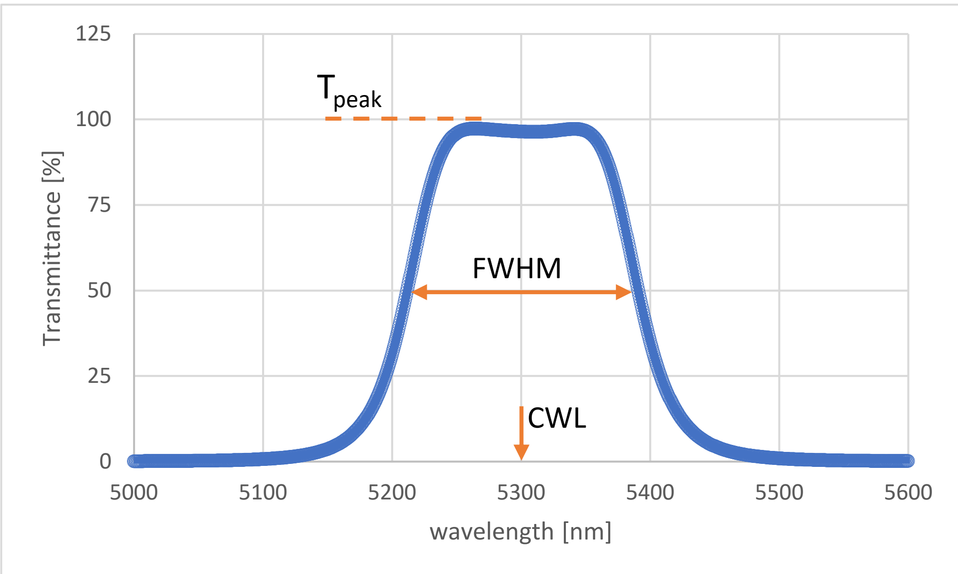

Figure 2 Optical spectrum of a 5.30/180 IR filter

3.2 Spectral Response and blocking range

Interference filters use a stack of interacting layers to produce a material that allows a very specific range of wavelengths to be transmitted. These are part of the pyroelectric gas sensor and allow the changing in signal of the detector to be attributed to a known range of wavelengths.

An important aspect of interference filters is that they have a range of wavelengths that they let through up to a limit. Below is an example of a CO_2 interference filter's wavelength transmissions (Figure 3).

This filter has excellent transmission at the desired wavelength of 4.26µm and blocking range up to ~11µm in wavelength. For some applications, blocking range needs to be extended in order to prevent any unwanted wavelengths on the detector.

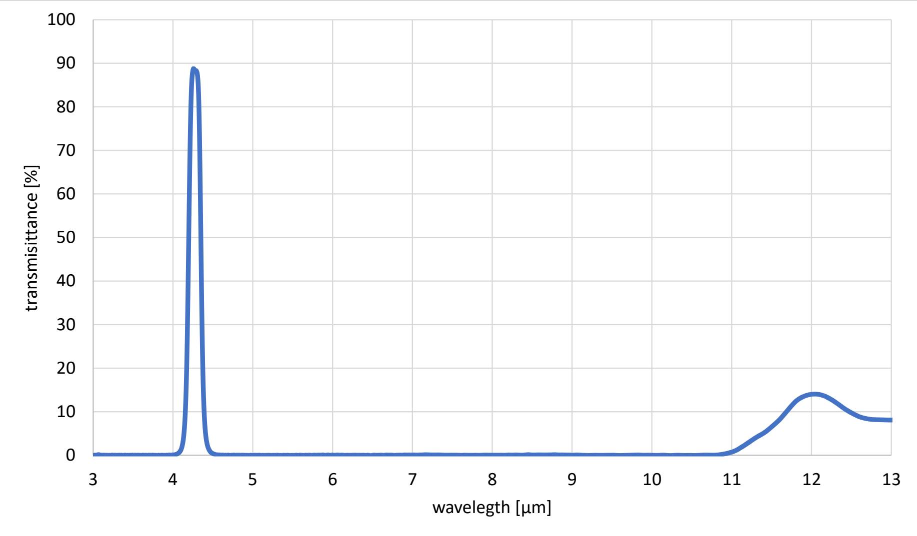

Figure 3 Filter Transmittance spectrum: 4.25µm CWL (central wavelength), 180nm FWHM (Full width at half maximum). Measured in an FTIR spectrometer

This can be achieved with pairing the filter with an IR blocking window of suitable absorption characteristics. For example, a 0.5mm thick MgF_2 would start blocking at ~6µm and extend towards higher wavelengths. Combination of an interference filter used in conjunction with the above blocking window removes any unwanted wavelengths from providing energy to the pixel. Care must be taken in the selection of the blocking window or other optical components to provide adequate attenuation of wavelength selection for the application requirements.

