

# Lippmann waveguide spectrometer with enhanced throughput and bandwidth for space and commercial applications

MOHAMMAD MADI,<sup>1,5,\*</sup> FREDERIK CEYSSENS,<sup>2</sup> IVAN SHORUBALKO,<sup>3</sup> HANS PETER HERZIG,<sup>4</sup> BENEDIKT GULDIMANN,<sup>5</sup> AND PHILIPPE GIACCARI<sup>1</sup>

<sup>1</sup>Micos Engineering GmbH, Überlandstrasse 129, CH-8600, Dübendorf, Switzerland <sup>2</sup>ESAT-MICAS, University of Leuven, Kasteelpark Arenberg 10, B-3001 Heverlee, Belgium <sup>3</sup>Transport at Nanoscale Interfaces, Swiss Federal Laboratories for Materials Science and Technology (Empa), Überlandstrasse 129, CH-8600 Dübendorf, Switzerland <sup>4</sup>Ecole Polytechnique Fédérale de Lausanne (EPFL), Optics and Photonics Technology Laboratory, Neuchâtel CH-2000, Switzerland <sup>5</sup>European Space Agency (ESA), European Space Research and Technology Centre (ESTEC), Postbus 299-2200 AG Noordwijk, The Netherlands

<sup>\*</sup>mrmadi@gmx.ch, philippe.giaccari@micos.ch

Abstract: This article presents an innovative high spectral resolution waveguide spectrometer, from the concept to the prototype demonstration and the test results. The main goal is to build the smallest possible Fourier transform spectrometer (FTS) with state of the art technology. This waveguide FTS takes advantage of a customized pattern of nano-samplers fabricated on the surface of a planar waveguide that allows the increase of the measurement points necessary for increasing the spectral bandwidth of the FTS in a fully static way. The use of a planar waveguide on the other hand allows enhancing the throughput in a waveguide spectrometer compared to the conventional devices made of single-mode waveguides. A prototype is made in silicon oxynitride/silicon dioxide technology and characterized in the visible range. This waveguide spectrometer shows a nominal bandwidth of 256 nm at a central wavelength of 633 nm thanks to a custom pattern of nanodisks providing a 0.25  $\mu$ m sampling interval. The implementation of this innovative waveguide FTS for a real-case scenario is explored and further development of such device for the imaging FTS application is discussed.

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#### 1. Introduction

The inherent challenge in classical Michelson-based interferometers of displacing a moving mirror with high precision for producing optical path difference (OPD) has stimulated the development of simpler FTS devices without moving parts, but at the same time without compromising the large throughput advantage [1]. The detection of a interferogram directly in the spatial domain, which is the basis of Lippmann-based waveguide spectrometers, was proposed in early development of FTS [2]. Nonetheless, the development of such spectrometers has not been possible before the availability of photo-detector arrays [3].

In Lippmann concept, waveguide spectrometers work based on the principle of light interference phenomena that was used for the first time in 1891 by Gabriel Lippmann [4]. A first realization of high spectral resolution waveguide spectrometer did not happen until 2007, when Le Coarer et al. [5] introduced Stationary-Wave Integrated Fourier-Transform Spectrometry (SWIFTS) based on the Lippmann interference concept by taking advantage of photonics and near-field optics in which direct sampling of evanescent standing-waves is achieved using a collection of optical nano-samplers.

We report the conceptual design and prototype development of a fully integrated waveguide spectrometer with enlarged throughput and enhanced spectral bandwidth, compared to conventional waveguide spectrometers [5–9]. In this new instrument, customized patterns of nano-samplers are fabricated on the surface of planar waveguide. This new technique has made it possible to perform spatial sampling with variable sampling distance in the same waveguide aiming at increasing the measurement points of the interferogram which is required for enlarging the spectral bandwidth in a static way without mechanism. Likewise, this helps to adapt the sampler design to any specific need and avoid the Bragg grating effect in the waveguide.

The developed prototype consists of various subsystems, as shown in Fig. 1, including a light source, front-end optics for Gaussian beam shaping, waveguides for interferogram formation, nano-samplers (nanodisks) for sampling the evanescent fields, imaging sensors for data acquisition, and the post-processing software for data treatment and spectral reconstruction. In the heart of the device, the propagation in the unconfined direction of the planar waveguide is controlled using the adapted front-end optics to maintain the superposition of forwarding and reflected beams to form the interferogram under the nano-samplers grids. The final prototype is a waveguide spectrometer with no moving parts; it is simple, robust, accurate (radiometrically and spectrally) and at the same time low cost and reliable.



Fig. 1. Subsystems of a waveguide spectrometer prototype.

Polymeric- and silicon oxynitride-based planar waveguides were manufactured, evaluated and tested for studying mode profile in planar waveguides. The nano-samplers are gold nanodisks of few tens of nanometers in diameter and thickness, optimized for sampling the visible light coupled in the waveguide module of the spectrometer. A waveguide spectrometer prototype is made in silicon oxynitride/silicon dioxide technology and characterized in visible range at 633 nm using a stable monochromatic laser source. This waveguide spectrometer as a first prototype shows a nominal bandwidth of 256 nm thanks to a custom pattern of nanodisks providing 0.25  $\mu$ m sampling interval at central wavelength of 633 nm.

# 2. State of the art

Investigation on miniaturized spectrometric devices is actually a worldwide effort covered by a number of different approaches with ongoing studies at different research institutes. In spaceborne applications, spectrometers have long been a key element and their miniaturization is of high interest, since the launch cost of such complex devices is greatly amplified by factors like mass, volume and alignment stability [10] (e.g. a launch price offered by SpaceX, Falcon 9 v.1.1 is around \$4,109/kg to LEO [11]). The launch cost per dry-mass increases significantly for interplanetary missions. It is notable that reduction in the size of an optical system yields reduction in the mass of

the mounts, and this in its turn improves the robustness of the system to launch vibrations as well. Therefore, minimization of spaceborne instruments is an important technological goal. The NASA Goddard team for instance is working to demonstrate the Miniaturized Spectrometer-on-a-Chip with a footprint of some cubic centimeters which, like the Composite Infrared Spectrometer (CIRS) on board the Cassini Mission, would be sensitive to mid-infrared bands [12]. The potential device is a greatly scaled down version of a Michelson-type FTS commonly used to study the spectra of planets and stars to identify their chemical makeup and other physical properties [12]. To give an idea of the compactness of the new generation of FTS, it is enough to say that CIRS on the board of Cassini spacecraft is as big as a dishwashing machine, despite the fact that it is powerful and has made valuable discoveries. However, the discussed device under study at NASA would be capable of measuring only a single-pixel and its concept cannot be evolved into an imaging spectrometer.

