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Integrated multi-wavelength Mid-IR light source for gas sensing

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ABSTRACT

Cost effective multi-wavelength light sources are key enablers for spectroscopic applications at Mid-IR wavelength range. Utilizing a novel Mid-IR Si-based photonic integrated circuit filter and wide-band Mid-IR SLEDs, we show the concept of a light source that covers 2.7…3.5 µm wavelength range with a resolution <1nm. The spectral bands are switchable and tunable and they can be modulated. The source allows for the fabrication of an affordable multi-band gas sensor with good selectivity and sensitivity. The unit price can be lowered in high volumes by utilizing tailored molded IR lens technology and automated packaging and assembling technologies.

The status of the development of the key components of the light source are reported. The Mid-IR PIC is based on the use of thick-SOI technology, SLED is based on AlGaInAsSb materials and the lenses are tailored single crystal, non-oxide glass and heavy metal oxide glasses fabricated by the use of hot-embossing. The packaging concept utilizing automated assembly tools are depicted.

In safety and security applications, the Mid-IR wavelength range covered by the source allows for the detection of several harmful gas components with a single sensor. At the moment, affordable sources are not available. The market impact is expected to be disruptive, since the devices currently in the market are either complicated, expensive and heavy instruments, or the applied measurement principles are inadequate in terms of stability and selectivity.

Keywords: SLED, Si photonics, Mid-IR integrated optics, PIC, Mid-IR lens, photonics packaging, gas sensing

1. MOTIVATION

Cost effective multi-wavelength light sources are key enablers for wide-scale penetration of gas sensors at Mid-IR wavelength range. Utilizing a novel Mid-IR Si-based photonic integrated circuit filter (Mid-IR PIC) and wide-band Mid-IR SLEDs, the H2020 MIREGAS consortium aims at demonstrating an innovative light source that covers 2.7…3.5µm wavelength range with <1nm resolution.[1] The spectral output bands of the light source are ON-OFF switchable and wavelength tuneable. The output cannels can be modulated. When successful, the source allows for the fabrication of affordable multi-band gas sensors with good selectivity and sensitivity. The aim is that the unit price can be lowered in high volumes by utilizing tailored molded IR lens technology and automated packaging and assembling technologies.

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2. OBJECTIVES

The MIREGAS project objectives are the following:

- Use of infrared absorption measurement principle in gas sensing at 2.7 … 3.5 µm wavelength band with up to 100 nm range; Obtain at least 10 times better signal to noise ratio compared to thermal emitters when using a Super luminescent Light Emitting Diode (SLED) emitter.
- Achieving specificity and "re-programmability" of response for different types of target gases by utilizing a novel filtering technique based on the use of a Si Photonic Integrated Circuit (PIC).
- Spectral resolution 10 times better compared to conventional MOEMS filters used currently in gas sensors. Capability for fine tuning then filtering response up to 1 nm resolution allowing for probing single absorption lines.
- Manufacturing cost less than 300€/unit (with 5000 units/year for an example product) when utilizing advanced integration and automated assembling technologies and molded Mid-IR optics. Possibility to upscale production and reduce unit cost.

3. APPLICATIONS

In safety and security applications, the Mid-IR wavelength range covered by the source allows for the detection of several harmful gas components with a single sensor. The project is filling a gap: affordable Mid-IR light sources are not available. The market impact is expected to be disruptive, since the devices currently in the market are complicated, expensive and heavy instruments, or the applied measurement principles are inadequate in terms of stability and selectivity. At the foreseen price level, the proposed approach is extremely competitive against conventional gas sensors. The source will be validated in several key applications including high voltage asset monitoring, emission monitoring, gas leakage monitoring as well as process control and safety.

4. IR GAS SENSING

An IR gas sensor utilizes the fact that gas molecules absorb specific frequencies that are characteristic of the structure of the molecules, so called **spectral signature**. The IR spectrum of a gas sample is recorded by passing a beam of infrared light through the sample and measuring transmission. Gas molecule absorption is seen as absorption lines in the transmission spectrum. The analysis of the position, shape and intensity of peaks in the spectrum reveals details about the molecular structure of the sample. In the gas sensor, the measurement and reference bands can be selected by filters. Gas component concentration can be measured by defining the ratio of the IR transmissions at the measurement and reference bands. This is based on the fact that the absorption at the absorption line is proportional to the concentration of the gas.

