Title	**Multi-wavelength mid-IR light source for gas sensing**
Author(s)	Karioja, Pentti; Alajoki, Teemu; Cherchi, Matteo; Ollila, Jyrki; Harjanne, Mikko; Heinilehto, Noora; Suomalainen, Soile; Viheriälä, Jukka; Zia, Nouman; Guina, Mircea; Buczynski, Ryszard; Kasztelanic, Rafal; Kujawa, Ireneusz; Salo, Tomi; Virtanen, Sami; Kluczynski, Pawel; Sagberg, Håkon; Ratajczyk, Marcin; Kalinowski, Przemyslaw
Citation	Proceedings of SPIE. Vol. 10110, 9 pages
Date	2017
URL	DOI: 10.1117/12.2249126
Rights	Copyright 2017 Society of Photo Optical Instrumentation Engineers (SPIE). One print or electronic copy may be made for personal use only. Systematic reproduction and distribution, duplication of any material in this publication for a fee or for commercial purposes, or modification of the contents of the publication are prohibited.

Multi-wavelength Mid-IR light source for gas sensing

Pentti Karioja*[a], Teemu Alajoki[a], Matteo Cherchi[a], Jyrki Ollila[a], Mikko Harjanne[a], Noora Heinilehto[a], Soile Suomalainen[b], Jukka Viheriälä[b], Nouman Zia[b], Mircea Guina[b], Ryszard Buczyński[c], Rafał Kasztelanic[c], Ireneusz Kujawa[c], Tomi Salo[d], Sami Virtanen[d], Paweł Kluczyński[e], Håkon Sagberg[f], Marcin Ratajczyk[g] and Przemyslaw Kalinowski[g]

[a]VTT Technical Research Centre of Finland Ltd, Kaitoväylä 1, POB 1100, FI905710 Oulu, Finland;
[b]Optoelectronics Research Centre, Tampere University of Technology, Tampere, Finland;
[c]Institute of Electronic Materials Technology, Wolczynska 133, Warsaw, Poland;
[d]Vaisala Oyj, Vanha Nurmijärventie 21, 01670 Vantaa, Finland;
[e]Airoptic sp. z o.o., Rubierz 46H, Poznan, Poland;
[f]GasSecure, Hoffsveien 70C, Oslo, Norway;
[g]VIGO System S.A., ul. Poznanska 129/133, 05-850 Ozarow Mazowiecki, Poland

ABSTRACT

Cost effective multi-wavelength light sources are key enablers for wide-scale penetration of gas sensors at Mid-IR wavelength range. Utilizing novel Mid-IR Si-based photonic integrated circuits (PICs) filter and wide-band Mid-IR Super Luminescent Light Emitting Diodes (SLEDs), we show the concept of a light source that covers 2.5…3.5 µm wavelength range with a resolution of <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 PIC is based on the use of micron-scale SOI technology, SLED is based on AlGaInAsSb materials and the lenses are tailored heavy metal oxide glasses fabricated by the use of hot-embossing. The packaging concept utilizing automated assembly tools is depicted.

In safety and security applications, the Mid-IR wavelength range covered by the novel light source allows for detecting 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, PIC, Si photonics, Mid-IR optics, Hot-embossing, photonics packaging automation

1. MOTIVATION

Cost effective multi-wavelength light sources are key enablers for wide-scale penetration of gas sensors in the Mid-IR wavelength range. Utilizing novel Mid-IR Si-based PIC filters and wide-band Mid-IR SLEDs, the H2020 MIREGAS consortium aims at demonstrating an innovative light source that covers 2.5…3.5µm wavelength range with sub-nanometer resolution. The spectral output bands of the light source can be tuned and also individually switched on and off; and therefore, modulated for time-domain multiplexing and lock-in amplification. When successful, the source allows for the fabrication of affordable multi-band gas sensors with good selectivity and sensitivity. The aim is to lower the unit price in high volumes by utilizing tailored molded IR lens technology and automated packaging and assembling technologies.

---

*pentti.karioja@vtt.fi; phone +358 407307529; www.vtt.fi

2. OBJECTIVES

The MIREGAS project objectives are the following:

- Use of infrared absorption measurement principle in gas sensing at 2.5 … 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 sub-nanometer 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 proposed source allows for detecting 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, filters are selecting the measurement and reference bands specific for the application. 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 the 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 2.5 µm to 3.5 µm wavelength range.