The Fourier Transform Infrared (FTIR) spectrometers have been carefully designed, tested and flown for space applications. For instance, a high resolution (0.12 nm or 0.02 cm<sup>-1</sup>) FTIR spectrometer operating from 2.4 to 13.3 microns is built by ABB-Bomem in Quebec City (2003) for the Atmospheric Chemistry Experiment (ACE) mission detecting trace organic compounds from orbit [13, 14]. The instrument is an adapted version of the classical Michelson interferometer using an optimized optical layout. This is combined with a folding mirror inside the interferometer to increase the OPD. Its highly folded double-pass optical design results in a very high performance instrument with a compact size. A signal-to-noise ratio (SNR) greater than 100 is achieved. The instrument's mass is about 41 kg (including Telescope, IR Detector/Cooler, Electronics, Imager Subsystem), and it has an average power consumption of 37 W [15]. The interferometer subsystem has a volume of around  $30 \times 25 \times 25$  cm<sup>3</sup>.

Various Fourier-transform interferometers which do not require scanning or other moving parts have been proposed [16]. As an example, Spatial Heterodyne Spectrometers (SHSs) which are a type of Michelson-based instrument with grating rather than mirrors, providing a one-dimensional spatially dispersed interferogram of the input light [17]. SHS is useful for providing high spectral resolution observations of a diffuse source over a waveband (e.g. observing diffuse interstellar emission lines in far-ultraviolet regions [18], imaging of hydroxyl solar resonance fluorescence from low earth orbit and observation of nebulae [19]). The SHS instrument has significant advantages concerning throughput and size over conventional grating spectrometers in the study of faint, spatially extended sources in far-ultraviolet regions [16].

Various miniature grating-based spectrometers have been proposed, but their applications are typically limited to low-spectral resolution [20–22]. For instance, researchers at the Technical University of Delft have investigated a compact spectrometer configuration based on a dispersive principle, performing in visible and near-Infrared (NIR) ranges with spectral resolution of 0.7 nm [23]. To give an idea about the market demand on spectral resolution, the CarbonSat mission which was originally proposed to improve the global greenhouse gas monitoring capabilities, has a requested spectra resolution in NIR of 0.03 nm, and in SWIR of 0.15 nm with an SNR above 300 [24]. Another example is the lamellar grating interferometer developed at University of Neuchâtel in 2004, which can be used as a time-scanning Fourier-transform spectrometer providing a 1.6 nm spectral resolution at 400 nm and 5.5 nm at 800 nm with a footprint of 5 mm $\times$ 5 mm [25].

RESOLUTION Spectra Systems in Grenoble, France, has been developing SWIFTS-based high performance spectrometers since 2011. SWIFTS-based instruments have been designed to be a rapid solution for checking the tuning of laser sources with narrow-linewidth emission [7]. Typical products of RESOLUTION Spectra Systems provide high spectral resolution down to 0.01 nm, however their bandwidth is highly limited e.g. 5 nm at 630 nm (ZOOM Spectra) and devices are not designed for applications which deal with low power real-life signals (e.g. for remote sensing applications).

In an activity funded by ESA Technology Research Programme (TRP), in order to circumvent the sub-sampling limitation due to nano-sampler spacing and to expand the spectral bandwidth of the recollected spectrum, the basic principle of a static Lippmann spectrometer is combined with a dynamic Fourier-transform spectrometer, by adopting a movable mirror, which introduces small OPD changes [26]. In France, researchers at Joseph Fourier University have recently explored the idea of introducing an external Mach-Zehnder intensity modulator prior to the waveguide spectrometer (e.g. SWIFTS) with an initial imbalance between the arms for scanning the interferogram fringes under the nano-samplers in a dynamic manner by applying a voltage (~100 V) [27]. It is clear that the use of a movable mirror [26] or an external optical signal conditioning element [27] (e.g. Mach-Zehnder modulator) increases the size and complexity of the waveguide spectrometer and these techniques are spiritually against the miniaturization concept.

Nonetheless, miniaturization is not without drawbacks, reducing the size of an optical system limits the throughput of the system. Hence, one trend in compact spectrometers is to increase the throughput of the system for targeted customers. The throughput is especially important in spaceborne applications. For instance in remote sensing from LEO, the instrument has a low integration time whereas the SNR is directly related to the amount of photons entering the instrument through the aperture per second. In such applications, a high SNR requires a large aperture which is a volume/mass driving factor.

Ideally, miniaturization of a spectrometer should not limit its light gathering capability or otherwise compromise its performance [28]. In many spectroscopy applications, specifically in the space domain, a large optical throughput and a high spectral resolution is needed. Therefore, one scope of research is to increase the throughput. In this sense, compact spectrometers in planar waveguides based on waveguide gratings have been developed [28–30]. In order to increase the device throughput the grating concept is replaced by the interferometer-based spectrometer [31, 32]. M. Florjańczyk et al. [33, 34] have shown that the optical throughput is increased by a factor of 200 compared to single input spectrometer devices by using multiple input waveguide apertures which feed into an array of Mach-Zehnder interferometers. A multi-aperture planar waveguide spectrometer based on 50 arrayed Mach-Zehnder interferometers has provided spectral resolution of 0.1 nm over 2.5 nm bandwidth at 1.36  $\mu$ m [3]. The optical input is formed by many independent planar waveguides, stacked in layers, providing an increase of throughput compared to single-waveguide input configurations [31]. This device is, however, band-limited due to the fact that the maximum optical path difference which determines the spectral resolution is dictated by the stepwise imbalance introduced by the Mach-Zehnder interferometer integrated into the device. One should bear in mind that in these configurations, the optical path difference is formed on the detector array similarly to the classical Michelson interferometers. The only difference is the use of multi-aperture waveguides combined with Mach-Zehnder interferometers for creating optical path difference instead of moving parts. This concept is far from a Lippmannbased waveguide spectrometer where the optical path difference is formed in the single-waveguide itself.

## 3. Waveguide spectrometer concept review

In the Lippmann interferometer configuration, the light injected in the single-mode optical waveguide with a reflective surface (mirror) at its end generates an interferogram along the waveguide [35]. This phenomenon generates a stationary wave. The energy extraction required to sample the standing wave is obtained by sampling the evanescent field on one side of the waveguide using nano-samplers (also called evanescent field samplers or antennas) located in the evanescent field [5–9]. These nano-samplers scatter the light around an axis perpendicular to that of propagation of the waveguide. For each nano-sampler, the scattered light is detected by a pixel aligned with this axis. The intensity detected is thus proportional to the intensity of the

interferogram at the exact location of the nano-sampler. A processing unit, programmed based on Fourier transform, takes into account all the calibration data and, when applied to the linear image, returns the spectrum of the light.