Figure 1 shows the IR spectra of a gas mixture and selection of measurement and reference bands for gas sensing. In the MIREGAS concept, these **2.5 nm (1nm)** and **5nm** bands are selected by the use of a Si PIC filter from the emission spectra of a wide-band (**100nm**) SLED light source. The PIC filter includes filtering function to **select spectral bands**, switching or modulating function to **switch** required band(s) to the output or to **modulate** the selected output, and tuning function to **wavelength-tune** the selected outputs. The MIREGAS source is a **programmable, multi-wavelength, Mid-IR source** for Mid-IR **gas sensor** applications in 2.7 µm to 3.5 µm wavelength range.

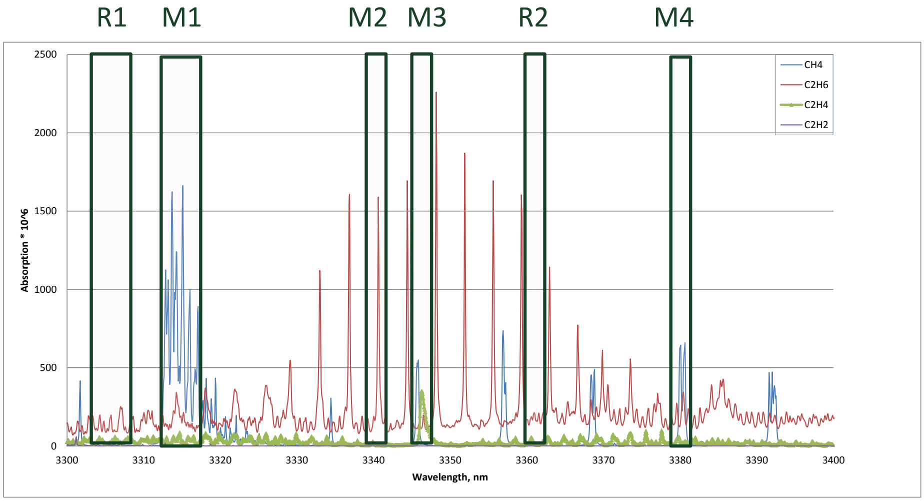

Figure 1. Typical spectral bands used in a Mid-IR instrument: R1= reference, M1= CH_4 measurement, M2=C_2H_6 measurement, M3=CH_4+CSH_4 measurement, R2= reference, M4= C_2H_4 measurement.

5. GAS SENSOR

The schematic drawing of the MIREGAS light source module is shown in Figure 2 left. The functional components of the light source are the SLED, Si PIC filter and molded lens. The gas sensor system is shown in Figure 2 right. The light source and detector are coupled with a gas cavity that includes the gas mixture, which needs to be analyzed. The system analyses the spectral signature of the gas mixture in the sample cavity.

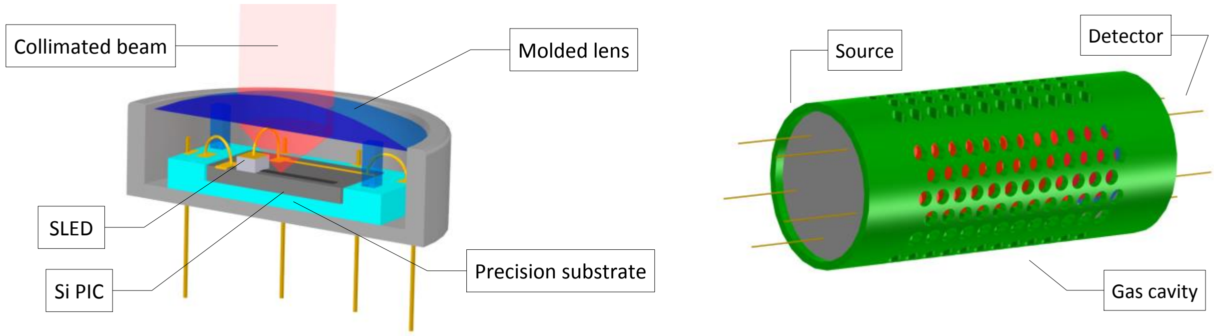

Figure 2. Left: Cross-section view of the MIREGAS source packaged in a non-hermetic package. SLED bonded on the Si PIC, which performs the filtering; collimated output beam by the molded lens. Right: Schematic picture of a gas sensor with the multi-wavelength source, gas cavity and detector.

