An introduction to optical windows

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ABSTRACT

This paper provides and introduction to optical windows. Several aspects of window design are discussed and simple equations to calculate window deformation effects are provided. Several materials that can be used for window substrates are presented and their advantages and disadvantages are discussed. The coating of windows is briefly discussed as well. The topics discussed here are only meant as an introduction to optical windows and only a few aspects of window design are presented.

1. INTRODUCTION

Many optical systems require transparent windows for various reasons. Windows can protect a system from dust and debris and provide environmental and vacuum seals. There are several factors a designer must be aware of when designing a window for an optical system, which include strength, transmission range, environmental durability and available coatings. The most common type of window for an optical system is a plane parallel plate but can also include domes, segmented windows and conical sections[1, 2]. Since windows provide protection for the optical system they are often the most important optical elements in the system, which can make them one of the most costly[3]. Even though windows can be simple plane parallel plates, environmental conditions such as pressure and temperature differentials can cause the window to distort and decrease the performance of the optical system. Several materials are available to use as substrates for windows and a few of them are listed in this report.

2. OPERATING ENVIRONMENTS

Optical systems operate in a wide variety of environments and windows provide transparent protection from those environments. A simple example of a window is one that provide high transmission at the desired wavelengths while protecting the rest of the optical elements from dust and debris. More complicated windows transmit a wide range of wavelengths while being subjected to high pressure and temperature differentials. Those systems include deep ocean cameras, cryogenic systems and seekers on missiles[2, 4]. For systems that operate in harsh environments that include high humidity, salt spray and dust, the windows require protective coatings in order to shield the substrate from environmental degradation.

3. DESIGN CONSIDERATIONS

When designing an optical system it is very important to include any windows early in the optical design. Depending on the system requirements, windows can have a significant impact on system performance. How the window is mounted will affect the performance of the window and the performance overall system. Proper mounting must ensure that the window is sealed from the outside environment and that thermal and pressure differentials are properly accounted for. Figure 1shows a typical mounting scenario for a window[1].

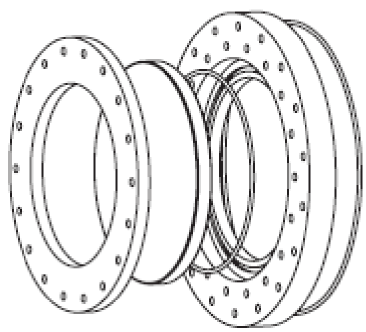

Figure 1: Typical window mount (from Schwertz and Burge)

The window mount shown in figure 1 includes a top plate, o-rings and a window cell. In this case the the window is sandwiched between two o-rings and the top plate bolts to the window cell causing the o-rings to compress and seal the optical system. Windows can also be mounted using an RTV type adhesive as shown in figure 2[2].

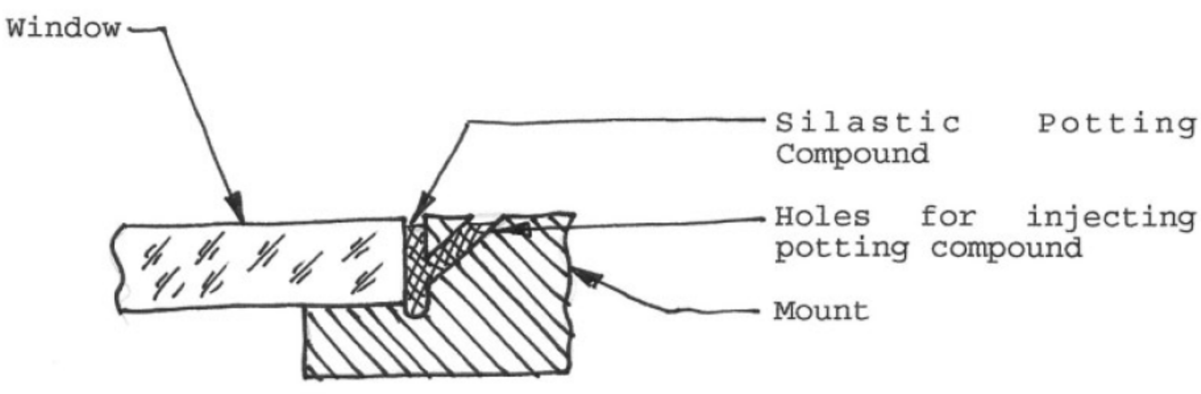

Figure 2: Window mounted with silastic compound (from Vukabratovich)

Window tilt has little effect on system performance and windows are often manufactured or mounted with a wedge to prevent back reflections[2]. However, windows must be mounted in a low stress state to reduce the surface distortion caused by thermal and pressure differentials. In the case of using hard mounts, the retainer and window cell material must match or be close to the window substrate CTE in order to reduce window stress over temperature change[2,5]. Figure 3 shows an example of a hard mount[2].

