Gas sensors using single layer patterned interference optical filters

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Abstract

A method for fabricating filters for fiber optic sensors is presented. The interference filter's construction is laid on it's side to allow for the use of air as the low refractive index material. Bandpass filters tuned to the absorption line of a trace gas can then be used as a sensitive means of detecting gas concentration. Complex filter designs can be fabricated in a single patterned layer. A CO_2/CH_4 gas sensor is presented as a design example.

Keywords: fiber optic sensors, patterned filters, interference filter design

1: Introduction

Optical filters, passive optical switches and polarizing elements are used extensively in a wide range of sensors[1,2,3] and sensing technologies for medical, environmental and threat detection. The design of a complex optical interference filter used to detect a specific chemical can involve 100 or more discrete alternating layers of high and low index materials. The cost of these filters can be quite high owing to long deposition times and limited yield. We are developing an approach which will allow these filters to be deposited as a single, printable layer for use in fiber optic and wave guide based sensor systems. Using emerging 3D printing techniques, extremely low cost, high volume fiber optic sensors can be fabricated. Complex visible through far infrared filters consisting of hundreds of discrete layers can be printed in a single layer deposition. The corresponding low index material can be air, or a second deposition, or both with some layers left as air while other layers are added to provide for other design considerations such as ultra-narrow, high optical density reflection notches and stable performance over a wide range of incidence angle.

There are several advantages to using air as the low index layer. From a design perspective, air is non-dispersive and offers the highest index contrast with the material chosen for the high index layers. By designing the filter to pass or reflect at a specific trace gas absorption band, the transmission or reflection of the open air filter design is a sensitive function of the gas absorption. This paper presents filter construction and a study of design trade-offs for these open air printed (OAP) filters.

Optical interference filters consist of multiple groups of high and low refractive index materials. By precisely controlling the thickness of each layer, reflected light from each interface can constructively or destructively interfere to produce unique spectral performance as a function of wavelength[4]. OAP filter construction turns the layer stack construction on its side. All layers of a particular material are deposited, or printed, at the same time. Layer thickness becomes line thickness and is determined by patterning the filters using either photolithography or precision printing techniques. These filters can be patterned at the same time as the optical interconnects or wave guides are deposited. The result is a complex filter design with high volume and low individual component cost.

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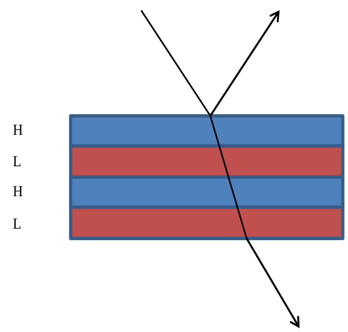


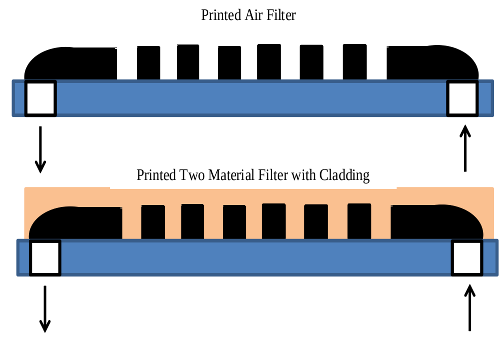
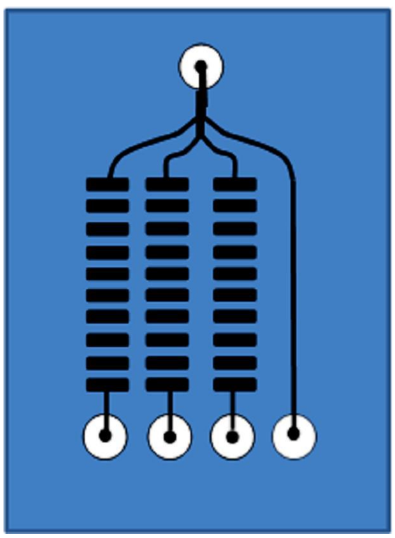


Figure 1: Standard optical filter construction consists of a stack of high and low refractive index materials. Reflections off each interface can interfere either constructively or destructively to create complex spectral performance as a function of wavelength. Each layer is deposited serially. The thickness of each layer must be tightly controlled creating a challenge for design with a large number of layers.