6. SLED

Superluminescent light emitting diodes (SLEDs) are light sources offering a unique combination of optical characteristics including high brightness, good beam directionality and broad emission spectrum. Compact, wavelength tunable, single-mode light source with low-power consumption emitting at Mid-IR spectral region 2…4 µm are on the demand list of many applications, such as gas sensing, environmental monitoring and medical applications. Detection of multiple environmental gasses with a single measurement device would be enabled by integration of the Mid-IR SLED with the novel Si-PIC filter.

We reported the development of superluminescent diodes (SLDs) emitting almost 40-mW average output power in a broad spectrum centered at 2.55 µm wavelength.[2] The emitting structure consisted of two compressively strained GaInAsSb/GaSb-quantum wells placed within a lattice-matched AlGaAsSb waveguide. According to Figure 3(a), the average output power of more than 3 mW and a peak power of 28 mW were demonstrated at room temperature under pulsed operation. A cavity suppression element was used to prevent lasing at high current injection allowing emission in a broad spectrum with a full width at half maximum (FWHM) of 124 nm shown in Figure 3 (b). The measured far-field of the SLD confirmed a good beam quality at different currents.

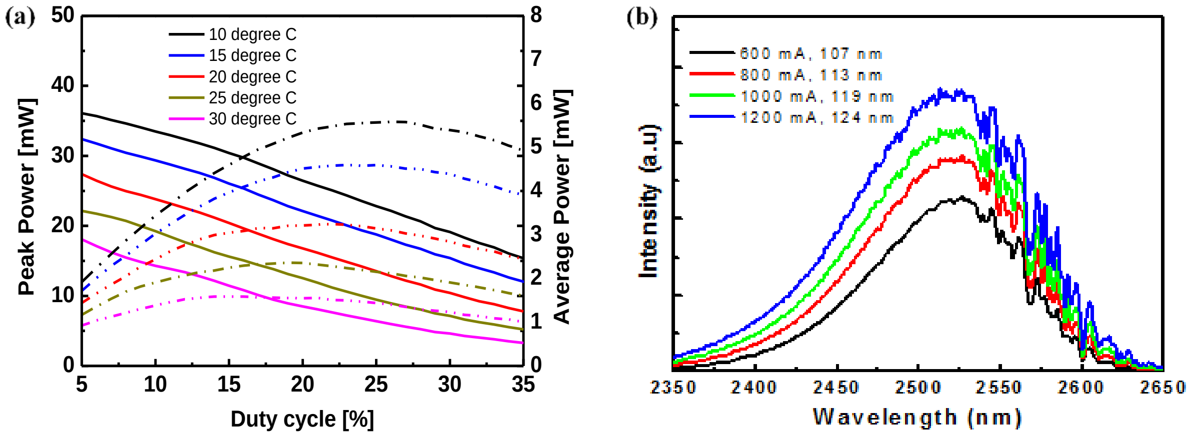

Figure 3. Average (dash line) and peak power (solid line) at different duty cycles for different temperatures. Measurement done with 500 ns pulse width. (b) Spectra at different pulsed current. Measurement done in room temperature with 5 % duty cycle and 500 ns pulse width. Spectral ripples on the trailing edge are possibly due to absorption in air.

Currently, we are working on extending the emission wavelength to the 3-µm region. Devices operating at 2.65 µm are currently under tests. The challenges grow as the operation wavelength increases due to higher Auger recombination (loss mechanism) and degenerated carrier confinement. We will investigate different material and bandgap engineering options to tackle this issue.