In certain cases, a rigorous and wide blocking range is not required. In NDIR systems, where the IR emitter is an IR bulb, the glass envelope around the emitting material attenuates any light above ~5µm to go through. This is a very cost-efficient solution.

Another way of achieving the required blocking range, which is sometimes used by filter manufactures is to use a blocking window as a substrate for the interference filter (e.g sapphire). In such 'sandwich' configuration it is possible to achieve both narrow band transmission and required blocking range in a single detector product (see Figure 4).

Additionally, an important parameter when it comes to filter choice is the filter substrate material. The most common substrate types are:

1. Silicon,
2. Germanium,
3. IR grade Fused Silica, and
4. Sapphire.

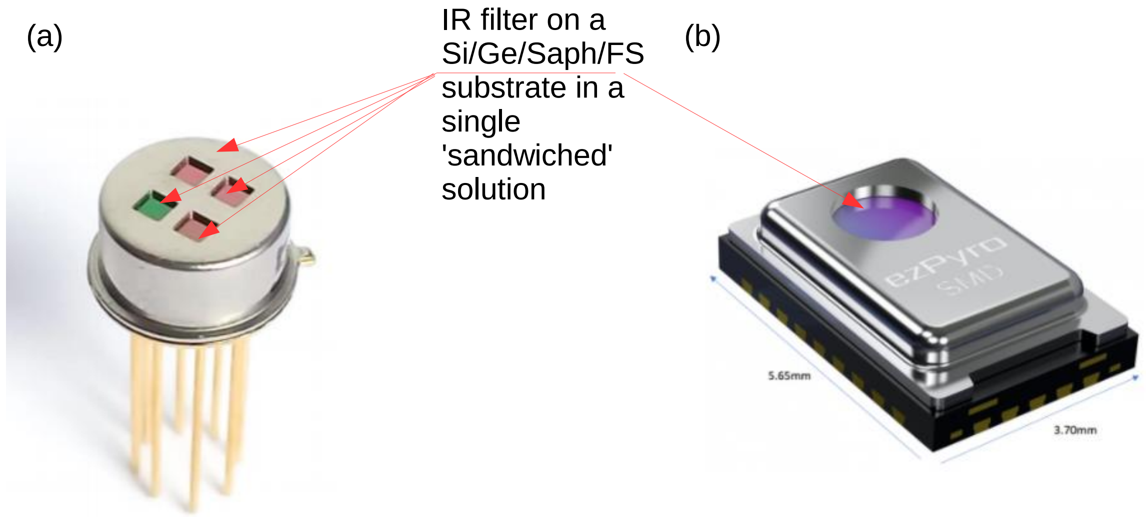

Figure 4 (a) PYREOS quad detector for NDIR spectroscopy (b) Pyreos ezPyro smallest form factor – single digital detector. Si- Silicon, Ge- Germanium, Saph – Sapphire, FS – Fused Silica

Each one of these materials has a different blocking range for a given thickness. Si and Ge lend themselves to cost effective volume manufacturing, while some materials such as Sapphire are less manufacturable due to low yield from filter substrates.

Pyreos can provide IR detectors with diced filters regardless of the material used.

3.3 Main filter parameters and their tolerances

Choosing filter parameters carefully will determine the type of measured gas in NDIR spectroscopy (i.e. by the spectral alignment of the filter with a given gas absorption band) as well as the detection limit (e.g. the narrower the filter bandwidth the lower the peak transmittance of a filter).

Naturally, both CWL and FWHM are prone to manufacturing tolerances. These are specified by filter's supplier and can be tailored to a given application. It is worth reminding that these are extremely important to take into consideration, when gases with close spectral proximity are to be determined by two (or more) separate filters.