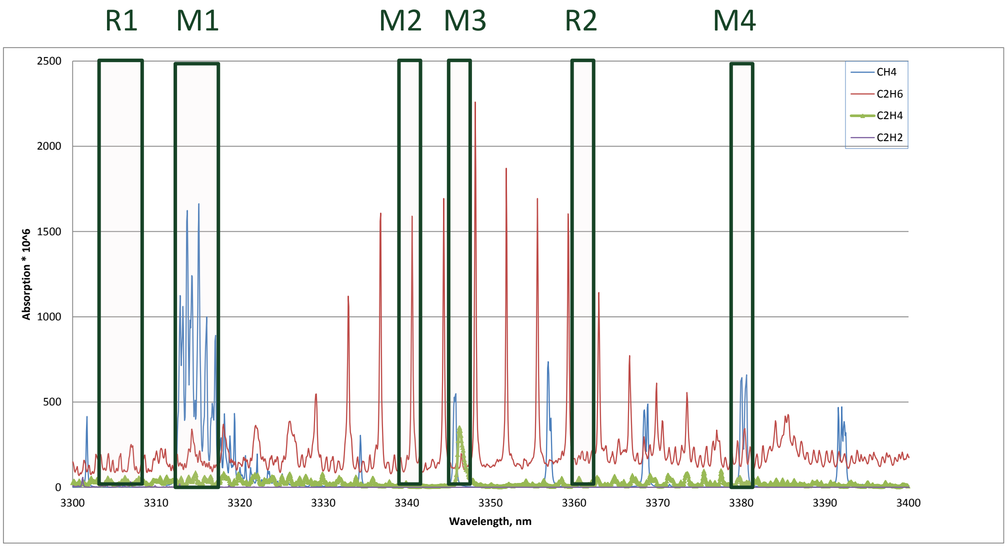

Figure 1. Typical spectral bands used in a Mid-IR instrument: R1= reference, M1= CH_4 measurement, M2=C_2H_6 measurement, M3=CH_4+CSH_4 measurement, R2= reference, M4= C_2H_4 measurement.

5. GAS SENSOR SYSTEM

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.

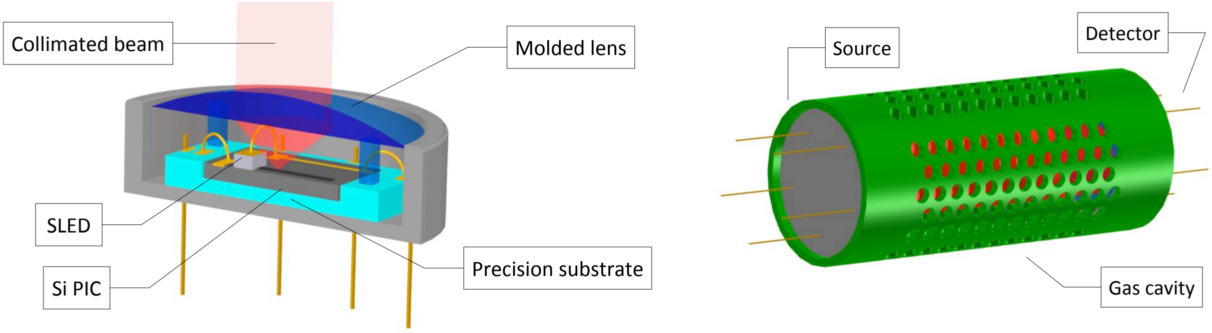

Figure 2. Left: Cross-section view of the MIREGAS source packaged in a non-hermetic package. SLED bonded on the Si PIC, which performs the filtering; collimated output beam by the molded lens. Right: Schematic picture of a gas sensor with the multi-wavelength source, gas cavity and detector.

6. PIC FILTER

The switch or modulator will take advantage of the high flexibility of filter design in integrated optics. A simple example is shown in Figure 3. A demultiplexer (DEMUX) is used to separate different spectral bands. Each waveguide can be modulated (switched on and off) and the output of the switch array can be multiplexed again in a single waveguide using a mirror-symmetric version of the DEMUX as a multiplexer (MUX). Alternatively, multiplexing could be skipped, if all the waveguides are placed very close to each other (micron-scale pitch).