7. PIC FILTER

The Si PIC designs utilize spectral filtering and switching or modulation functionalities. The PIC filters for 3.1…3.5 µm wavelength range were designed to match the specs provided by the end users. The designs included echelle gratings with thermo-optic switches. The mask layout is shown in Figure 4 including eight 5 mm × 10 mm devices. The first device on the left top combines the light of two SLEDs in a single output selecting overall nine absorption lines plus two reference channels all independently switchable through 11 switches. The two chips in the bottom-right corner include each two independent designs each of them using a single SLED. In all four case, the absorption peaks belong to a comb structure and a single switch moves the wavelength of all outputs from on-resonance to off-resonance serving at the same time as a switch and as a reference.

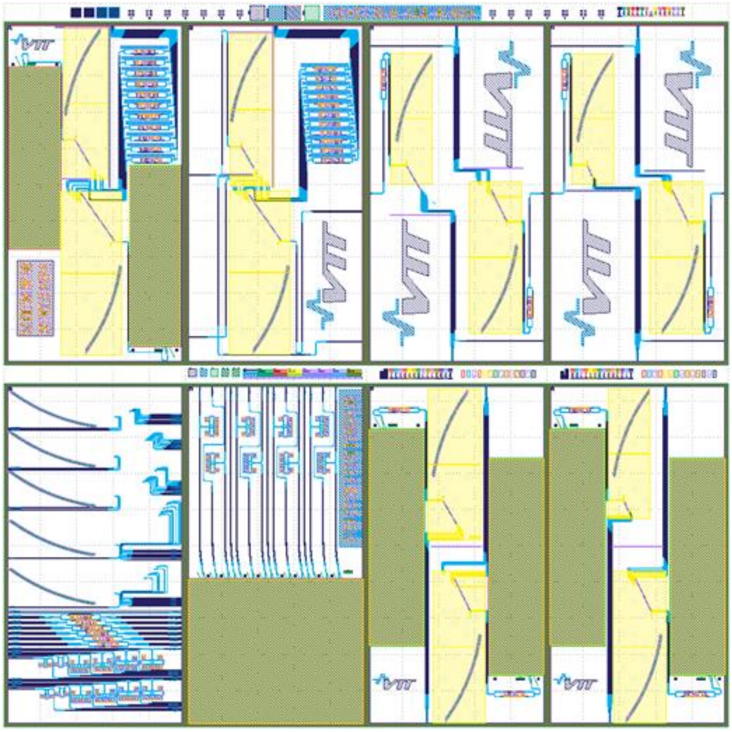

Figure 4. Mask layout of the MID-IR Si photonics filters.

Four SLEDs devices were flip-chip bonded on two PIC chips from the first fabrication run, see Figure 5. Achieved alignment of the SLEDs were quite good and repeatable.

Figure 5 Two SLEDs mounted on a MIREGAS silicon photonics chip.

It is important to highlight that the VTT micron-scale silicon waveguides platform is particularly suitable for Mid-IR applications. In fact, mainstream submicron silicon waveguides suffer from high losses induced by silica absorption already around 2.6 µm wavelength. This is due to the large evanescent field of the mode spreading in the silica cladding. The modes of VTT micron-scale waveguides, however, are very well confined inside the silicon and much less affected by absorption occurring in the silica cladding resulting in low losses till about 4 µm wavelength (< 0.2 dB/cm at 3 µm wavelength and < 0.5 dB/cm at 4 µm wavelength). Another advantage is the low-loss Euler bends allow for reasonably small footprint of devices.[3] They were found to be tolerant to fabrication errors and to work properly on wide wavelength ranges. The device footprints can now be made comparable to those on submicron waveguide platforms, while avoiding many critical issues that are presently faced in dense photonics integration, such as high sensitivity to fabrication errors, polarization dependence, difficult fibre coupling and high cost of fabrication tools.

8. IR LENS

Recent progress in development of new low-cost light sources and optical components stimulate rapid development of mid-IR materials systems. Most of the commonly used optical materials, such as fused silica glass, cannot be used in the Mid-IR wavelength range due to their high attenuation beyond 2 µm. There are three groups of materials especially suitable for refractive optics components for these wavelengths: single crystal, non-oxide glass and heavy metal oxide glass. In particular, heavy metal oxide glasses can be considered interesting because they offer a compromise between low-cost, relatively simple processing and reasonable transmission in the Mid-IR range. In order to shape the output beam of the MIREGAS light source, we report on the development of new refractive and diffractive components using hot embossing technique.