For example a CO_2 filter specifications used more commonly are:

4.26/180, CWL ± 30nm, and FWHM ± 20nm

Both tolerances along with the bandwidth can be supplied with a tighter spec if these are crucial for the success of our customer's application, e.g.:

4.26/180, CWL ± 10nm, and FWHM ± 5nm

Pyreos offers detectors in single, dual and quad configurations, with one, two or four pyroelectric chips respectively. In some applications, where a single detector is used to measure up to four gases, a quad detector is chosen. When these gases' absorption spectra overlap between each other (or are located in a spectral vicinity of each other), tolerances on each filter need to be kept tight to prevent spectral overlap.

Anaesthesia is one of such applications, where gases like Desflurane, Isoflurane, Sevoflurane, or Halothane are detected. Pyreos has successfully been providing detectors for this application. For details please see our quad detector datasheet on https://pyreos.com/wp-content/uploads/2020/11/Pyreos-Analog-TO-Four-Channels.pdf

3.4 Filter combinations

In most NDIR spectroscopy applications, main gas channels (in either a single or a multi-channel IR detector) need to be specified according to a couple of rules:

1) CWL/FWHM must overlap with the absorption band of a particular gas
2) Blocking range must be chosen so that the sensing gas signal is not interfering with the reference channel wavelength

Also, in many NDIR applications a reference channel needs to be selected to correct measurement errors caused by emitter drift and environmental conditions (e.g. water condensation). Such reference channel must:

1) not be positioned (spectrally), where the absorption band of a sensing gas is, or other gases expected in the measurement may interfere

Examples:

3.91µm Reference and 4.26µm Gas

The above sensor uses two filters quite close together in wavelength this means that we can pick a cut-off wavelength with a single blocking window that will stop the higher wavelength of transmission for each interference filter. For example Sapphire or magnesium fluoride would cut-off everything over 8µm so these would be suitable choices but research and testing must be done for your specific application to ensure that the system performs as desired under the conditions that it is required to work set by your applications specifications.

3.91µm (Si) Reference and 12.23µm Gas

The above sensor cannot share the same blocking window. Whereas a Sapphire window would block the high wavelength content of the Reference channel it would simultaneously block the main 12.23µm signal for the gas (see Figure 5).

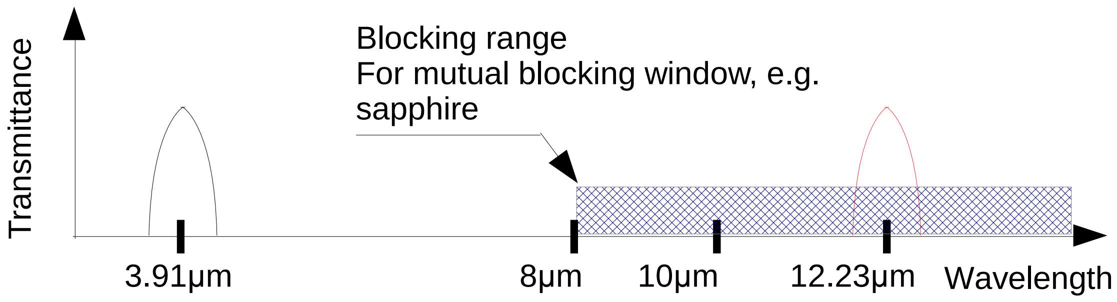

Figure 5 Simplified sketch showing transmittance spectra for both channels blocked with a mutual blocking window

Typically, for a 0.2 - 0.5mm thick, Silicon (Si) based filter at CWL 3.91 µm, the blocking range extends only up to ~10 µm. In such case, both gas signal and the reference signal would be picked up by the reference channel, therefore disrupting the purpose of a reference channel in the first place. By providing a reference filter based on a sapphire substrate instead of silicon, would allow blocking up to ~30µm for the reference channel while not interfering with the gas channel at 12.23µm.