The resolving power obtainable in a waveguide spectrometer is given by the length of the sampled interferogram L as defined in Eq. (1).

$$R = \frac{\lambda}{\Delta \lambda} = \frac{2n_{eff}L}{\lambda} = \frac{\text{OPD}}{\lambda}$$
(1)

In Eq. (1),  $n_{eff}$  is the effective refractive index of the mode in the waveguide (refractive index of the core and cladding and geometry that fixes the mode distribution),  $\Delta\lambda$  is the spectral resolution and  $\lambda$  is the wavelength of light in free space. This equation shows the intrinsic advantage of waveguide spectrometers because the longer the length of the waveguide with nano-samplers in the evanescent field, the higher the spectral resolution of the spectrometer [35]. The minimum length of the sampled interferogram ( $L_{min}$ ) at FWHM is dictated by the required spectral resolution ( $\Delta\lambda$ ).

$$L_{min} = \frac{0.605\lambda_{max}^2}{2\Delta\lambda n_{eff}} \tag{2}$$

The distance between nano-samplers (P) and the number of nano-samplers along the waveguide,  $N = \frac{L}{P}$ , is directly determined by the spectral bandwidth of the spectrometer [35]. Considering  $\lambda_{min}$  and  $\lambda_{max}$  are, respectively, the lowest and the highest wavelengths of the spectrum to be analyzed, the largest pitch ( $P_{max}$ ) of nano-samplers is defined by Eq. (3).

$$P_{max} = \frac{1}{4n_{eff}} \left( \frac{1}{\lambda_{min}} - \frac{1}{\lambda_{max}} \right)^{-1}$$
(3)

Equation (1) shows that a waveguide spectrometer based on the Lippmann concept has no intrinsic limit on spectral resolution. Equation (3) describes the technology bottleneck at the nano-samplers and detector level. For perfect reconstruction of a spectrum with no loss of information, the Nyquist-Shannon sampling theorem dictates that the spatial sampling interval (sample-rate, *P*) should not exceed half of the guided wavelength of the interferogram  $(\lambda_g = \frac{\lambda}{(2n_g \epsilon_f)})$ .

$$2P_{max} \le \frac{\lambda}{2n_{eff}} \tag{4}$$

Hence at 633 nm,  $P_{max} \le 105.5$  nm. Such sub-micron sampling distance is not feasible with the current technologies. The limiting factors are driven from fabrication constraints, cross-coupling phenomena between adjacent nano-samplers, the detector pixel-size and optical limitations (e.g. diffraction limited optics). Nevertheless, under-sampling is a useful approach for reconstruction of band-limited signals which allows sampling at much higher spatial sample-rate.

## 4. Lippmann-based planar waveguide spectrometer (LiPWS)

In the following paragraphs, the throughput restrictions in channel waveguides and the novelty in employing planar waveguide to enhance the system throughput and increase the number of interferogram measurement points are demonstrated. The novel intermediate sampling technique in planar waveguides has significant advantage over single-mode channel waveguides with similar effective mode size and acceptance angle (similar core/cladding materials). Lippmann-based planar waveguide spectrometers are hereafter called LiPWS.



Fig. 2. Illustration of two waveguide spectrometers. (a) Single-mode waveguide spectrometer here based on a channel waveguide. (b) Lippmann-based Planar Waveguide Spectrometer (LiPWS) based on planar waveguide. In the planar waveguide, a beam expansion is achieved in horizontal direction (along y-axis) at the exit of optical element in object space. The black waves in the waveguides represent polychromatic interferogram patterns.

# 4.1. Throughput in a planar waveguide spectrometer

In waveguide spectrometers the throughput of the system is dominated by the parameters of the waveguide. It may be emphasized that once the cut-off frequency for single-mode operations in certain waveguide materials is given, the throughput of the waveguide is constant through different varying parameters. Therefore, the application of single-mode waveguides in waveguide spectrometers is accompanied by setting a fixed and limited system throughput.

The limited throughput in single-mode waveguides can be enhanced by optimization of the unguided light in the unconfined direction of the planar waveguide. In principle, mode expansion in planar waveguides provides larger acceptance area, yielding a higher throughput which is the key novelty in design of waveguide spectrometers proposed in this article. The front-end optics must, in addition, be optimized in order to couple light in the unconfined direction of the planar waveguide.



Fig. 3. Comparison of interferogram spatial sampling method in channel waveguide and planar waveguide. (a) Top surface of channel waveguide showing the configuration of nano-samplers (here nanorods) with the pitch and sampling interval of 4  $\mu$ m. (b) An innovative customized sampling pattern including nano-samplers (here nanodisks) on planar waveguide providing 1  $\mu$ m spatial sampling interval.

# 4.2. Intermediate-point sampling technique

Figure 2 shows two waveguide spectrometers, one based on the single-mode waveguide (Fig. 2(a)) and the other based on the planar waveguide (Fig. 2(b)). In the waveguide spectrometer of Fig. 2(a), nano-samplers are geometrically fixed on the waveguide and the interferogram is sampled discretely along the z-axis. On the other side, because of the beam expansion in the planar waveguide of Fig. 2(b), the interferogram is expanded in the horizontal plane (y-z) and this allows intermediate-point sampling through custom sampling patterns. The nanorods on the top of the single-mode waveguide have a pitch of 4  $\mu$ m in Fig. 3(a). The pitch of nano-samplers is chosen to have a resolvable image in the detector and to avoid crosstalk between nano-samplers. The nanodisks in Fig. 3(b) also have a pitch of 4  $\mu$ m, meaning nanodisks are at least 4  $\mu$ m distant, but the sampling interval along the z-axis is 1  $\mu$ m, thanks to the expanded beam in the y-direction and the shifted sampling layers. According to Eq. (3), a single-mode waveguide spectrometer with 4  $\mu$ m sampling pitch and a refractive index of 1.5 has around 16 nm spectral bandwidth at 633 nm central wavelength. The planar waveguide of Fig. 3(b), with 1  $\mu$ m sampling pitch, has a bandwidth increased by a factor of ~4 at 633 nm central wavelength compared to that of single-mode waveguide in Fig. 3(a), when made with the same material as the single-mode waveguide (i.e. similar effective mode size). This is a significant bandwidth enhancement which is achievable due to 16  $\mu$ m beam expansion (beam shaping elements are illustrated in Fig. 15) in the unguided direction of the planar waveguide, without introducing any moving mechanism. The increase of measurement points, in its turn, reduces the calibration and radiometric errors in post-processing FTS software.

The maximal achievable bandwidth in a LiPWS is defined by the maximal beam expansion in the planar waveguide. In other words, the wider the beam in the unconfined direction of the waveguide, the larger the number of sampling layers yielding more intermediate sampling points. Figure 4 shows various custom sampling patterns applicable on the top surface of a planar waveguide.

In Fig. 4(a), one repetitive sampling layer is shown on the top. In general, the sampling grid is periodic and repetitive sampling information can be averaged to increase the sampling accuracy



and to decrease the sampling errors due to e.g. fabrication defects of nano-samplers at specific locations. In Fig. 4(b) and Fig. 4(c) not all the sampling layers are shown.



Fig. 4. Different custom sampling patterns taking advantage of the beam expansion in planar waveguides. (a) Pitch 4  $\mu$ m, sampling interval 1  $\mu$ m, beam expansion 16  $\mu$ m, LiPWS bandwidth 66 nm at 633 nm. (b) Pitch 4  $\mu$ m, sampling interval 0.5  $\mu$ m, beam expansion 32  $\mu$ m, LiPWS bandwidth 132 nm at 633 nm. (c) Pitch 4  $\mu$ m, sampling interval 0.25  $\mu$ m, beam expansion 64  $\mu$ m, LiPWS bandwidth 256 nm at 633 nm. (d) Pitch 5  $\mu$ m, sampling interval 1  $\mu$ m, beam expansion ~21  $\mu$ m, LiPWS bandwidth 66 nm at 633 nm. The bandwidth is calculated at the central wavelength of 633 nm in a waveguide with refractive index of 1.5. Pitch is the minimum distance between nano-samplers.