The ongoing work was related to synthesizing a new type of glass, selecting parameters of the hot embossing process, design, fabrication and characterization of the refractive lenses. We developed a new glass (SAB-1A), which does not contain lead and have less attenuation in the range of 2.7 µm to 3.4 µm. Additionally, the SAB-1A glass proved to be mechanically stable and did not adhere to the stamp during hot embossing process.

At the lens design stage, based on computer simulations a plano-convex lens was designed and optimized for wavelength 2.65 µm. On the basis of this design, cemented carbide stamps were made. The SAB-1A glass lenses shown in Figure 6 were fabricate using a tailored hot embossing equipment. What is important the fabrication process with the cemented carbide stamp does not need any additional process. The fabricated lenses were checked for the surface quality and the shape of the spherical surface. The measurements, carried out with the use of the white light interferometer showed that the roughness is at the level of 400 nm. It is an acceptable value for the working wavelength equal 2.65 µm. However, it was found that depending on parameters of the hot embossing process (temperature, force, time) there were fluctuations in the shape of the spherical surface. The developed SAB-1A glass and fabricated refractive lenses meet the requirements of the project.

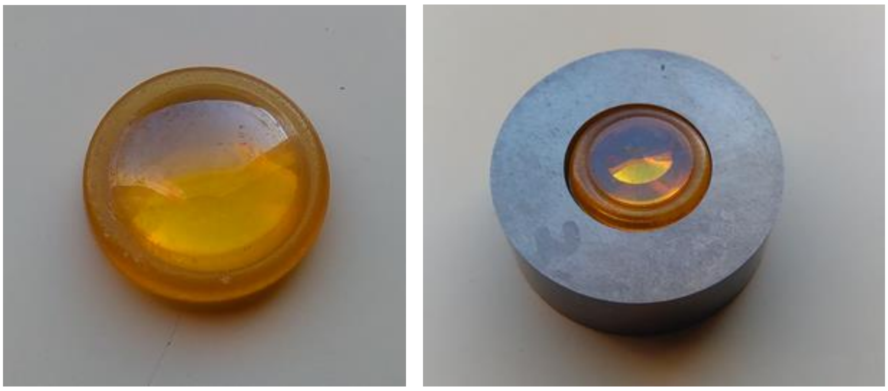

Figure 6. Final refractive lens fabricated without additional process: a) lens, b) lens in the cemented carbide stamp.

9. LIGHT SOURCE PACKAGING

Passive alignment approaches should be always pursued to simplify photonics assembly processes. However, there are situations when passive alignment cannot be accomplished due to technological or economical reason, and therefore, active alignment is needed. Today, high-precision active alignment and bonding processes in the photonics industry rely upon manual or at best semiautomatic processes executed by human operators causing production to be carried out in Asian countries where labor costs are at reasonably low level. High proportion of manual work in the assembly process leads also to low yield in the production and thus increases costs.

We used a high throughput assembly process for the molded lens assembly using an automated assembling tool PMAT, see Figure 7. The aim is to use a combination of machine vision and active alignment techniques together with epoxy bonding for fast (less than 30 s cycle time) and accurate (alignment precision ±1µm) automatic molded lens assembly process. This is an improvement over the state-of-the-art photonic module assembly processes where today either the cycle time is much higher (in the order of a few or even tens of minutes) or alignment precision is lower (in the order of ±10…20µm) – when medium-scale production volumes are considered.