Figure 2: The open air printed (OAP) construction turns the filter stack on its side. This allows all the filter layers of the same material to be printed in a single step resulting in significant savings in deposition time and material. Filter designs consisting of several hundred layers can be fabricated at low cost and high yield. The low index layers can be a complimentary material or air. The open air construction is of use for trace gas sensors.



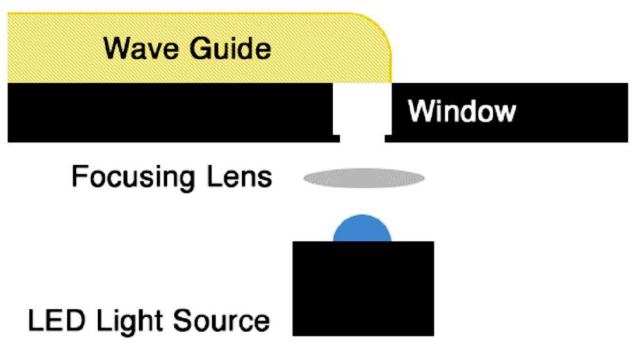


Figure 3: Illustration of the top view of a OAP filter. The filters are grown along with the filter optic or wave guide interconnects. The filters can be used independently or as an inter-networked array. The filter set can be thought of as an optical processing chip.

Figure 4: Light can be brought into or out of the filter chip by pads laid on the optical circuit board. In this example, small clear substrates are placed around the board at component locations. The wave guide is terminated on these substrates and provides the ability to mount a source, emitter or detector on the reverse side of the window.

Figures 1 through 4 illustrates OAP filter construction. Figure 1 presents a standard optical interference filter where light is reflected from each interface in a stack of films. Figure 2 presents a cross section of the printed patterned filter. Two design options are presented in figure 2, the low index layers can be left as air layers, or the lithography pattern can be reversed and the alternate layers filled with a low index material. The printed filters are coupled to wave guides. Multiple filters can be printed at the same time as well as reference channels replacing a complex filter wheel with a single, light weight, all optical óchipô. Figure 3 presents a top down view of a three filter optical circuit board with a reference channel. Figure 4 details the fiber optic óthrough the boardô entrance and exit pads which allow for efficient coupling of external fiber optic light sources and detector ports. Electronics can be mounted on one side of the board while the other side remains all optical. A single coating run has the potential of producing several hundred to several thousand filter-sets on a chip.

Since the filter is built on its side, the low index layers are air or even a vacuum. This unique design capability provides several advantages - the air/vacuum layers are nearly dispersion free. The vacuum layers offer no absorption over the full spectral range. Air filter designs can be exploited for detection of minute levels of contaminates, aerosols, and gas based hazards. An example design discussed here proposes a carbon dioxide sensor design using open air optical filters that are tuned to the absorption bands of these gases.

2: Patterned Filters

The optical filters and wave guides are deposited on the substrate using photolithography and shadow masks. The optical connects and waveguide channels on the substrates are patterned and the pattern is etched to create a soft rolling wall on the surface of the substrate. The deposition of the initial layer will fill these etched patterns and raise the pattern above the substrate surface. Through-the-board windows will be created by cementing small windows at emitter, source and detector sites. A partial shadow mask is used above the through the board pads to provide a smooth rolled surface on the windows. Initial work is focusing on filters for infrared applications. Infrared applications allow for reasonable line widths. The line width for a high optical density 10.6 micron rejection notch is in the range of 1 to 5 microns depending on desired bandwidth and the choice of the low index material.

Figure 5 presents a flow chart of the photolithography process. The wafer substrate is cleaned and a photo resist is spun on and baked. The lithography pattern is exposed and the photo resist is developed. The wafer is then etched to create a soft rolling walled pattern in the surface of the substrate. The wafers are loaded into the Helios sputtering coater and the thick layer of high index material is deposited. A shadow mask, illustrated in figure 6, is used to limit the amount of material which is deposited on uncoated areas thus aiding removal of the resist later as well as providing a means of rolling the edge on portions of the pattern - particularly the termination patterns.

Air can be used as the low index material, or a second layer of low index material can be deposited using a complimentary pattern of low index material. For initial development, designs using germanium are considered and the second material, when used, is zinc sulfide (ZnS).