## 5. System design and validation

### 5.1. Interferogram module: slab planar waveguide

Two sets of waveguides have been fabricated: 1) polymeric waveguides based on EpoCore/EpoClad epoxy material with a thick cladding layer for a primary validation of mode expansion in planar waveguides and 2) anorganic waveguides based on silicon oxide and silicon oxynitride material with a thin upper cladding layer for the final prototype that contains nano-samplers on top.

The main driver for choosing polymeric materials was the ease of fabrication [36, 37]. This way, smooth sidewalls can be reached using only lithographic steps, i.e. without polishing. Nevertheless, for reasons that will be discussed later we have switched to anorganic materials for the final prototypes.

# 5.1.1. Fabrication of the EpoClad/EpoCore planar waveguide

Single crystal silicon wafers, 75 mm in diameter, were used as a substrate. They were cleaned and Aluminium alignment markers were deposited using a standard process.

Then, as illustrated in Fig. 5, three epoxy layers were deposited. After each deposition, care was taken to crosslink the layer sufficiently in order to avoid layer intermixing. First, a layer of



Fig. 5. EpoClad/EpoCore Fabrication process. (a) Silicon substrate with spun-on EpoClad layer. (b) UV exposure through mask and thermal step for selective crosslinking of the EpoClad (c) Spin coating and baking of EpoCore layer (d) UV exposure through mask and thermal step for selective crosslinking of the EpoCore (e) Spin coating and baking of second EpoClad layer (f) UV exposure through slightly bigger mask and thermal step for selective crosslinking of the EpoClad (g) Developing the resist stack (h) Dicing of substrate.

EpoClad-20 was spin coated over the substrate and a softbake was done. Then, UV exposure through a mask with 5 mm square openings and a short post exposure bake was performed to selectively crosslink the layer. Afterwards, a thin EpoCore-2 layer was spin coated over the substrate, baked and selectively crosslinked using the same mask as the EpoClad layer. Finally, a second EpoClad-20 layer was spin coated over the substrate and underwent the same treatment using a mask with  $3\mu m$  wider openings in order to avoid steps at the sidewalls, reassuring their smoothness. The assembly was then developed and hard-baked at 130°C for one hour. The detailed process parameters can be found in Table 1.

This process yielded flawless, smooth samples without defects in the center of the substrate. The samples more to the edge were containing streaks though, which originated when spin-coating the thin EpoCore over the lower EpoClad layer as this layer contained steps because of the shrinking of the UV exposed, crosslinking parts with respect to to non-exposed parts. Therefore, the yield of the process was only 10%, which was still sufficient for our work.

The two following steps were applied on several chips for coating gold on one side of the chips. The gold coated side acts as a reflecting mirror with above 95% reflectance at 633 nm for formation of the interfering pattern within the waveguide:

• Oxygen plasma activation of side for better Au adhesion.

Table 1. Process parameters used for EpoCore/EpoClad process. UV exposure was done with a wideband high pressure mercury lamp, with dose measured at the 365 nm peak. If not mentioned, temperatures were increased gradually by 8 °C/min; the temperature ramp is included in the mentioned baking time.

Material	Spin Coat	Softbake	UV Exposure	Postbake	Develop
Bottom	30'' @ 3000	10' @ 20°C	500 mJ/cm <sup>2</sup>	Start at 50°C	none
EpocClad-	rpm	5′ @ 50°C		14′ @ 120°C	
20		30' @120°C		ramp to 40°C	
		ramp to 40°C		in 20'	
		in 20'.			
EpoClad-2	30'' @ 6000	2′ @ 50°C	200 mJ/cm <sup>2</sup>	2′ @ 50°C	none
	rpm	7′ @ 90°C		7′ @ 85°C	
		ramp to 40°C		ramp to 40°C	
		in 15'.		in 15'	
Тор	Same as for Bottom EpoClad-20				3'45" in
EpoClad-					mr-Dev
20					600

• Sputter a 100 nm thick gold layer on one side, by putting wafer pieces in a suitable holder in a sputter tool.

## 5.1.2. Characterization of the EpoClad/EpoCore planar waveguide

The guiding performances are verified by coupling an expanded beam into the fabricated planar waveguide. The light is coupled from the front-end optics into the chip. The optical mode profile in far-field is reflected on a screen. Figure 6 shows the extracted mode profile at two different sections of the polymer-based planar waveguide under test. It was envisaged that since the thickness of fabricated planar waveguides is not uniform (observed in SEM images), some sections might carry higher order modes as depicted in Fig. 6(b).



Fig. 6. The optical mode profile in far-field in the fabricated EpoClad/EpoCore planar waveguides. (a)  $TE_0$ . (b)  $TE_1$ .

## 5.2. Silicon oxide-silicon oxynitride planar waveguides

Thin films of silicon oxynitride  $(SiO_mN_p)$  can be grown on silica using a variety of plasma deposition techniques [38–42]. One advantage of silicon oxynitride is that by changing the nitrogen/oxygen ratio in these films, their refractive index can be continuously tuned between the value of ~ 1.45 for silicon dioxide (SiO<sub>2</sub>) and ~ 2.025 for silicon nitride (Si<sub>3</sub>N<sub>4</sub>). A plot of the variation of the refractive index as a function of nitrogen content of the layer based on data from several experimenters compiled and tabulated in [42] is shown in Fig. 7.

For the rest of this work, we have selected these materials for several additional reasons as well:



Fig. 7. Refractive index of silicon oxynitride versus the ratio of atomic nitrogen to the sum of atomic nitrogen and oxygen in  $SiO_mN_p$ .

- Improved thermal stability as the oxides have a much lower thermal expansion coefficient (0.55 ppm/K for silicon oxide vs 87±10 ppm/K for EpoClad [43]).
- Improved environmental stability, as polymers tend to swell by water uptake and to age.
- Improved process stability, as polymers can be damaged during common thin film processing steps such as liftoff in a solvent, which could be used to deposit nanodisks on the waveguides.
- Avoiding the streaks described above.
- Improved control of layer thickness by using a well-controlled PECVD processes.

Especially considering the application of the final product in an aggressive environment such as space with harmful environmental factors such as radiation which cause corrosion and aging in materials, the switch to a waveguide material with robust chemical/physical properties was unavoidable. Silicon oxide / silicon oxynitride waveguides will have no issues in qualifying for space applications as a large number of silicon-based components are already space qualified according to the ESCC Qualified Parts List [44].

The main manufacturing challenge is to get the right parameters to achieve a thin layer of silicon oxynitride with a refractive index slightly different from - and always larger than - the surrounding layers to serve as waveguide core ( $\Delta n = 0.001$  to 0.01).