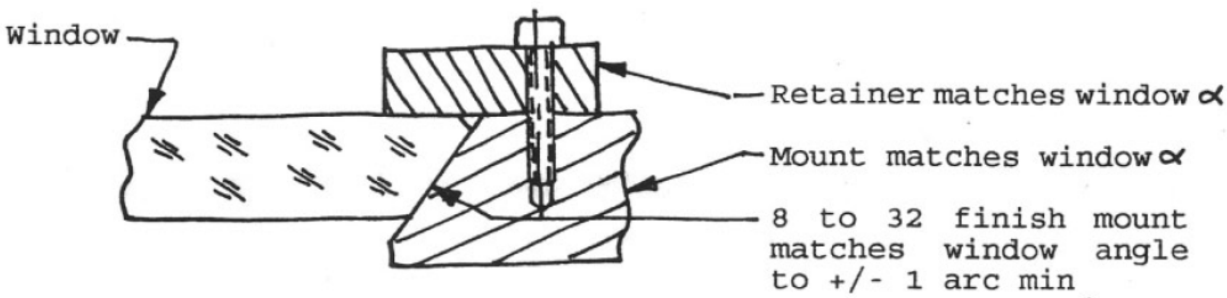

Figure3: Window hard mount (from Vukobratavich)

Axial temperature gradients in windows are caused by absorption of an incident heat flux. Yoder (2006) shows that a plane parallel circular window becomes a concentric meniscus when exposed to an incident heat flux[6]. Equation (1) gives the power of the window when exposed to an axial temperature gradient[2].

$$P = \frac{1}{f} = \frac{n-1}{n}(\frac{\alpha}{k})^2 tq^2 \tag{1}$$

Where f is the focal length, n is the window refractive index, t is the thickness, q is the incident heat flux per unit area, α is the window CTE and k is the window materials' thermal conductivity.

Many optical systems have windows that are exposed to pressure differentials such as airborne FLIR and cryogenic systems. Vukobratovich showed that for a simply supported circular window exposed to a uniform pressure differential the optical path difference (OPD) through the window is given by equation (2).

$$OPD = (8.89\ x\ 10^{-3})\frac{(n-1)\Delta P^2 d^6}{E^2 h^5} \tag{2}$$

Where n is the refractive index of the window material, ΔP is the pressure differential, d is the window diameter, E is the material Young's modulus and h is the window thickness[2]. If the window is exposed to acceleration loading then ΔP can be replaced by equation (3).

$$\Delta P = \frac{a\rho h}{g} \tag{3}$$

Where a is the acceleration, ρ is the window density and g is the acceleration due to gravity[2].

If the window is in the presence of a diverging beam then the focus of the system will be affected. For example, if a system has a cryogenically cooled focal plane then it is possible that the last element of the system is a window that seals the dewar. In that case the window will cause the focus of the system to shift as shown in figure 4. Equation 4 gives the approximate focal shift (Δz) in terms of the index (n) and the thickness (t) of the window.

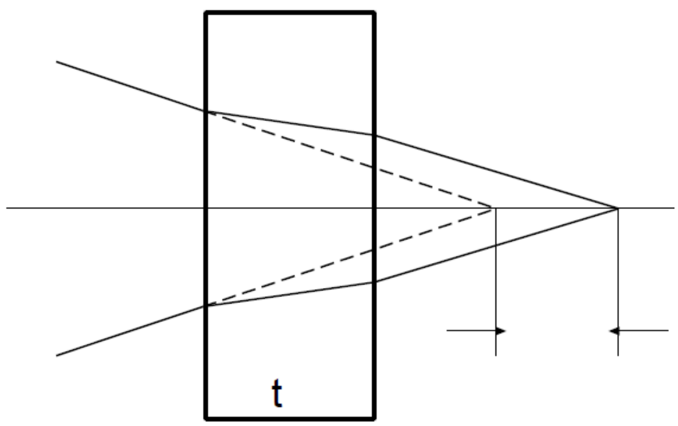

Figure 4: Focal shift due to a plane parallel plate (from Burge OPTI521)

$$\Delta z = \frac{n-1}{n} t \tag{4}$$

Another concern for windows in the presence diverging or converging beams is the induced aberrations. Windows can induce spherical aberration, coma and astigmatism as well as transverse and longitudinal chromatic aberrations[7].