After a thorough evaluation of different possible implementations of the (DE)MUX, echelle gratings were chosen as the most suitable solution for these applications. They can be easily designed to have channel bandwidths ranging from several nanometres to fraction of nanometres, and free spectral range (FSR) exceeding the bandwidth of the SLED source. Switching is achieved via Mach-Zehnder interferometers (MZIs) with a thermo-optic control of the relative phase between the arms, providing up to ~100 kHz modulation frequency and low power consumption (25 mW for a π phase shift).

We point out that more than one switch can be tuned on at the same time, making it possible to shine multiple bands at once. This could be used for example to match the most important C_2H_6 lines shown in Figure 1 to highlight the unique "signature" of the gas. A similar approach could be adopted to singularly match all the peaks in the M1 band in Figure 1.

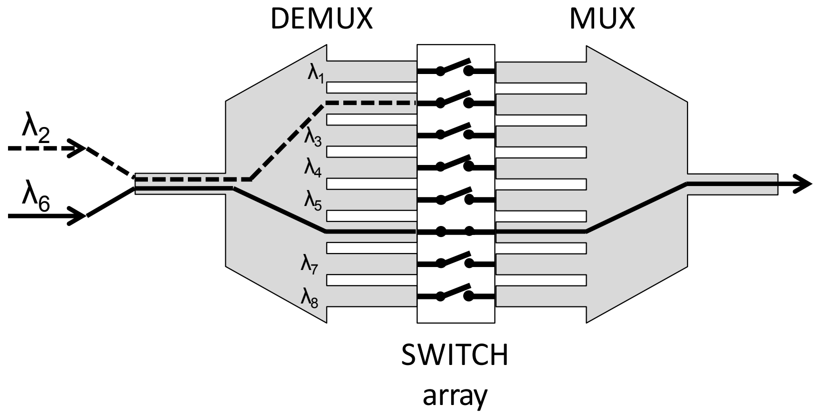

Figure 3. Schematic of the proposed (de)multiplexing and switching approach.[1]

The relatively high thermo-optic coefficient of Si will be also exploited to fine tune the filters and also for continuously tuning them across the resonance. Wavelength tuning of several nanometers is possible through suitably designed micro-heaters with low power consumption.

The possibility to tailor a spectral response to match any wanted set of absorption lines with any desired bandwidth is clearly a major advantage of the proposed filtering approach when compared to the intrinsically periodic response of Fabry-Perot combs or to the single narrow line of a tunable laser. Suitable architectures including cascades of MUXs and DEMUXs can be efficiently used to select hundreds of different bands using only a few tens of switches, as depicted in Figure 4.