#### 5.2.1. Design of a silicon-based planar waveguide

It is understood that due to lower mechanical stress in the layers, it will be better to use a silicon dioxide–silicon oxynitride–silicon dioxide structure. Then, an easily available fused silica wafer can be used as substrate, and only two relatively thin layers need to be deposited by PECVD. For this structure (SiO<sub>2</sub> – SiON – SiO<sub>2</sub>), a  $\Delta$ n of 0.01 to 0.001 must be maintained between the film and the cladding refractive indexes, to reach the required effective guide thickness. In this case, for an optimum  $\Delta$ n = 0.002, the atomic ratio of Nitrogen / (Nitrogen + Oxygen) is slightly bigger than 0, r = p / (m+p) = 0.003. Thus, the final structure consists of a 500  $\mu$ m fused silica (silicon dioxide) substrate, a 1.6  $\mu$ m silicon oxynitride core layer and a 2  $\mu$ m silicon dioxide top cladding.

#### 5.2.2. Fabrication of a silicon-based planar waveguide

An Oxford Plasma Systems PECVD reactor was used with the deposition parameters described in Table 2. The only difference between the oxide and the oxynitride deposition process was the

addition of a 1 sccm  $NH_3$  flow in the latter. Using this procedure instead of two rather dissimilar process recipes for the two layers was found to be a robust way of reassuring a slightly higher refractive index in the waveguide core. It should be mentioned that a relatively low deposition pressure was used, as this was shown to yield layers that are not unstable due to moisture absorption [45]. Some authors also use a high temperature annealing step at the end of fabrication to eliminate hydrogen from the layers, reducing losses in the infrared [46]. This was not done here.

Table 2. PECVD deposition parameters.				
Temperature	300°C			
Pressure	650 mTorr			
RF power	30 W			
2% SiH <sub>4</sub> :N <sub>2</sub>	100 sccm			
N <sub>2</sub> O	700 sccm			
NH <sub>3</sub> (oxynitride only)	1 sccm			

Using ellipsometry the refractive index of the deposited oxynitride was measured to be 1.469 at 600 nm while the refractive index of the deposited oxide was 1.467. Increasing the NH<sub>3</sub> flow rate to 2 or 3 sccm increased the refractive index with another 0.002 or 0.004, respectively. The substrates were then diced to  $12 \times 10 \text{ mm}^2$  pieces.

## 5.3. Spatial samplers: gold nanodisks

The nano-samplers for sampling the interferogram are nanodisks placed in the evanescent field of the waveguide. Nano-samplers scatter a portion of the interferogram towards the detector array, which is directly in touch with them, or using an image transfer system including optics, as done for the prototype.

The nano-samplers can be any optimized shape of scatterer/particle. An engraved hole or even a local change in refractive index of the waveguide cladding enabling one to extract a portion of the light propagating underneath, fulfilling the sampling action. For realizing the innovative sampling grids shown in Fig. 4, a symmetric nano-sampler such as a nanodisk or a local hole in the cladding is more adequate than a nanorod. The nanodisks were chosen because of their adaptability and ease of design for the custom sampling patterns. In addition, the fabrication of nanodisks was found to be easier and more reliable compared to other techniques, e.g. engraved holes in the cladding or photonic crystals.

In trade-off among different materials available for nanodisks (e.g. Au, Pt, Al, Ag), gold is chosen as the material of which nanodisks are made. The main drivers are its high extinction coefficient in the spectral range of interest, ease of fabrication and relatively low radiation loss compared to other materials [47–55]. Nevertheless, this choice is not unique and other metals can be optimized for LiPWS applications.

#### 5.3.1. Analytical design of the gold nanodisk

The analytical design of nanodisks intends to optimize the scattering efficiency of individual nanodisks in the desired spectral band. It is known that a small particle has a maximum light transmission at wavelengths near its plasmon resonance frequency which is an intrinsic characteristic of each species [56]. The geometry of the nanodisk defines the wavelength at which the maximum scattering efficiency occurred [56,57]. The limited spectral bandwidth of nanodisks due to degradation of scattering efficiency over bandwidth is the key limitation of the proposed technology in this article. Nevertheless, in the innovative LiPWS due to the beam expansion in the planar waveguide, optimized nanodisks for various sub-spectral bands can be

fabricated on the waveguide, besides each other, in order to efficiently fulfill the needs of the entire spectral band for the broadband applications.

The maximum diameter of nanodisks is limited by another factor - guided wavelength. A sampler should not be bigger than the Nyquist-Shannon sample-rate and be at least 4 times smaller than the interferogram guided wavelength otherwise the interferogram is not sampled properly. For instance, at 633 nm with guided wavelength  $\lambda_g$  of 211 nm ( $n_{eff} = 1.5$ ), the sampler diameter should be 53 nm. This requirement prevents the use of an optimum nanodisk, in respect to its scattering efficiency, at the design wavelength.



Fig. 8. Colormap representing the scattering efficiency as a function of diameter (D, horizontal axis) and thickness (t, vertical axis) of gold nanodisk at 633 nm, in a medium with average refractive index of air and waveguide material.



Fig. 9. Colormap representing backscattering efficiency at far-field as a function of diameter (D, horizontal axis) and thickness (t, vertical axis) of gold nanodisk at 633 nm, in a medium with average refractive index of air and waveguide material.

In order to evaluate the nanodisk behavior inside an applied field, the extinction coefficient of the disk must be extracted. For this, the nanodisk is approximated by a spheroid (oblate) [57]. The best performance of the nanodisk is obtained when the scattering spectrum is at its maximum and the backscattered light is at its minimum at the design wavelength, i.e. at 633 nm. Two colormaps are generated in Fig. 8 and Fig. 9 for the given wavelength of 633 nm. These graphs help to select the optimum dimension of the nanodisks (a guide to the selection of diameter and thickness) for maximum scattering efficiency and at the same time minimizing backscattered light at the design wavelength.

According to Fig. 8, an optimum choice for the gold nanodisk dimensions for the maximum scattering efficiency at 633 nm is 60 nm $\leq$ D $\leq$  90 nm and 85 nm $\leq$ t $\leq$  100 nm. Figure 9 confirms that in the selected region the far-field backscattered light are at their minimum value (similar is the near-field backscattered light). Nevertheless, the guided wavelength constraints and the fabrication limitation may enforce other choices.

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#### 5.3.2. Fabrication of the gold nanodisk

Gold nanodisks were fabricated by electron-beam lithography combined with chemical etching and ion milling techniques (process illustrated in Fig. 10). To fabricate the nanodisks on the waveguides, first a 5 nm thin titanium adhesion layer and then a gold layer were deposited using sputter coating (3 inch US Gun II sputter target holders, 100 W RF power,  $2 \times 10^{-3}$  mbar Ar pressure). The gold thickness was varied between samples, and was either about 50 or 100 nm.



Fig. 10. Gold nanodisk fabrication process. (a) Fused silica substrate (b) Waveguide deposition by PECVD, dicing into individual chips and polishing (c) Ti / Au coating (d) Depositing e-beam resist (e) E-beam exposure of the resist (f) Developing the resist (g) Sputter etching the Au and chemical etching of the Ti (h) Removal of the resist in oxygen plasma.