Thus, it is very important that optical windows be taken into consideration early in the optical design so that any powered elements in the system can negate the aberrations induced by the window.

4. MATERIALS

Choosing a material for a window is critical. The material must be able to transmit over the desired wavelengths, be strong enough for the application and easy to coat. Table 1 lists a few materials that are used for optical windows and some of their important properties[7,8,9,10].

Material	Index @µm	Wavelength range (µm)	Young's modulus (GPa)	CTE (10^{-6}/C)	Thermal conductivity (W/m-k)	Poisson's ratio
N-BK7	1.5168@0.589	0.35-2.5	82	7.1	1.11	0.206
Sapphire	1.7545@1.06	0.17-5.5	335	5.3	27.21	0.25
ZnSe	2.403@10.6	0.6-16	67.2	7.1	18	0.28
CLEARTRAN	2.2008@10	0.37-14	74.5	7.0	27.2	0.28
Germanium	4.0026@11	2-14	102.7	6.1	58.61	0.28
Silicon	3.4223@5	1.2-15	131	2.6	163.3	0.266
CaF2	1.4338@0.589	0.35-7	5.8	18.85	9.71	0.26

Table 1: List of window materials

N-BK7 – This is a very versatile optical material that is easy to make high quality and is inexpensive. BK7 is easy to coat and can be made in very large sizes. A drawback of this material is that its transmission range is limited to the visible and near infrared.

Sapphire – Sapphire is a very hard and scratch resistant material but this makes it difficult to machine. It has a very large transmission range and can be used for windows and domes from the UV to the IR. Sapphire is also used in consumer applications for transparent button covers on cell phones.

ZnSe – Zinc selenide is an infrared transparent material that is commonly used for IR windows. However, it is a soft material and degrades quickly when subjected to particle-impacting environments. This mean that ZnSe must coated with something, such as a diamond-like carbon in order to protect it[8].

CLEARTRAN – CLEARTRAN is a water clear form of zinc sulfide and is very similar to zinc selenide. However, while ZnSe is limited in transmission to the infrared CLEARTRAN transmits from the UV to the far IR[9]. This makes it a great material for multispectral applications that require a single window to transmit all the desired wavelengths.

Germanium – Germanium is another material that transmits well in the infrared. It has good environmental qualities, but poor thermal properties. Germanium has a high dn/dT and becomes nearly opaque at temperatures above 100^{o} C and completely non-transmissive at 200^{o} C[10].

Silicon – Silicon is similar to germanium in that it transmits well in the infrared, but has a high dn/dT. Silicon has a high transmittance in the mid-wave infrared range and is also half the density of germanium. It is also much harder than germanium making is less brittle[11].

Calcium fluoride – CaF2 transmits a wide range of wavelengths from the UV to the IR and is commonly used in cryogenically cooled thermal imaging systems[12]. It also has excellent water, chemical and heat resistance. However, CaF2 is a soft material and has a relatively high CTE so care must be taken when using it in systems with large temperature variations.

5. COATINGS

Coatings are an important part of the optical window design. The coating is specified based on the operating environment and the desired wavelength range of the system. For systems that operate in harsh environments a diamond-like coating might be appropriate to protect the window from things like dust and moisture[8]. In optical systems that operate over a wide range of wavelengths a broadband coating is required. These particular coatings have the added requirement of having high transmission over a wide spectral range which adds complexity and cost to the window. Coatings for multi-spectral systems, such as 3rd generation infrared, must be able to stand up to the severe abrasion environment and significantly improve the transmission of the bare window substrate[13].

6. CONCLUSION

Windows are a crucial component in nearly all optical systems. They perform the important task of providing a transparent barrier from the outside environment. Operating environments for windows can range from large pressure and temperature differentials to abrasive dust and debris. When subjected to such environments the mounting of the window becomes critical so that stresses are minimized. Several materials are suitable for use as optical window substrates, but the designer must be careful when choosing which material to use. Proper research of the window material must be done to ensure the substrate can withstand the operating environment, can transmit the desired wavelengths and is easy to coat. For windows that need to operate in a highly abrasive environment a diamond-like coating will protect the substrate while transmitting the desired wavelengths. Several references are presented on the following page for more information regarding optical windows.

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