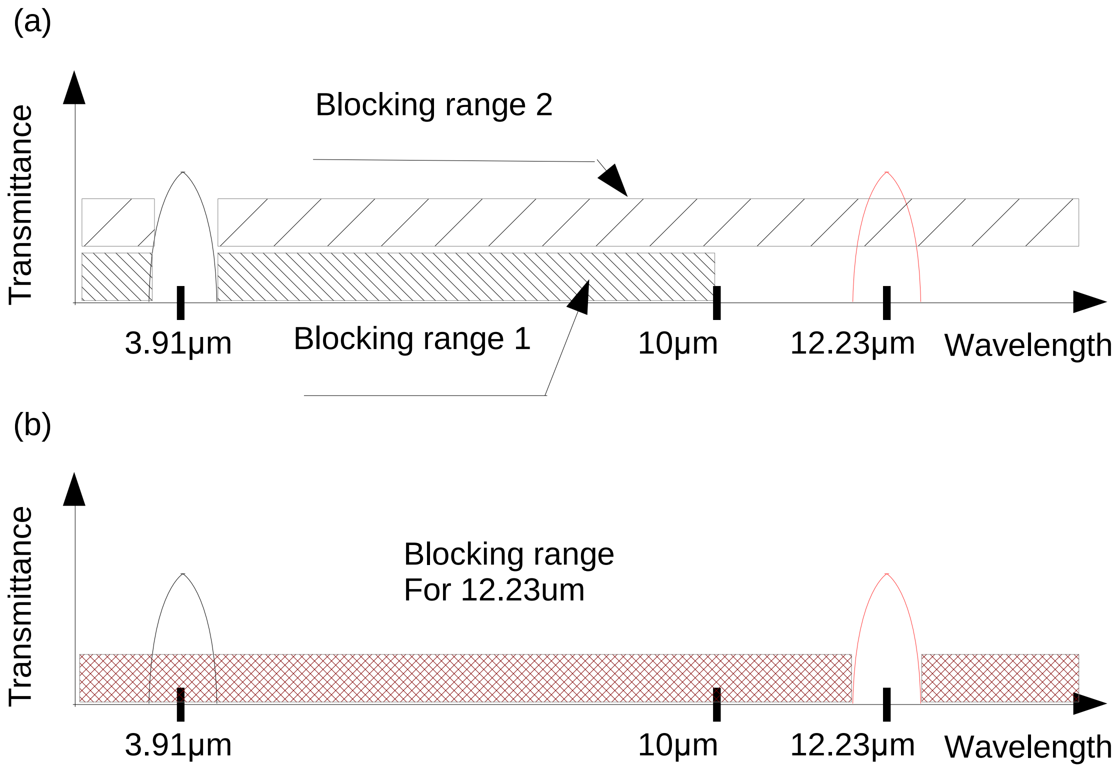

Figure 6 Simplified sketch of transmittance for both channels. (a) reference channel with two blocking ranges depending on the substrate material used, (b) signal/gas channel with its standard blocking range

In some cases it may be desirable to adjust the filter bandwidths of multiple filters used in a given system in order to equalise the signal levels and achieve comparable signal-to-noise ratio on all channels. This is usually not as straightforward as selecting the same FHWM for all of the filters. There are many factors that affect channel signal strength including: spectral profile of the IR source and optics,

3.5 Spectral shift of the central wavelength (CWL)

An IR filter can be described by two main parameters: CWL and FWHM (see paragraph 0). These are true for a normal incidence of light on the surface (see Figure 7) of the filter as well as for a constant environmental temperature mimicking the one for which the filter was manufactured (usually ambient temperature).

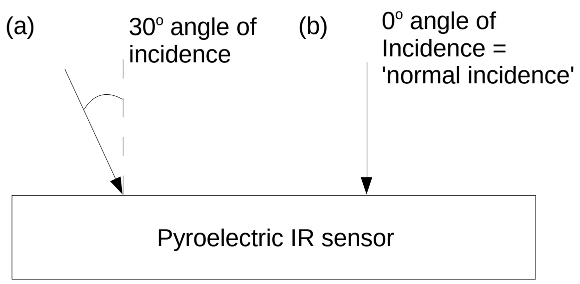

Figure 7 Exemplar light angles of incidence on the detector surface. (a) 30º, (b) 0º, also called 'normal'

If infrared light enters the detector package off-axis or with varying temperature, the CWL will shift. It is particularly important for NDIR spectroscopy when the structure of a gas cell is non-collinear (Figure 8a) or if the IR emitter has a sufficient emission divergence (Figure 8b).