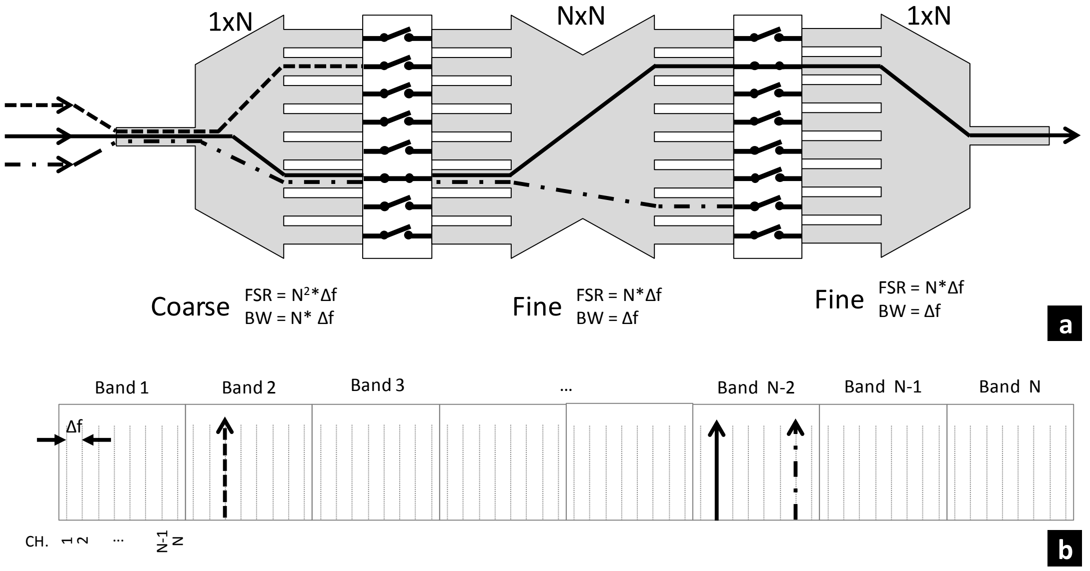

Figure 4. Suitable cascade of (DE)MUX stages can be used to select hundreds of different channels using a few tens of switches.

We point out that MUX stages similar to the ones presented so far can be designed and fabricated to combine, in a single waveguide, the light coming from multiple SLEDs optimized for different wavelength ranges. This allows for increasing the spectral brightness of the source (to improve sensitivity) or to further expand the wavelength range covered by the source module.

It is important to highlight that micron-scale silicon waveguides of VTT platform are 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. This is due to the large evanescent field of the mode spreading in the silica cladding. Instead, the modes of VTT micron-scale waveguides 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).

7. 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 or medical spectroscopy. 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.

The development of SLEDs emitting in the 2…3 µm spectral range has until recently received little attention due to several peculiar aspects of GaSb-technology, which is not widely available. We have recently demonstrated GaSb-SLEDs emitting at 2 µm with different waveguide designs[2, 3]. By selecting the waveguide design, we were able to increase the output power from sub-mW level to several tens of mW, see Figure 5.

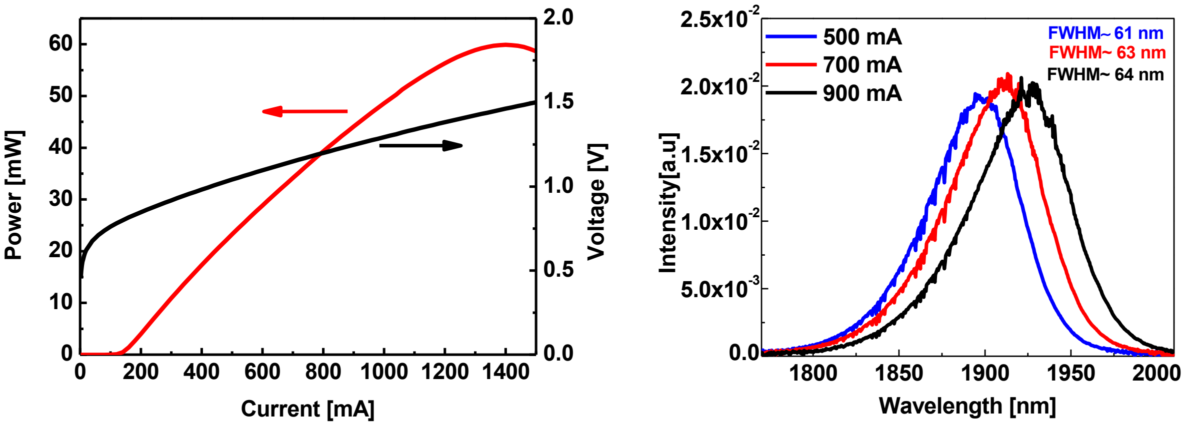

Figure 5. Left: Illustration of LIV-properties of the SLED chip mounted on a heatsink at room temperature[3]. Right: Illustration from spectrum at different current[2].

Recently, we reported SLEDs emitting at 2.65 µm. The structure consists of two GaInAsSb-quantum wells embedded in lattice-matched AlGaAsSb-waveguide and cladding-layers on a GaSb-substrate. The SLED exhibited nearly 0.5 mW output power and the spectrum was 300 nm wide, as shown in Figure 6. To the best of or knowledge these are the first SLED results at such long wavelength.