After sputtering, the samples were prebaked at  $150^{\circ}$ C for 5 minutes. Immediately afterwards, hexamethyldisilazane was applied by spin coating as adhesion promoter. Then, a 350 nm thick layer of ma-N 2403 negative photoresist was applied by spin coating at 4000 rpm for 30". The layer was baked for 1 minute at 90°C on a hotplate. Afterwards, the layer was exposed using e-beam lithography (150  $\mu$ C/cm<sup>2</sup>, 20 kV beam) and developed in 3:1 diluted Microposit 351 developer during 60 seconds.

To etch the gold layer, RF sputter etching was used for 4.5 minutes at a power of 100 W and an argon pressure of  $2 \times 10^{-3}$  mbar. The RF powered electrode was 75 mm in diameter and no magnetic fields were used to enhance the plasma. As titanium tends to etch much slower than gold under these conditions, the etch tends to stop at the thin titanium layer which can then be removed chemically without damaging the underlying substrate. As the common HF-based etchants create too much underetch due to the presence of an electrochemical couple (Ti-Au) causing increased etching of Ti near exposed gold surfaces, thereby releasing fine structures from the surface, an adapted hydrogen peroxide based etchant is used [58]. Etching was done for two minutes in a solution containing 1.5 M H<sub>2</sub>O<sub>2</sub> and 2.5 M (NH<sub>4</sub>)<sub>2</sub>HPO<sub>4</sub> at 40°C. Afterwards, the

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resist was removed using oxygen plasma cleaning.

This process still leaves a rim of gold near the edges of the sample, caused by the edge bead of the resist which was not developed away. Therefore, in a next phase the gold dots are protected with positive S1818 photoresist, which is deposited and patterned using common UV based lithography. The gold rim is then removed by a chemical etching in diluted Aqua Regia (3 HCl (37%): 1 HNO<sub>3</sub> (68%): 3 H<sub>2</sub>O, parts by volume) and the S1818 is removed again in a solvent.

5.3.3. Characterization of the gold nanodisk

The geometry of the realized nanodisks are characterized using SEM facilities. As the SEM images in Fig. 11 show, the smaller nanodisks are more irregular than larger ones.



Fig. 11. SEM images of realized gold nanodisks. Left to right shows nanodisks of target diameters (D): 50 nm, 70 nm, 130 nm, 500 nm.



Fig. 12. Measured scattering spectrum of fabricated gold nanodisk (D  $\approx$  150 nm and D  $\approx$  75 nm) in the integration time  $\tau = 0.5$  ms. The solid lines show the analytical extinction spectra of a uniform gold nanodisk calculated in a medium with average refractive index of air and glass.

A spectrometer setup in the Czerny-Turner configuration is used to examine the scattering efficiency of individual nanodisks over the wavelength. The spectrometer setup, consists of a tungsten lamp, a polarizer, a dark-field condenser, and a long working distance objective for reflecting the scattered light from the nanodisk to the spectrometer [59]. Figure 12 shows the measured scattering efficiency spectrum for a selected nanodisk ( $D \approx 150$  nm and  $D \approx 75$  nm) compared to an analytical modeling of the scattering efficiency for a similar nanodisk. The vertical axis in Fig. 12 shoes the relative amplitude. For the bigger gold nanodisk a narrower slit aperture of 100  $\mu$ m (instead of 150  $\mu$ m) is used to isolate the nanodisk from dust particles around it. The shifts in the measured spectra are due to the fact that the fabricated nanodisks are not a perfect disk (see Fig. 11) and the shape of particle influences the scattering spectrum (analytical spectra consider a uniform disk).

# 6. Development of the sampling grid

This section reports the development of custom sampling patterns on the surface of planar waveguides. Nanodisk patterns are fabricated on the top surface of a planar waveguide in the regions, which are marked with golden L-shaped markers. In Fig. 13, the region has a dimension of 500  $\mu$ m×500  $\mu$ m. The main driver for choosing 500  $\mu$ m is the field-of-view of the image transfer system which is used for the experiments. Figure 13 shows a test sample which was prepared for characterization purpose. This sample contains nanodisks of large diameter (1  $\mu$ m) with pitch of 10  $\mu$ m, visible under an optical microscope. Instead, Fig. 14 shows a developed grid of nanodisks in the pattern as shown in Fig. 4(b). The thickness of gold nanodisks in this sample is t = 50 nm, and nanodisks have diameters of D = 70 nm.



Fig. 13. Optical microscope images of fabricated patterns of gold nanodisks on a silicon oxynitride planar waveguide. A region of 500  $\mu$ m×500  $\mu$ m with L-shaped markers on its corners is shown in (a). (b) and (c) show the realized pattern of nanodisks within a selected region.



Fig. 14. SEM images showing a developed grid of nanodisks of 70 nm diameter in the pattern as shown in Fig. 4(b).

## 7. Experimental setup

The design of front-end optics is crucial in overall system performance. The effort is an optimal coupling with minimal coupling perturbation in the waveguide's cladding. The main role of front-end optics (Subsystem II in Fig. 1), is to expand the light beam in the unconfined direction of the planar waveguide. The beam is focused only in one direction into the planar waveguide and it is expanded in the orthogonal direction through optical elements. In Fig. 15, dimension of



lenses and distance are exaggerated for visual representation of the front-end optics, the output beam at the right side of Lens #2 projected on the face of a planar waveguide.



Fig. 15. Input light source and elements of front-end optics for beam shaping.

A wavelength stabilized, single-mode, fiber-coupled laser diode is used in order to ensure a stable emission spectrum as a reference for the spectrometer calibration. The QFBGLD-633-30 FBG (QPhotonics) laser module in butterfly package has a built-in monitor photodiode, thermoelectric cooler and thermistor. In addition, the CLD1015 laser driver is acquired from Thorlabs which provides a high degree of output stability.

The experimental setup contains all subsystems of the waveguide spectrometer prototype including light source, optical isolator, front-end optics, image transfer system, detector, camera and objective for far-field mode profile observation and mechanical translation stages for precise alignment of the sample, far-field observation objective, image transfer system and front-end optics. Figure 16 shows the schematic of the setup. Here, the Image Transfer System is scaled down to fit the schematic and the LiPWS sample is not shown however its location is marked between the aspheric lens and the objective for far-field observations.



Fig. 16. The optical schematic of experimental setup.

## 8. Analysis of experiment results

## 8.1. Interferogram acquisition

The beam expansion in the waveguide is tested at wavelengths of 633 nm. The expanded light beam is coupled from the left-side and reflected back on the right-side of the chip. Figure 17



put in inverted colors. The black dots are the Airy disks of nanodisks representing the sampled information at different locations on the interferogram. These images are at the next step treated to retrieve the interferogram.



Fig. 17. The sampled interferogram data at 633 nm.

The interferogram data reconstruction starts with importing the raw image data in the processing software. The image data is stored in a 2D-array. In the next step, the sampling layers are extracted from the raw image data and stored in separate 2D-arrays. Each array contains a batch of sampled interferogram data with a sampling interval equal to the pitch of nanodisks (e.g. 5  $\mu$ m sampling pitch for the rotated pattern of Fig. 4(d)). The treated information of data batches (each batch contains data from one sampling layer) is put together to construct a continues sampling data containing intermediate sampling points.