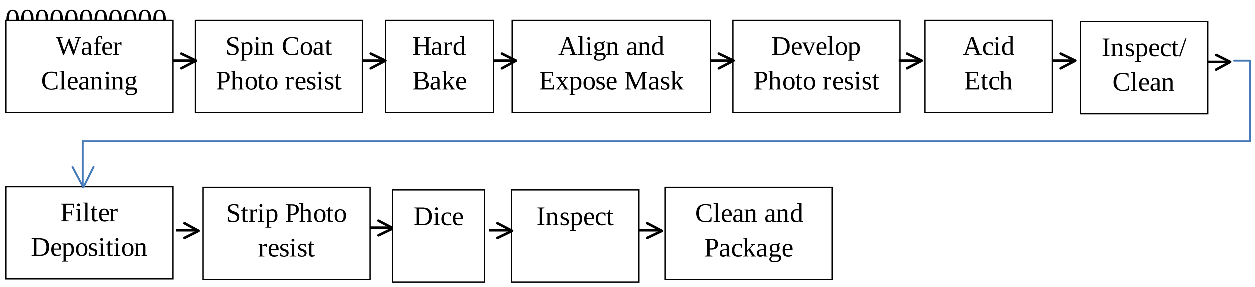


Figure 5: Flow of processing steps for the fabrication of patterned fiber optic based filters.

3: Filter Design

A unique aspect of these filters is that since the layers are supported from the sides, air or vacuum voids can be used for the low index layers. Air is nearly dispersion free and vacuum provides a perfect absorption free low index material across the full spectrum. Selecting a low dispersion, broad band transmitting material such as germanium allows for the design of filters from about 1.8 microns to beyond 40 microns. The use of materials such as lower index fluorides instead of germanium allows for filter design from the ultra-UV through 25 microns and beyond. Air layers can be used to provide nearly perfect, very broad band anti-reflection coatings across very broad spectral ranges. While these filters are only 5 to 20 microns in the z axis, perpendicular to the board, and limited to fiber based sensors, they offer the potential of optical performance here to unimagined.

A carbon dioxide sensor can be created using an open air filter design. The carbon dioxide filter is designed to band pass light in the region of 4.2 to 4.45 microns using a Fabry-Perot design. Since carbon dioxide absorbs in this region, the presence of this gas impedes the performance of the matched reflectors and the band pass transmission decreases as a function of CO_2 concentration. The open air filter would be used with a co-located sealed reference filter for calibration to temperature and pressure.

Figure 6 presents modeled transmission for a open air printed filter with a transmission band tuned to the absorption band of CO_2 gas. Modeled transmission for various values of the extinction coefficient at 4.3 microns are overlaid.

Figure 7 presents the CO_2 filter design. The total distance of the filter is 94 microns along the optical path. The filter is designed using needle layer synthesis techniques[5], but the film thickness is constrained to a minimum thickness of 1 micron. This constraint is made to enable fabrication using 1 micron line thickness lithography techniques. Figure 8 presents a plot of average transmission through the 4.2 to 4.45 micron passband. The average modeled transmission is a exponential function of the extinction coefficient.