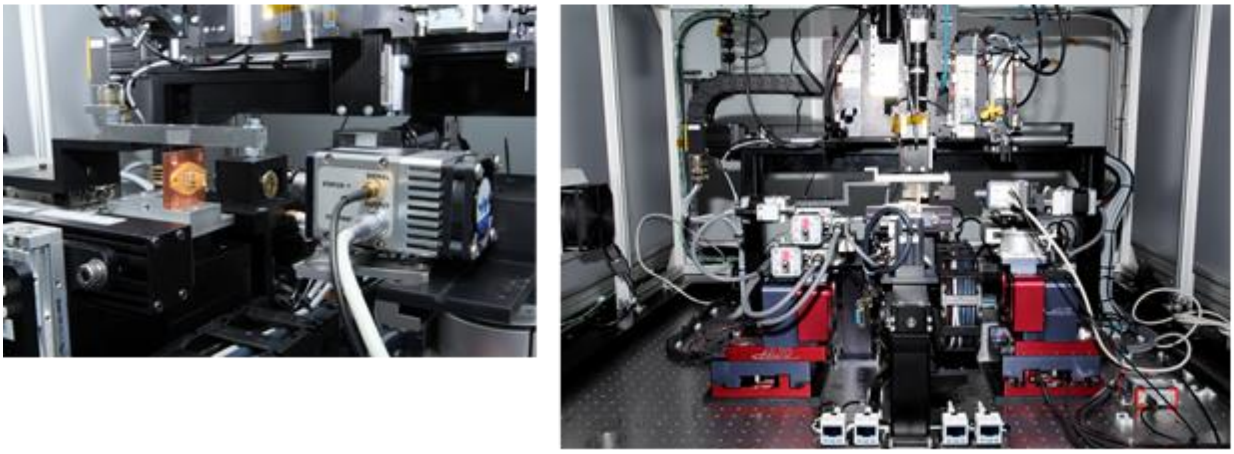

Figure 7 IR lens assembly setup in the PMAT automatic assembly and bonding station.

First, the 2.65 µm SLED devices were bonded on a TO platform shown in Figure 8.

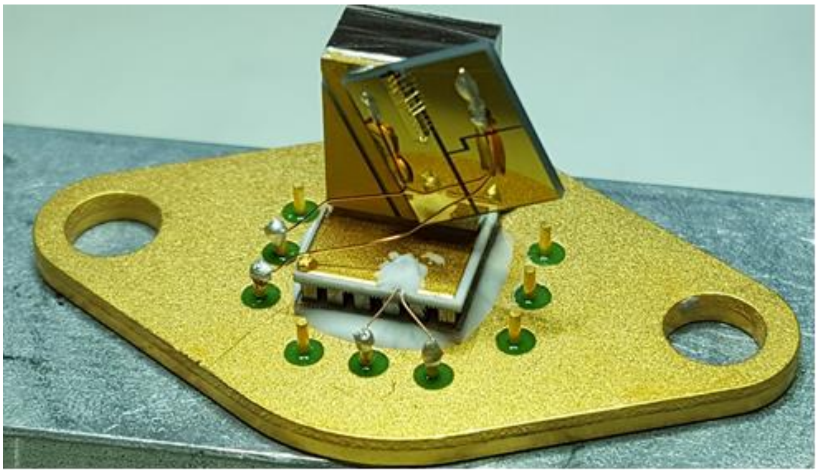

Figure 8. 2.65 µm SLED source packaged on the TO base without a cap.

Then, an IR lens was actively aligned and bonded onto the TO base, see Figure 9.