Figure 18 shows the interferogram data retrieved from Fig. 17. The next step before constructing the spectrum information is to remove the DC offset from the retrieved interferogram signal. The offset is calculated using the smoothing algorithm and it is overlaying the interferogram signal as shown in red in Fig. 18 in the top. The treated interferogram ready for spectrum reconstruction is shown on the bottom in Fig. 18.



Fig. 18. In the top, the retrieved interferogram signal from Fig. 17 is shown in blue and its offset is shown in red. The interferogram after removing the offset is shown on the bottom.

## 8.2. Spectrum analysis

The retrieved interferogram in Fig. 18 is sampled with the period of 1  $\mu$ m. The total length of sampled interferogram is 0.5 mm in this experiment. This sampling length provides 0.16 nm spectral resolution. However, the resolution of the waveguide spectrometer is not limited to this value. The sampling interval of 1  $\mu$ m provides 66 nm bandwidth at 633 nm. The sampled interferogram is further prepared for spectrum analysis following zero-filling and apodization. The Fourier transform is applied on the treated interferogram to reconstruct the spectral information. The outcome is the spectrum depicted in Fig. 19 in black. The reconstructed spectrum exhibits a



dominant peak at around 633 nm. The noise level can be reduced by averaging the interferogram data in spatial domain and increasing the length of sampled signal.



Fig. 19. The retrieved interferogram at 633 nm is shown in the top and its reconstructed spectrum is shown on the bottom. The interferogram is sampled with intervals of 1  $\mu$ m over a distance of 0.5 mm.

In another experiment, the interferogram is retrieved from a region on the planar waveguide where a sampling grid similar to Fig. 4(c) providing 0.25  $\mu$ m sampling interval is located. Figure 20 shows the sampled interferogram and its corresponding spectrum when the 633 nm laser source is coupled into the planar waveguide. The results confirm that increasing the number of sampling points enhances not only the bandwidth of the LiPWS but also the SNR. The presence of a side-glitch is notable in the reconstructed spectrum. Numerical modeling predicts that side-glitches in a Lippmann-based waveguide spectrometer are due to retro-reflections (cross-talk between nano-samplers) and energy dissipation in the waveguide. In addition, aliasing due to under-sampling causes the replication of the original spectrum.



Fig. 20. The retrieved interferogram at 633 nm is shown on the top and its reconstructed spectrum is shown on the bottom. The interferogram is sampled with intervals of 0.25  $\mu$ m over a distance of 0.5 mm.

In a similar way, the sampled interferogram data at 685 nm is reconstructed with sampling intervals of 1  $\mu$ m. The reconstructed spectral peak is depicted in Fig. 21 (Left) containing a dominant peak at around 685 nm. In the same figure, for comparison the spectral peaks of Fig. 19 and Fig. 20 are shown with the same scale.



Fig. 21. Three reconstructed spectral picks at 685 nm and 633 nm. The interferogram of reference laser beams were sampled with intervals of 1  $\mu$ m at 685 nm, 1  $\mu$ m and 0.25  $\mu$ m at 633 nm respectively from left to right.

# Real-case scenario: implementation of an LiPWS for the CarbonSat NIR imaging spectrometer

The implementation of an LiPWS for the CarbonSat mission is explored and an LiPWS fulfilling system level requirements of the NIR Imaging Spectrometer aboard CarbonSat is designed. The system level requirements of the CarbonSat mission imaging spectrometer defines a spectral range of 18 nm (757 nm - 775 nm), a spectral resolution smaller than 0.03 nm and an SNR bigger than 500. The spectral resolution ( $\Delta\lambda$ ) defines the minimum length of a sampled interferogram. In a waveguide with effective refractive index of 1.5, a minimum sampling length of 4 mm is required to achieve 0.03 nm spectral resolution. The maximum sampling interval ( $P_{max}$ ) in order to cover the bandwidth of 18 nm is 5.43  $\mu$ m according to Eq. (3). The nano-samplers must be optimized for a best performance in the range 757 nm - 775 nm. To finalize the system design while fulfilling the requirements of CarbonSat mission, given an e.g. 20  $\mu$ m beam expansion in the planar waveguide, a sampling pattern as shown in Fig. 22 is designed. In this sampling pattern, nanodisks are at least 6.6  $\mu$ m apart and the interferogram is sampled each 3.3  $\mu$ m over 4000  $\mu$ m.



Fig. 22. Sampling pattern fulfilling CarbonSat NIR imaging spectrometer requirements: Airy pattern of nanodisk samplers imaged by  $10 \times$  objective with NA = 0.25 to reach 0.03 nm spectral resolution and bandwidth of 18 nm. The pattern is repetitive in the horizontal direction for 4000  $\mu$ m to reach the required spectral resolution. The sensor active area is 40 mm×0.02 mm in this case.

The configuration in Fig. 22 already fulfills the system level requirements of CarbonSat mission. The SNR and available bandwidth can go even higher by exploiting more horizontal sampling levels, providing more intermediate sampling points. The limiting factor is the image resolvability in the imaging sensor. For instance, in a similar case when mode expansion provides a 20  $\mu$ m expanded interferogram in the unconfined direction, the grid can be designed with 7 levels of nanodisks where the vertical distance between subsequent levels is 3.3  $\mu$ m. Having 7 levels of nanodisks, they can be set in a configuration as in Fig. 23 where samplers have 0.55  $\mu$ m pitch in interferogram space. This configuration provides 176 nm spectral bandwidth at the

central wavelength of 766 nm, which is 10 times broader than the configuration in Fig. 22, in an under-sampling state, improving the performance of the LiPWS for CarbonSat NIR imaging spectrometer.



Fig. 23. Sampling pattern providing 176 nm spectral range at 766 nm central wavelength. The Airy pattern is simulated using  $10 \times$  objective with NA = 0.25.

It is notable that a direct on-chip detector would work in near-field and Fraunhofer limitations are not introduced there. A compact LiPWS would even go higher in terms of spectral bandwidth and SNR within a much smaller sensor active area (no magnifying optics). The only intrinsic limitation of an on-chip LiPWS is the pixel-size of the detector. The minimum samplers' pitch should not go below the pixel size of the detector. As already indicated, another advantage is that in a direct on-chip detector system, there is no magnifying optics. Therefore, the size of the detector array is defined according to the minimum length to fulfill the required spectral resolution. Table 3 shows the specification of waveguide and on-chip detector for an on-chip LiPWS fulfilling the CarbonSat NIR imaging spectrometer requirements.

Parameter	Value
Spectral Resolution $(\Delta \lambda)$	0.025 nm
Waveguide Length $(L_{min})$	5.0 mm
Beam Expansion in Planar Waveguide	20 µm
Sampling Pitch	3.3 µm
Number of Sampling Levels	7 (Fig. 22)
Interferogram Sampling Intervals	0.55 μm
Gold Nanodisk optimum dimensions	60 nm≤D≤90 nm
D: Diameter, t: Thickness	90 nm≤t≤130 nm
On-chip detector maximal pixel-size	3.3 µm
On-chip detector sensor minimal active area	5.0 mm×0.02 mm

Table 3. Design specification of an on-chip LiPWS for CarbonSat NIR Imaging Spectrometer.

