Durable Optical Coatings for Robust Performance in Harsh Environments

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Advances in optical filter and window technologies address the need for higher performance, lower weight, and reduced cost demanded by drones, UAVs, UAS, and autonomous vehicles. A modular design approach to the windows and optics in a drone to withstand various environmental threats is presented. Optical interference filters and window coatings combine optical performance with needed mechanical and environmental requirements. Window performance in adverse weather conditions can be improved with the incorporation of thin film heaters, hydrophobic coatings, and surface treatments as well as transparent conductive layers to shield against electromagnetic interference. Linear variable filters reduced to the size of the imager, provide hyperspectral capability, grating order reduction for spectrometers and the capability of replacing the spectrometer completely. Fixed wavelength filters enable on-board cameras to survey a particular chemical species or contaminant. Examples of filter and window combinations are presented. We compare a number of hydrophobic treatments for exterior windows including PTFE based compounds, surface micro-etching, and various hard oxides. Contact angles are presented for the uncoated and treated windows. Transparent conductive oxide layers are compared and evaluated as heaters and EMI shields. Performance and design considerations of fixed wavelength filters are presented.

INTRODUCTION

Drones and automated vehicles are typically designed to go into uncontrolled environments and the optical system needs to maintain high signal quality under these conditions. Advanced window coatings are designed to maximize imager and sensor throughput for a wide range of harsh and challenging environments such as rain, wind, glare, sand and atmospheric pollution[1]. Antireflection (AR) coatings, hydrophobic surface treatments, transparent heater and electro-magnetic (EMI) films or grids and solar filters can be added as needed to the window surfaces to address these issues.

Within the sensor, narrow and ultra-narrow bandpass optical filters are used to maximize signal to noise for laser-based communication and LIDAR based systems. Wider bandpass filters are used to detect or image a particular spectral feature as in the case of gas sensing. Narrow band linear variable filters reduced to the size of a detector chip can be used for hyper spectral applications and significantly reduce system weight by eliminating the need for a grating spectrometer[2]. Such optics inside the sealed enclosure need to operate over a wide temperature range and should be designed with the presumption that the seal will fail at some point over the lifetime of the drone. Table 1 lists many of these concerns and some options to mitigate their impact on performance and lifetime.

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Table 1. Summary of environmental threats and solutions

Optical Component	Environmental Threat	Impact	Solution
Window	Rain/Acid Rain Condensation/Icing Solar Glare Sand Atmospheric Pollution EM Interference	Sight limitation/Degradation Heating Scattered Light Maintenance Degradation Electronic Noise/Security	Hydrophobics Heater Solar Blocker DLC EMI Shield
Filters	Temperature Excursion Moisture	Throughput/Crosstalk Haze	Athermalization Lamination Material Selection

There is no single solution to all problems that can arise while operating in a harsh environment. Each situation requires the selection of different coating options which can be built together to maximize performance. The following sections discuss the unique challenges and solutions for the window, filters, and optical components that make up the sensor to be operated in a harsh environment.

WINDOWS

The optical window is the first line of defense against the environment. Any icing, condensation or water accumulating on the surface will rapidly degrade image quality and sensor sensitivity.

Hydrophobic coatings can be used to reduce or limit water accumulation on the window surface. The two criteria that are used to evaluate the degree to which a surface is hydrophobic are contact angle of a bead of water, and the angle at which the bead will roll off the plate. Table 2 presents a summary of hydrophobic performance for a number of coatings that we have evaluated for use on an exterior window. Figures 1 and 2 present photographs of water droplets on an untreated surface and a surface coated with Al_2O_3.

Furthermore, hydrophobic coatings generally fall into two categories: organic and inorganic materials. Organic materials such as Topcoat E* are polymers and while they offer high contact angles, they are soft and are prone to rapid degradation from UV exposure. Inorganic options such as aluminum oxide are much more stable and cleanable over time. In either case, the hydrophobic coating can be integrated into an anti-reflection coating as the outer surface.