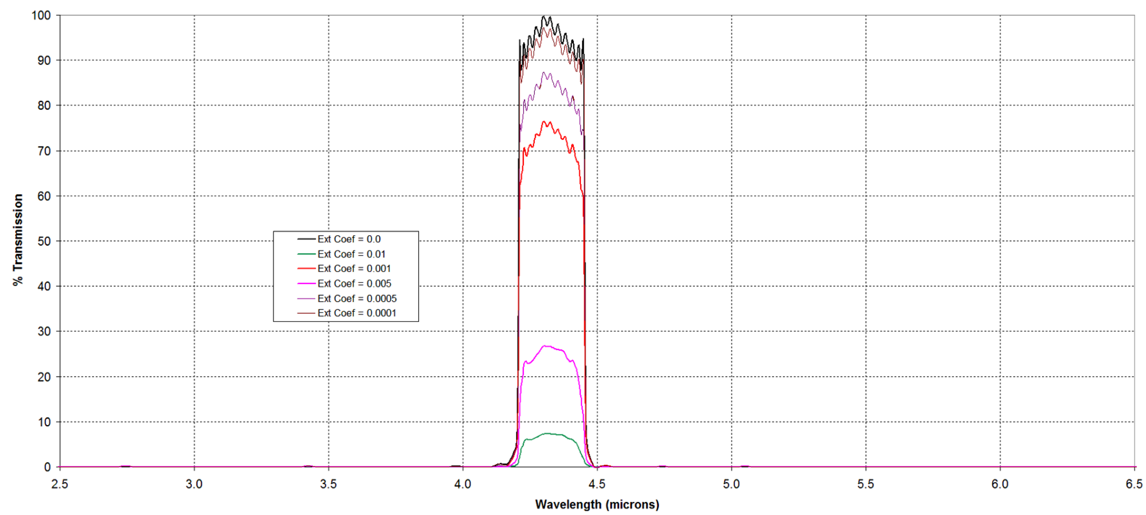


Figure 6: Modeled transmission for a 4.2 to 4.45 micron band pass filter. The filter is modeled for various values of extinction coefficient (k). This band corresponds to an absorption band for CO_2. The filter design is unusually thick - 94 microns. The layer thickness was limited to a minimum of 1 micron. The high filter thickness allows for high out of band rejection from the UV to out beyond 25 microns.

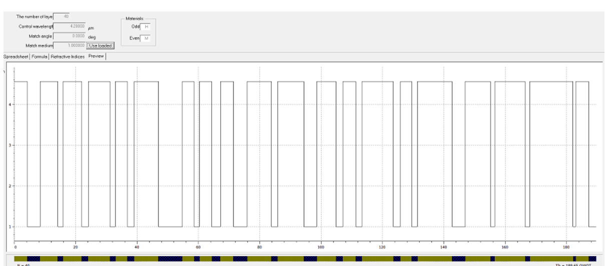


Figure 7: The filter design is only 40 layers, but is 94 microns thick. The layers are typically much thicker than would be found in a stacked interference filter construction. This is done to allow for 1 micron lithography.

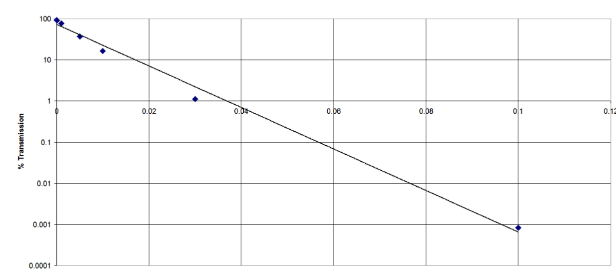


Figure 8: The average modeled transmission between 4.2 and 4.45 microns is plotted as a function of the absorption coefficient in this spectral region. Subtle changes in the gas concentration result in changes in the pass band transmission.

Figures 9 through 11 present a 10.64 notch filter. This filter is 0.5 microns wide and has a thickness along the optical axis of 193 microns. This filter would be expensive to fabricate as a stacked filter of 184 layers. The filter designs lend themselves to fabrication using patterned lithography and ultimately, printing techniques. Initial deposition work uses the Leybold Helios Pro coated presented in figures 18 and 19.

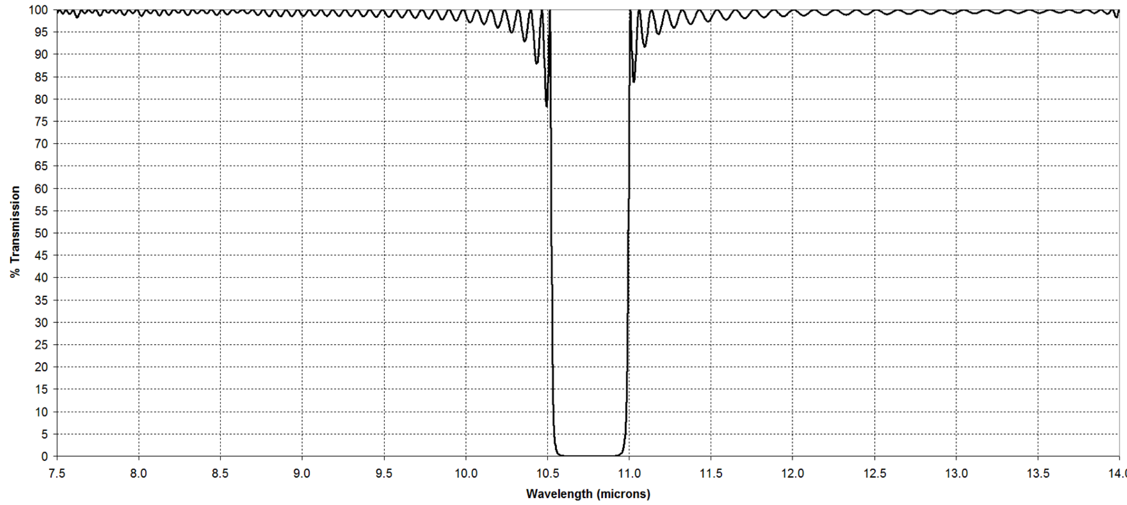


Figure 9: Modeled transmission of a 0.5 micron wide, 10.64 OD 4 notch filter. The filter width along the optical axis 193 microns and 184 layers.