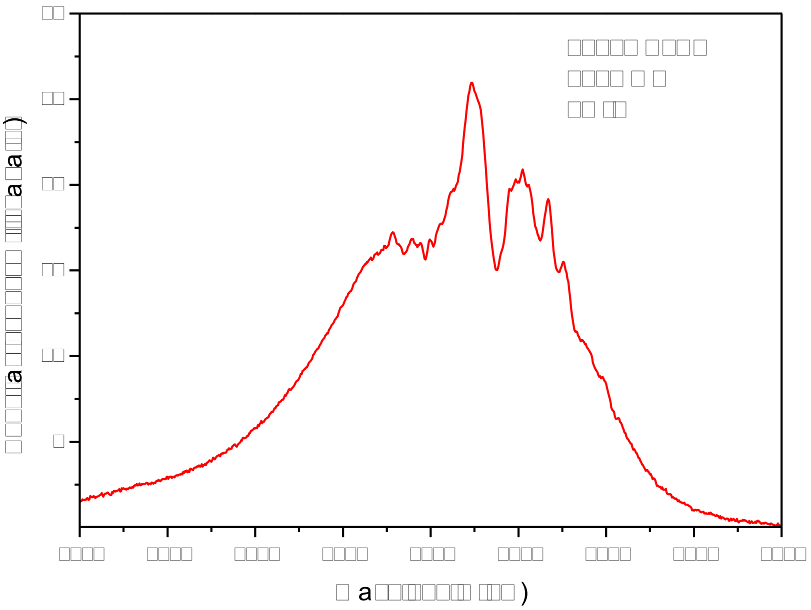

Figure 6. Typical spectrum demonstrating the broadband emission capabilities.

Currently, we are working on extending the emission wavelength to the 3-µm region. 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.

8. IR LENS

The output beam from the PIC filter is strongly divergent. In order to perform the measurement and detect the signal, we needed to collimate the beam with the use of a tailor-made macroscopic refractive lens. Unfortunately, most of the commonly used optical materials, such as fused silica glass, cannot be used to fabricate the lens for 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 the Mid-IR wavelengths: single crystal, non-oxide glass and heavy metal oxide glass. We used heavy metal oxide glasses due to the fact that they offer a compromise between low-cost, relatively simple processing and reasonable transmission in the Mid-IR range. We developed new glasses types, which do not contain lead and have low attenuation in the range of 2.5 … 3.5 µm, see Figure 7.

To fabricate the refractive lens of more than 10 mm diameter we used the Hot Embossing (HE) technique[4,5]. HE provides sufficient precision and can be used for the treatment of oxide glasses. However, HE requires the determination of multiple parameters like the speed of heating and cooling, the temperature of the embossing process and the force and time of pressure. There is also an important issue of selecting the glass material for the stamp and for the lens. The optimization of all these parameters allowed us to produce tailored refractive lenses, see Figure 8. In the setup the lens plays a dual role: it collimates the light onto the detector and hermetically seals the SLED source and PIC filters.

We fabricated a series of lenses with in-house developed heavy metal oxide glass labeled SAB1 with diameter of 12.8 mm and focal length of 15 mm to match diameter of TO package and separation between the lens and PIC filter required for beam collimation.

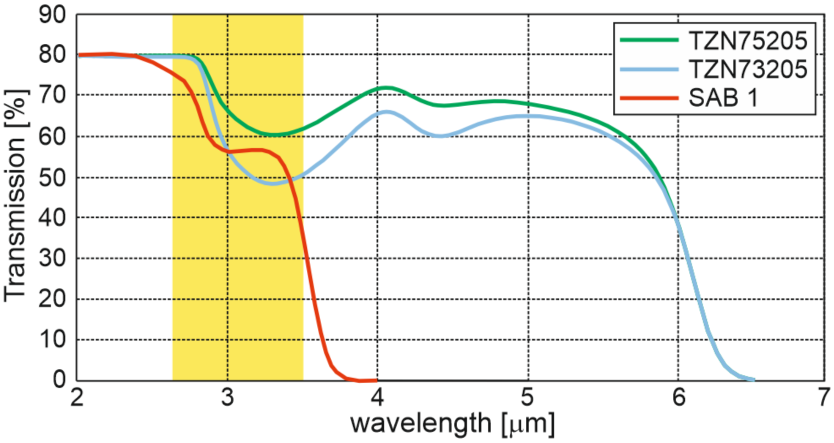

Figure 7. Spectral transmission of the developed glasses for a 2 mm sample. The yellow area represents an interesting wavelength range.