Table 2. Hydrophobic Coating Materials/Processes

Material	Process	Contact Angle
Umicore TopCoat	Resistive/radiative filament	92
Umicore EverClean	Resistive/radiative filament	113.1
Al_2O_3	E-beam	67.25
Al_2O_3	Magnetron Sputtered	67.4
Al_2O_3	Sputtered + 5 min post plasma	40.25
Al_2O_3	Sputtered + 15 min post plasma	27.0

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* http://www.thinfilmproducts.umicore.com/Products/TechnicalData/show_datenblatt_topcoat.pdf

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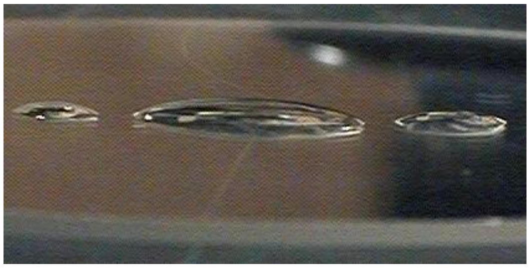
<tr><td></td><td></td></tr>
<tr><td>Figure 1. Water droplets on an uncoated window</td><td>Figure 2. Water droplets on an Al_2O_3 coated window</td></tr>
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The window can also be configured with an optically transparent heater to prevent condensation and ice formation. The heater consists of a thin layer of transparent conductive coating. Figure 3 presents a photograph of a heater designed to hold the window temperature 20^{o} C above ambient temperature with a power dissipation of 1 watt. Figure 4 is an infrared photograph of the heater in operation demonstrating good thermal uniformity across the window surface. The heater is typically placed on the inner surface of the window and is anti-reflection coated to maximize throughput and also to protect the transparent conductive layer.

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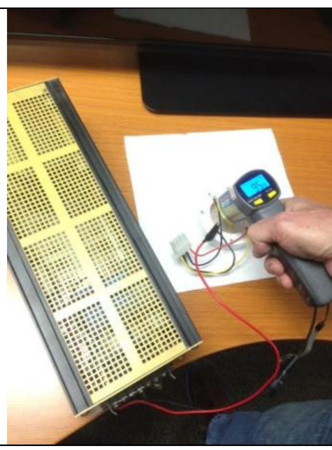
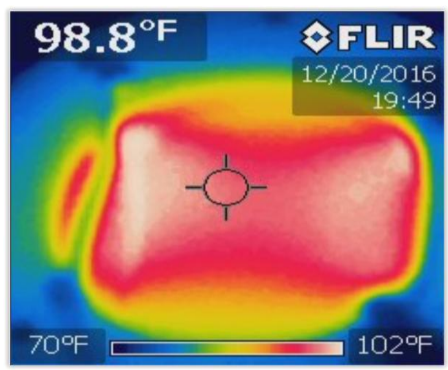
<tr><td></td><td>
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<tr><td>Figure 3. Photograph of the test heater window coated with transparent conductor. At 12 volts, the heater runs 20^{o} over ambient with power consumption of 1W</td><td>Figure 4. Infrared photograph of the heater demonstrating good thermal uniformity across the window surface.</td></tr>
</table>

A transparent conductive layer can also be used to act as an EMI shield to isolate and prevent electromagnetic interference from passing through the window. The heater resistance is typically in the range of 150 ohms/sq. EMI shielding resistance is typically in the range of 10 to 30 ohms/sq. Specific coating resistance can be tailored to the available power supply.

Solar blocking and bandpass filters provide a means of reducing the heat load on the sensor by reflecting off spectral bands that are of no interest. If the sensor is using the visible spectrum, 400 to 720 nm, a significant portion of the solar spectrum is outside this range. Although a silicon CCD does not convert photons with a wavelength longer than 1100 nm, it does absorb the light and this can lead to heating the detector and degrading performance.

Figure 5 and 6 present two examples of solar blocking filters. Figure 5 presents the spectral performance of an Indium Tin Oxide (ITO) layer. The film passes the visible and reflects the infrared. Figure 6 presents a more complex filter designed to pass multiple spectral bands. This filter is a high performance single surface oxide coating. The oxide coating can be placed on the outer surface of the window and incorporate an AR or AR with a hydrophobic outer layer.

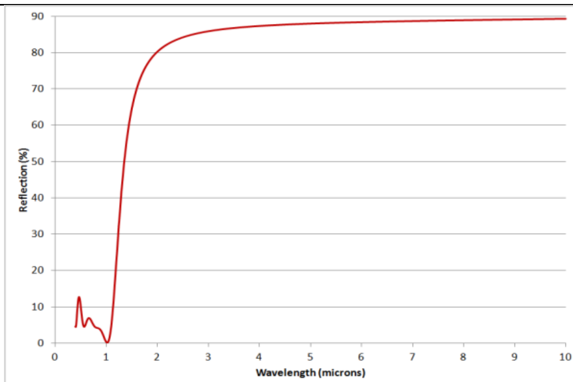

Figure 5. Spectral performance of ITO coating showing reflection of IR wavelengths.