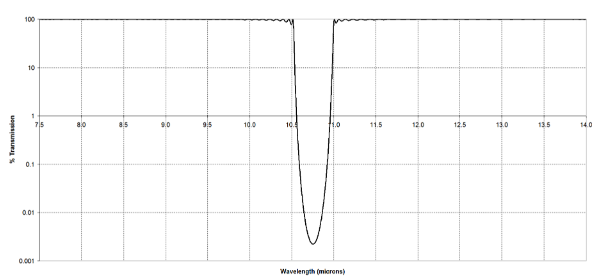


Figure 10: Modeled transmission the 10.64 notch filter plotted on log scale to highlight optical density.

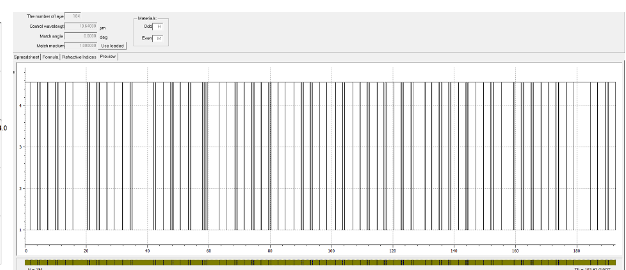


Figure 11: Plot of the notch filter design. Air is used as the low index layer. The filter would need to be sealed to avoid change in performance with changes in gas properties.

4: A CO2/CH4 Gas Sensor

The design for the 4.3 bandpass filter presented in figure 6 has an unusually high phase thickness for a commercial interference filter. In this example, the film thickness is in excess of 90 microns. The reason for this high thickness was so that all the film layers would be at least 1 micron in thickness. As a consequence of this constraint, the filter has a broad rejection region making it easier to scale to other wavelengths.

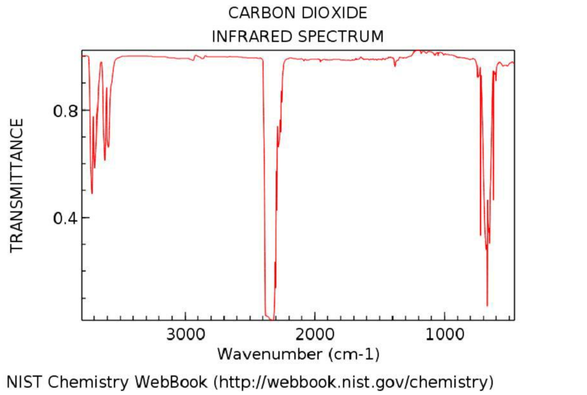


Figure 12: Transmission spectrum for CO_2 showing a strong absorption at 4.2 to 4.4 microns.

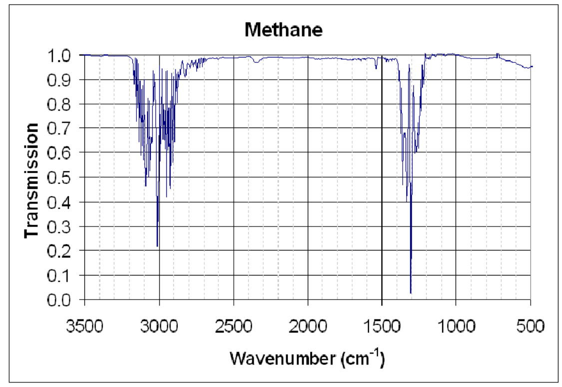


Figure 13: Transmission spectrum for CH_4 showing strong absorption at 3.3 and 7.7 microns.

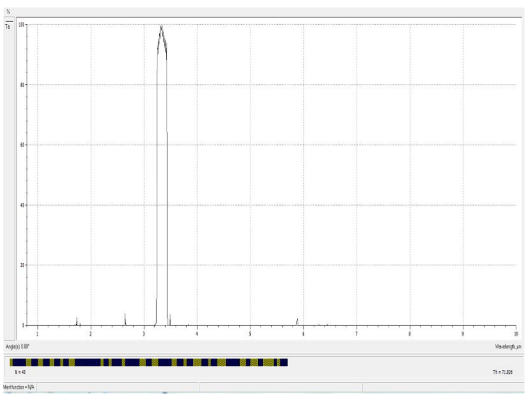


Figure 14: Bandpass notch for the 3.3 micron (3020 cm^{-1}) absorption line of methane.