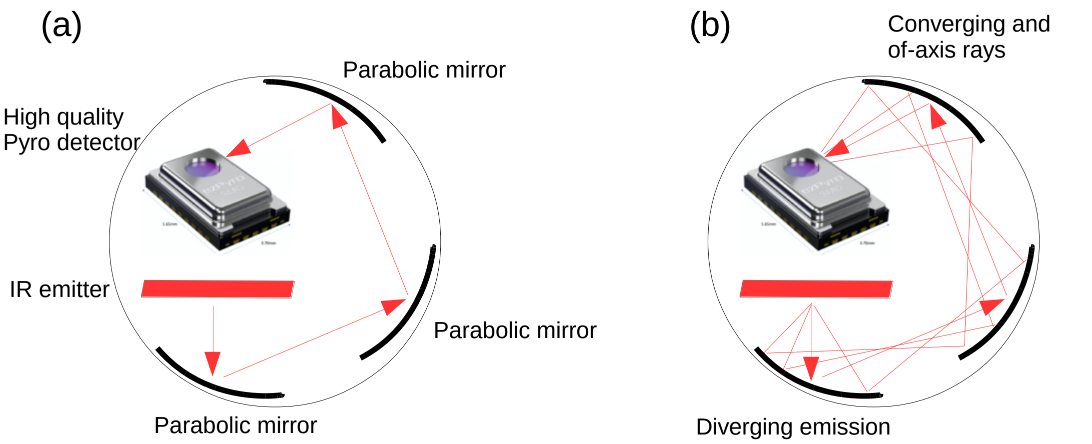

Figure 8 (a) Round gas cell system design (b) diverging IR emission on a pyro detector

The CWL will shift toward the shorter wavelengths while the angle of incidence is increased away from normal (perpendicular incidence). This effect in air follows the formula below:

$$\lambda_\theta = \lambda_0 \sqrt{1 - \frac{sin^2\theta}{n_{eff}}}$$

Where θ is the angle of incidence and n_{eff} is the effective refractive index of the filter.

Figure 9 below, shows measured transmittance spectra of a 5.30/180 IR filter. Four angles of incidence were used: 0º, 15º, 30º and 45º.

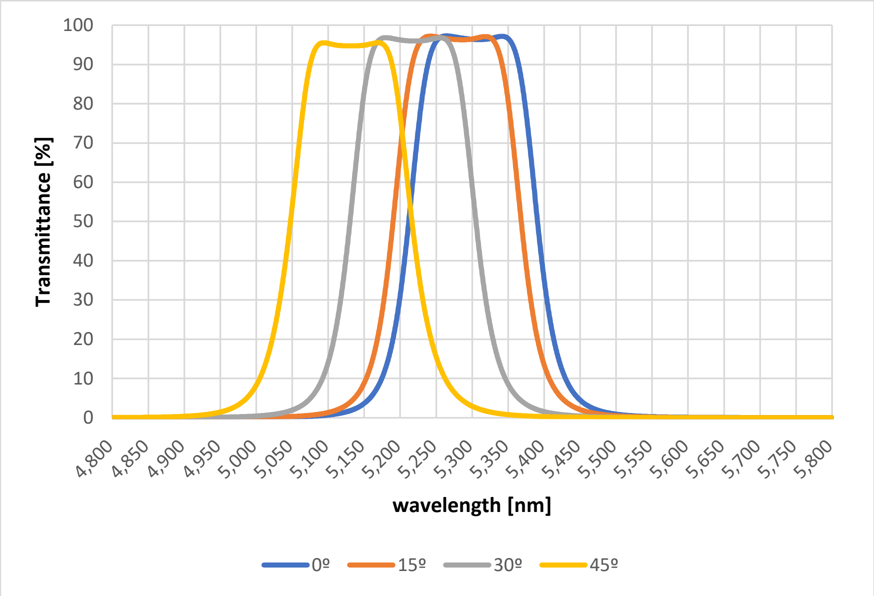

Figure 9 Optical spectrum of a 5.30/180 IR filter under four different angles of incidence

The change of CWL as a function of the ambient temperature of the environment follows the below formula:

$$\lambda_{temp} = \lambda_0 + \Delta T * temp_{coeff}$$

Temperature coefficients are usually in the range of 0.2-0.5nm/ºC hence only significant temperature variations can show substantial shifts in the CWL. In most applications this effect is small and can potentially be ignored.

4. Conclusions

Pyreos sensors are provided with built-in filters for a variety of applications. We source our filters only from trusted suppliers and we are able to work with our customers on bespoke wavelengths for novel gas sensing and substance analysis applications.

At Pyreos, we make sure that a chosen filter is not only suitable for a prototype build but also for a sustainable and cost-effective volume production enabling volume applications previously constrained by high solution cost