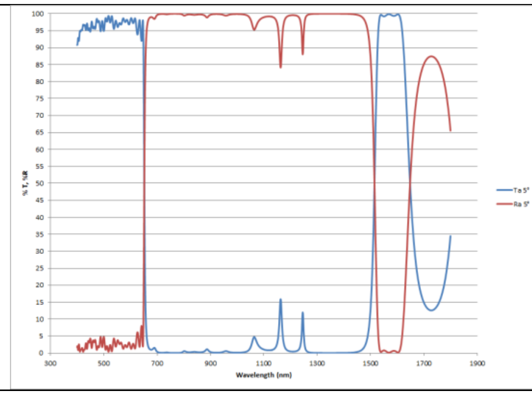

Figure 6. Spectral performance of the solar blocking filter.

THIN-FILM FILTERS

While the optical system may be in a sealed enclosure, there is always the possibility for the seal to fail particularly in a situation that experiences severe mechanical shock. Two options for ensuring long-term stability of the filters and optical components within the system are to use oxides deposited using a high energy process or to laminate the coatings between two glass substrates.

Figure 7 presents a photograph of our dual magnetron plasma assisted coating deposition system. This chamber uses a high-energy plasma source to assist in increasing density and fully oxidizing the coated layers. The resulting films exhibit no discernible shift in performance with humidity.

Performance stabilization with changes in temperature is accomplished by matching the coating materials to the glass with the most appropriate coefficient of thermal expansion[3] (CTE). Figure 8 presents an overlay of a narrow bandpass filter (~2.5 nm wide) over a range of temperatures from -50°C to +50°C. The measured wavelength shift over this 100° C range is 0.22 nm. The same technique has been demonstrated on laminated polycarbonate filters fabricated with zinc sulfide and cryolite[4].

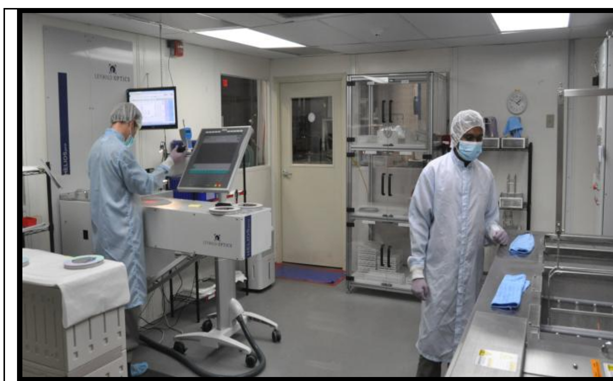

Figure 7. High yield dense oxides are produced in our dual magnetron plasma assisted coating chamber.

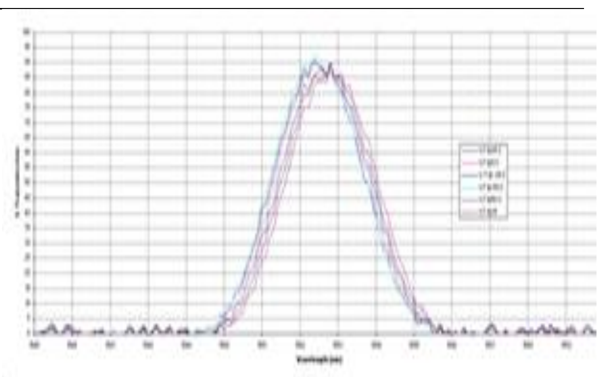

Figure 8. Measured transmission of the thermally stabilized narrow bandpass filter at -50^{0}C, 0C and +50^{0}C.

Metal mirror coatings are sensitive to environmental degradation and even protected metal coatings are prone to early failure. Metals such as silver fail quickly in an urban environment where air pollution contaminants such as sulfur dioxide from burning hydrocarbon fuels are in high concentration. The alternative to using a metal-based coating is to use an all oxide broadband mirror. Figure 9 presents a comparison of the reflection of an oxide broadband mirror and the reflection of freshly deposited silver and aluminum mirrors. The oxide mirror coating has the dual benefits of better reflectivity and increased durability over the metal mirror[5].