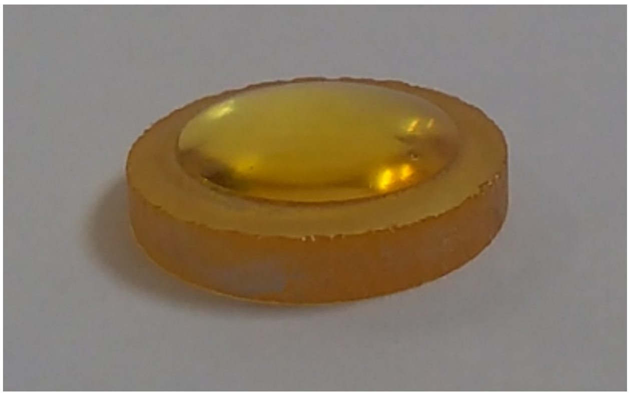

Figure 8. Example of a fabricated lens based on heavy metal oxide glass. The lens has a diameter of 12.8 mm and focal length of 15 mm.

9. LIGHT SOURCE PACKAGING

VTT has earlier made several photonics packaging demonstrators for different applications including optical interconnects, atomic clock, Photoacoustic gas sensor, for example. In harsh environments, we have mostly used Low Temperature Co-Fired Ceramics (LTCC) technology for packaging and integration.[6,7] For the MIREGAS light source packaging, however, conventional TO package seems to be the most favorable form factor as a starting point. The customization comes with assembling as well as sealing of the IR lens and thermal management and flip-chip bonding of the SLED. Volume manufacturing and affordable price is targeted; therefore, automated photonic packaging methods are developed and tested.

SLED bonding on the Si PIC: The SLED devices are flip-chip bonded on the Si PIC chips by the use of thermo-compression bonding. The alignment of the SLED chip with the single-mode waveguide requires sub-micron alignment tolerances. As a rule of thumb, the alignment tolerances must be about 10% of the mode size, which is typically in the order of 3…4 μm. Vertical alignment is well within the tolerances due to the precise thickness control (<100nm) of the gold layers used for thermo-compression bonding. Up to 1 μm gap between the waveguide and the SLED can be tolerated. The most critical alignment is the lateral direction.

Molded lens assembly: 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.

There are today just a few examples of high volume photonic products in the markets that require high precision alignment and are produced in automated production environments. Of the products utilizing fully passive alignment fiber pigtailed transceiver modules for high-speed Ethernet networks could be mentioned. Automated assembly process utilizing active alignment is carried out, for instance, in automotive camera assembly, see Figure 9. Actually, automotive cameras are today biggest market for automatic active alignment and bonding equipment. In these examples, automation is justified mainly because for product volume and cost reasons. However, since the repeatability and reliability of the automated assembly processes are significantly higher than that of manually achieved, automation should be considered for all designs.

In the MIREGAS project, high throughput agile assembly process will be developed for the molded lens assembly using an automated assembling tool, PMAT. 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.

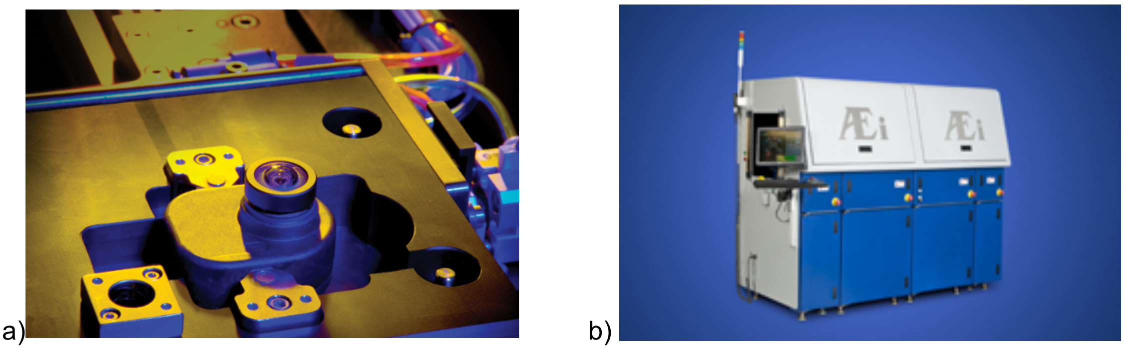

Figure 9. (a) Automotive camera in pallet fixture (b) CMAT assembly machine. Source: http://www.aeiboston.com