The system in Table 3 works in an under-sampling state. Knowing that the shortest guided wavelength in the spectral band of interest in a silicon oxynitride planar waveguide is ~260 nm, to have a baseband spectrum reconstruction, according to the Nyquist-Shannon sampling criterion in Eq. (4) a maximum sampling interval of ~130 nm is required. An on-chip detector with 1  $\mu$ m pixel size, with 10 sampling levels, perfectly fulfills the baseband spectrum reconstruction for Carbonsat NIR providing 100 nm sampling intervals within 10  $\mu$ m beam expansion (no diffraction limit, near-field conditions are valid in on-chip detector). The specification of such an LiPWS in a silicon oxynitride planar waveguide is summarized in Table 4.

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Parameter	Value
Spectral Resolution $(\Delta \lambda)$	0.025 nm
Waveguide Length $(L_{min})$	5.0 mm
On-chip detector pixel-size	$1.0 \ \mu m \times 1.0 \ \mu m$
Beam Expansion in Planar Waveguide	10 µm
Number of Sampling Levels	10
Interferogram Sampling Intervals	100 nm

Table 4. A baseband high SNR on-chip LiPWS for CarbonSat NIR Imaging Spectrometer.

#### 10. Roadmap for further implementation of LiPWS

An imaging implementation of FTS, targeting spaceborne and commercial applications, is its integration in "focal plane array spectrometer (FPAS)" configuration. The FPAS [35], a highly integrated instrument concept, is based on a bi-dimensional array of waveguide spectrometers. FPAS may be assembled in small size, and form a compact package of single spectrometers.



Fig. 24. Lay-out of the FPAS on-chip (the sketch is inspired by the original design in [35]). Here a block of 4 x 5 sub-arrays are shown. The radiation is collected from the scene (x-y plane) and imaged on the focal plane of the telescope where the arrays of FPAS are located. The spectral information is extracted along the waveguides (marked as  $\lambda$  in the block). Hence, the output is a 3D-image with two spatial axes reflecting the scene and one axis containing spectral information of the scene (i.e. each pixel in the output image contains a sampled spectral measurement of reflectance). The single-block of FPAS includes a waveguide, nano-samplers in the evanescent field and a compact photodetector.

In the original concept of FPAS [35], single-mode channel waveguides are placed in the focal plane of the imaging optics. The radiation is collected by the telescope, focused on the optical elements (e.g. microlenses) which couple the light into waveguides. The amount of light injectable into the system is intrinsically limited due to the small optical capacity of individual waveguides. Limited throughput at the level of individual waveguides limits the system's overall SNR.

LiPWS, with its enhanced features in terms of throughput and spectral resolution, has the potential to be used as a building block of focal plane array spectrometer, as illustrated in Fig. 24, for imaging applications. Figure 25 shows one single Lippmann Planar Waveguide Spectrometer (LiPWS) with fabricated nano-samplers on its top surface. The single-block LiPWS can be evolved towards an array of LiPWS where sub-arrays are developed in a single piece of substrate, and then stacked one after another as shown in Fig. 26. The detector electronic read-outs are on

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the back-side of the 2D block, not shown in this sketch. Furthermore, certain absorbing layers and anti-reflective coatings are required to avoid signal interference among different layers of the FPAS. In this configuration, the bare detector sensor matrix is in direct contact with the LiPWS surface. The sensor electronic read-out is shown in gray on the top of the detector layer. Nevertheless, to achieve an on-chip FPAS based on LiPWS as shown in Fig. 26, a suitable detector matrix shall be deployed.



Fig. 25. Schematic visualization of a single-block of LiPWS (developed prototype).



Fig. 26. Schematic 4x4 stacked FPAS spectrometer sub-arrays based on LiPWS and customized arrays of nanodisks.

#### 11. Conclusion

In this paper, for the first time a high spectral resolution waveguide spectrometer with enhanced throughput and wide spectral bandwidth is introduced. The optical throughput and spatial sampling spacing are currently the main constraints on performance of Lippmann-based waveguide spectrometers for real-life applications. State-of-the-art instruments are suffering from the number of nano-samplers/detectors on the waveguide and they achieve only a limited number of measurement points over the interferogram, which causes a narrow spectral bandwidth. Another challenge is the optical throughput of conventional waveguide spectrometers, which is intrinsically small because of using single-mode waveguides. The throughput is an important factor in imaging spectrometers especially for remote sensing applications, where the collected irradiance at the focal plane of the telescope is extremely faint. The novelty is the use of planar waveguide, as the core of the waveguide spectrometer in order to increase not only the optical throughput of

the system through mode expansion in unguided direction of the waveguide but also to augment measurement points thanks to the novel intermediate-points sampling technique implemented on the planar waveguide. In this novel concept, the interferogram sampling points are increased without decreasing the distance between adjacent nano-samplers but instead, by placing them into customized sampling grids. The bandwidth is only limited by the efficiency of nano-samplers and the beam waist of the expanded beam. In the realized prototype, with 64  $\mu$ m mode expansion in a planar waveguide a bandwidth of ~256 nm is achieved at 633 nm central wavelength (most commercialized waveguide spectrometers have sub-10 nm bandwidth). The novel intermediate sampling technique, allowed to sample the interferogram with 0.25  $\mu$ m sampling interval, which was not possible before. The innovative prototype can, in later stages, act as a single-block of focal plane array spectrometer (FPAS) for hyperspectral imaging applications: a 1D array of spectrometers to form an acquisition line to image with lateral scanning, heading towards a full cube of spectrometers in a 2D image acquisition scheme to probe directly a complete scene. Meanwhile it is competitive with state-of-the-art single-pixel spectrometers in terms of volume, bandwidth, and spectral resolution. It does not require temporal scanning, since it has no moving parts. Therefore, the system is immune to vibrations or other varying noise sources that need to be calibrated out in temporally scanned Fourier systems. All point-to-point errors in the interferogram are fixed at the time of manufacture and can be calibrated in advance per instrument. This waveguide spectrometer is very simple, robust, modular, accurate (radiometrically and spectrally) and at the same time affordable. It can be adapted for various spectral ranges where the material for the waveguide, the nano-samplers and the detectors are available and compatible (from ultraviolet to mid-infrared). It has therefore the potential to be useful not only for space applications such as remote sensing and in the applications where the sample is in a close proximity to the spectrometer (e.g. mineralogy from a rover or active gas detection in a capsule or space station), but also it is very attractive for various terrestrial applications in tele-surveillance, optical metrology, genomics and medical domain. Technology concepts and critical functions are formulated and experimental prototypes are made in the lab (TRL 2-3). The development of a proper photo-electric detector for compact integration of the system is still an open field of research and further technological efforts are required to realize a waveguide spectrometer on-chip for end-users.

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