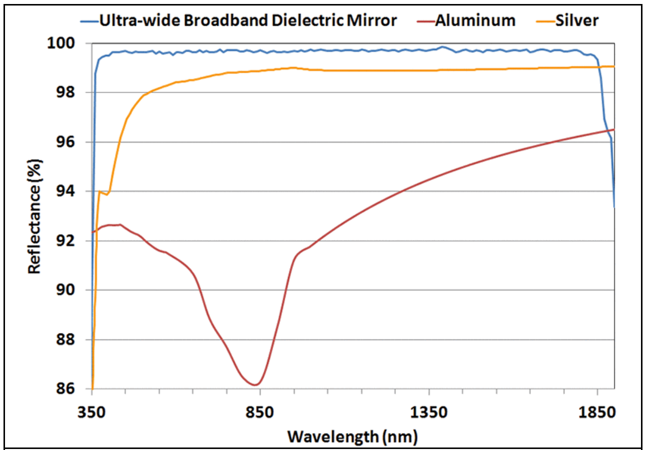

Figure 9. Reflection of broadband mirror vs silver and aluminum mirrors

A final approach to protect a filter is to laminate the coating between two pieces of glass substrates using an optical grade epoxy. The edges of the filter are typically scribed allowing the epoxy to form a complete glass-to-glass seal at the edge, thus protecting against penetration of humidity in from the edges. Figures 10 and 11 present an example of performance of such a filter made in 1983 compared with performance of the same filter measured recently demonstrating over 30 years of stable spectral performance[4].

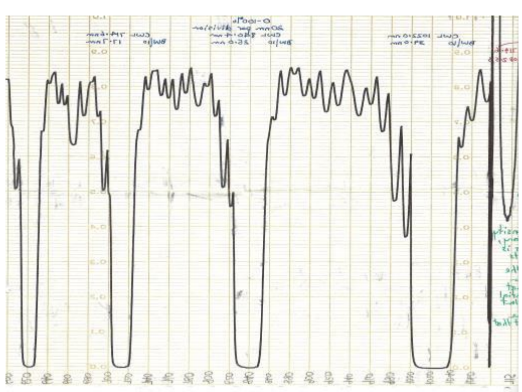

Figure 10. Transmission scan of a laminated rejection notch filter made in 1983.

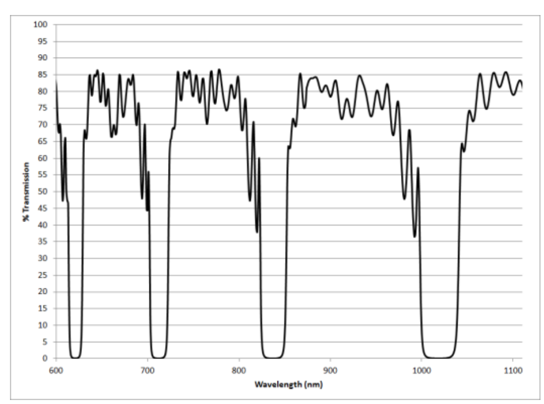

Figure 11. A recent transmission scan of the same filter demonstrates the filter's environmental stability over long periods of time.

EXAMPLE

Our approach to customizing the windows and optics to challenging environmental conditions is to build up the required performance from constituent films and coatings. Figure 12 presents a schematic of a high performance commercial aerospace window. The front surface coating consists of a dual bandpass solar blocking coating. The filter passes the visible spectrum as well as a narrow band of wavelengths at 1550nm to allow for free space laser communication. This filter blocks unwanted near infrared wavelengths to prevent overheating of the detector. An index matched anti-reflection hydrophobic coating is then overlaid on top of the solar blocking filter.

The inner surface of the window consists of a transparent heater to prevent icing and condensation on the window. This coating is then coated with an AR coating to optimize transmission and protect the heater layer from environmental degradation.

Within the sensor, several filters are used to enhance performance and meet system requirements. A laser pick-off dielectric mirror reflects the 1550nm laser communication band while passing through the visible band to the imager. Filter options for wavelength selection include: narrow bandpass and longpass filters for spectrometer order sorting, ultra-narrow bandpass filters for improvement of detector signal to noise, and dichroic beam splitter coatings for multiple sensor channels using a common optical aperture.

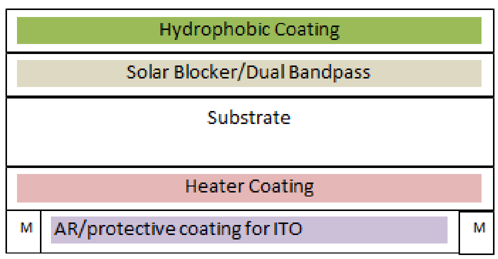

Figure 12. Window schematic

SUMMARY

Hardening optical windows, filters and anti-reflection coatings is a matter of understanding how the filter will be used. Performance requirements can be achieved by combining the appropriate thin film structures and materials. We are continuing to evaluate and develop solutions as needs of our customers evolve.

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