Device bonding: High-precision adhesive bonding has gained much interest during recent years due to the fact that the production equipment are much cheaper and metal subassemblies are not necessary leading to significantly lower costs and higher miniaturization level. There are currently very low-shrinkage epoxies available in the market, which can be used in bonding of photonic components. However, the assembly flow when applying adhesive bonding requires deep knowledge of material behavior and careful process optimization when high precision is required. Therefore, it is not widely used in photonics packaging, at least so far.

Advance in the MIREGAS project is to apply epoxy bonding process as much as possible. However, the sealing the lens is carried out by the use of solder glasses in order to guarantee the hermeticity of the package. Laser welding is used to bond the cap onto the TO header. In the same time, hermetic sealing of the package is achieved.

To date, we have achieved of our intermediate goals by developing a prototype of 2.7-µm SLED light source packaged in a TO can equipped with a Mid-IR lens. Figure 10 shows the first packaging mock-up demonstrating the form factor of the novel light source.

Figure 10. First mock-up module showing the form factor of the packaged MIREGAS light source.

10. SUMMARY AND CONCLUSIONS

Cost effective multi-wavelength light sources are key enablers for gas sensors at Mid-IR wavelength range. Utilizing novel Mid-IR Si-based PICs and wide-band Mid-IR SLEDs, we are targeting to demonstrate the concept of a light source that covers 2.5…3.5 µm wavelength range with a resolution <1nm. The PIC is based on the use of thick-SOI technology. Until now we have made PIC filter designs and processing based on echelle grating configuration. For the SLED, we have reported SLEDs emitting at 2.65 µm with nearly 0.5 mW output power and 300 nm wide emission spectra. To the best of our knowledge these are the first SLED results at such long wavelength. In addition, we fabricated a series of Mid-IR lenses with diameter of 12.8 mm and focal length of 15 mm using hot-embossing and in-house developed heavy metal oxide glass labeled SAB1. To date, we have fabricated a prototype of 2.7-µm SLED light source packaged in a TO can equipped with the Mid-IR lens. The packaging concept utilizing automated assembly tools will be elaborated in the next phase of the project.

REFERENCES

[1] Aalto T. *et al.*, “Multi-wavelength transceiver integration on SOI for high-performance computing system applications,” Proc. SPIE 9368, 93680B-93680B-10 (2015).

[2] Zia N., Viheriälä J., Koskinen R., Koskinen M., Suomalainen S., and Guina M., "Fabrication and characterization of broadband superluminescent diodes for 2 µm wavelength," Proc. SPIE 9768-24, (2016).

[3] Zia N. *et al.*, “High power (60 mW) GaSb-based 1.9 µm superluminescent diode with cavity suppression element,” Appl. Phys. Lett. 109, 231102 (2016); 10.1063/1.4971972

[4] Kasztelanic R., Kujawa I., Ottevaere H., Pysz D., Stepien R., Thienpont H., Buczynski R., “Optical quality study of refractive lenses made out of oxide glass using hot embossing,” Infrared Physics & Technology, Vol. 73, 212–218 (2015).

[5] Kasztelanic R., Kujawa I., Stępień R., Haraśny K., Pysz D., Buczyński R., “Molding of soft glass refraction mini lens with hot embossing process for broadband infrared transmission systems,” Infrared Physics & Technology, Vol. 61, 299-305 (2013).

[6] Karioja P. *et al.*, “LTCC toolbox for photonics integration,” Proc. of Ceramic Interconnect and Ceramic Microsystems Technologies (CICMT 2006), 12 p., (2006).

[7] Karioja P. *et al.*, ”MEMS, MOEMS, RF-MEMS and photonics packaging based on LTCC technology,” Proc. Electronics System-Integration Technology Conference ESTC 2014, 6 p. (2014).