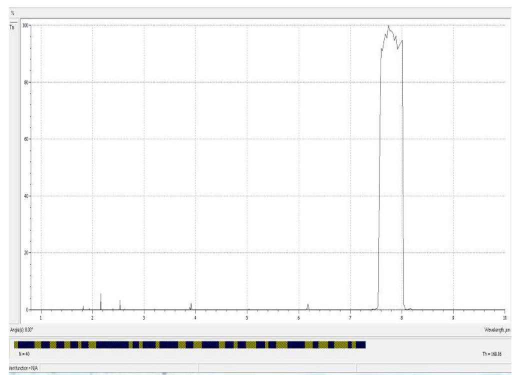


Figure 15: Bandpass notch for the 7.7 micron (1306 cm^{-1}) absorption line of methane.

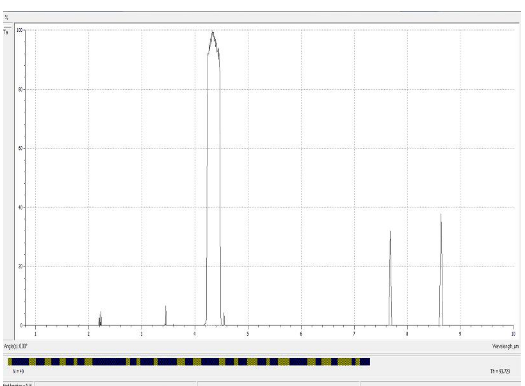


Figure 16: Bandpass notch for the 4.3 micron (2326 cm^{-1}) absorption line of methane.

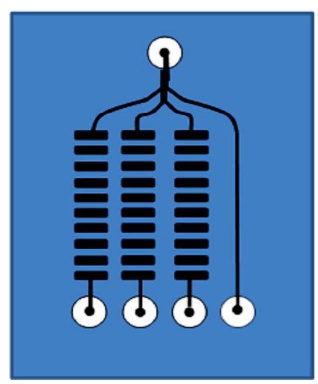


Figure 17: The optical chip will have three bandpass filter channels and a pass through reference channel.

Figures 12 and 13 present transmission spectra for carbon dioxide (CO_2) and methane (CH_4). A sensor with three parallel filters and a reference can be configured to simultaneously measure both gasses on a relatively small optical chip. Figure 14 and 15 present designs for the methane absorption bands and figure 16 presents the design centered on the CO_2 band. A concept schematic for the optical chip is presented in figure 17.

Figure 18: Parts and product are cleaned and handled in a clean room environment to ensure high yield and the most effective control of production cost.

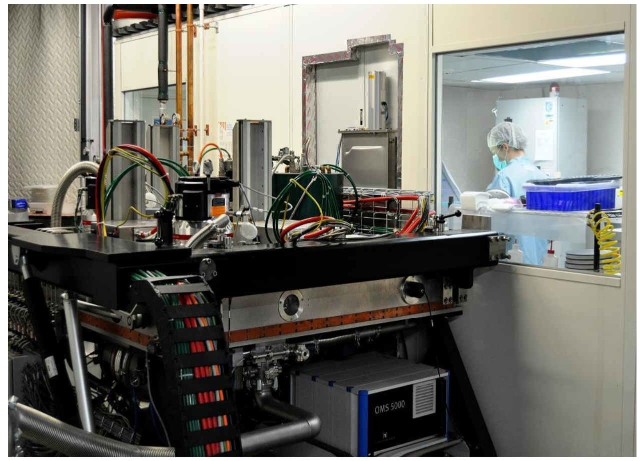


Figure 19: The Helios multi-target high volume reactive sputtering coater provides high volume capability and reliable performance for the most challenging designs.

4: Summary

In this paper, we have presented the concept and design for an open air filter construction for measuring gas concentration. By laying the filter on it's side, an open air construction is possible which allows for the low index layer to be air or other gas. Modeling shows the bandpass region of the filter to be a sensitive measure of the extinction coefficient of a trace gas. The example filter is designed to measure CO_2 gas levels. The open air construction allows for some unique design features including a high number of layers, high refractive index contrast between the high and low index materials and an unusually thick phase thickness. While standard deposition techniques are being evaluated for initial fabrication, this design and construction technique can be applied to emerging high resolution printing techniques.

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