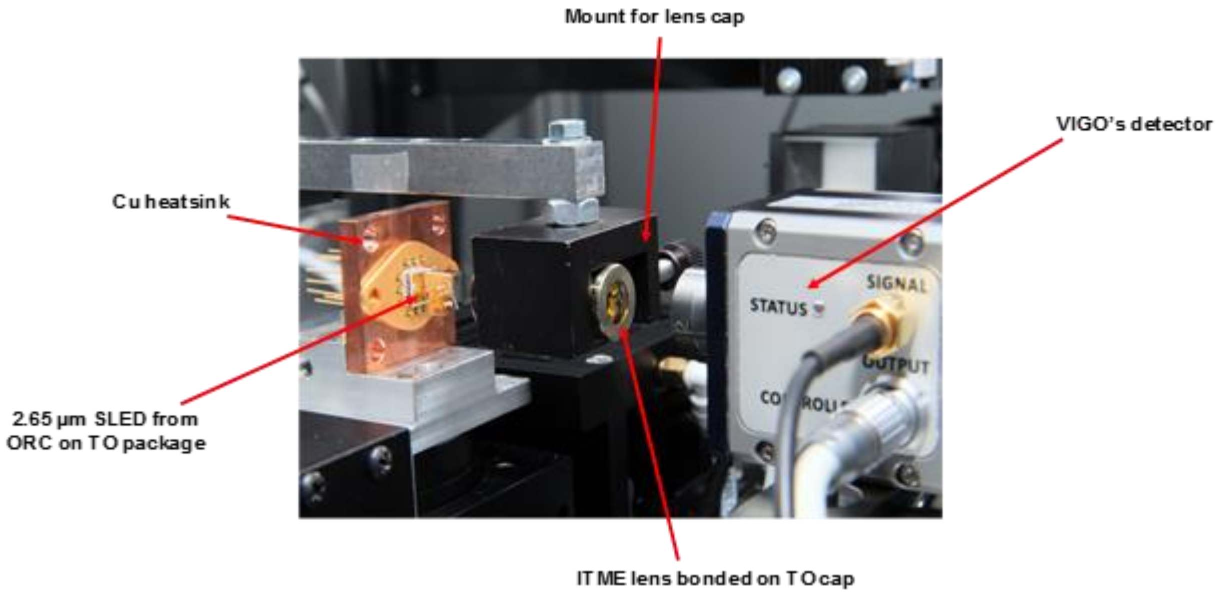

Figure 9 Lens assembly by the use of active assembling tools.

Sealed SLED module with a MID-IR lens is shown in Figure 10.

Figure 10. Assembled 2.65 µm source with an IR lens.

10. IR DETECTORS

We developed detectors for 3.4 µm wavelength based on different material – InAs instead of MCT. The new material does not contain mercury and cadmium and is safe to use in consumer market applications. The detectivities are shown in Figure 11. The results show that the detector is very sensitive for the wavelengths range 2.4…3.4 µm. The next step is the integration with preamplifiers and cooler controllers into the final dedicated detection modules. This opens up many more possibilities for SLEDs, also. Three versions of the sensors were prepared – non-cooled, two stage thermoelectric cooler and three stage thermoelectric cooler.

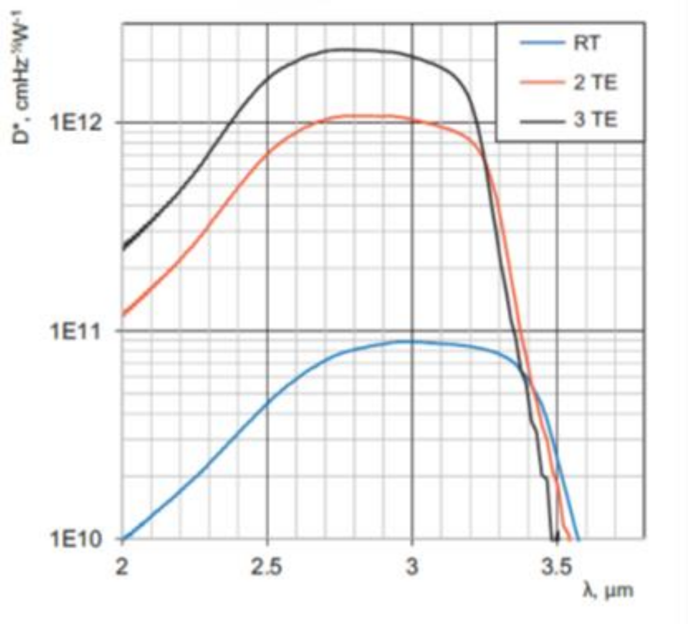

Figure 11. Detectivity curves of the VIGO System InAs sensor (non-cooled and two versions of cooled).

11. SUMMARY AND CONCLUSIONS

Cost effective multi-wavelength light sources are key enablers for gas sensors at Mid-IR wavelength range. Utilizing a novel Mid-IR Si-based photonic integrated circuit filter and wide-band Mid-IR SLEDs, we show the concept of a light source that covers 2.5…3.5 µm wavelength range with a resolution <1nm. The spectral bands are switchable and tunable and they can be modulated. The PIC is based on the use of thick-SOI technology, SLED based on AlGaInAsSb materials and the hot-embossed lenses are based on tailored single crystal, non-oxide glass and heavy metal oxide glasses. The packaging concept utilizing automated assembly tools are depicted.

12. ACKNOWLEDGEMENTS

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