Design of uniform window heating structures for electro-optical systems

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ABSTRACT

Temperature non-uniformity in a heated window can result in a significant distortion in the transmitted wavefront. Aberrations are introduced by actual physical distortion of the window due to differential thermal expansion and by localized optical path variations due to the change in index with temperature (dn/dT) of the substrate material. Typically, the second factor is the more pronounced. This effect represents a significant limitation in the performance of windows with non-symmetric geometries made from materials that exhibit combinations of high dn/dT and low thermal conductivity.

LightWorks Optical Systems (LWOS) has recently developed a software tool capable of quantitatively modeling the thermal distribution of a heated window in operation. This capability allows the design team to optimize the heater layer sheet resistance (whether the layer is a metallic grid or a transparent conducting oxide thin film) and the configuration of the bus-bar (electrode) connections prior to any hardware fabrication. Consideration of both of these factors is critical to achieving a uniform thermal distribution at the specified temperature across a given window.

This presentation will describe the recent efforts of LWOS to establish the capability for quantitatively modeling the temperature homogeneity across a heated window based on window material and dimensions, heater layer characteristics and bus-bar configuration. Data will be presented that demonstrates the validity of these models via comparison to actual heated windows observed under heated conditions.

Keywords: window heater, temperature non-uniformity, transmitted wavefront, conductive oxide, de-ice, dn/dT, metal mesh, metallic grid

1. INTRODUCTION

The heating of windows and other optics are important for de-ice/de-fog applications. Heating a window may be accomplished by external heaters (i.e., heater blankets, frame heaters, etc.), heating the bulk material or heating the window surface. Heating the window directly is often preferred over external heaters because of better temperature uniformity of the window and the efficiency of heat transfer in terms of delivered power. The temperature uniformity of the window is of particular importance in terms of wavefront distortion. This is because relative temperature differences in the window material will have a direct impact on the optical beam path deviation caused by differential thermal expansion and deviations in the index (i.e., dn/dT). Typically the second factor is the more pronounced. The focus of this paper will be on electrical heating of the window surface, looking specifically at the temperature uniformity across the window surfaces.

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To heat the window surface an optically transparent heating layer is placed over the window clear aperture. The heating layer may be a transparent conducting oxide (TCO) or metallic grid. An electrical current is passed through the layer to generate resistive heating. The amount of heat transferred to the window surface is primary a function of the power delivered to the heating layer. Thus, depending on the power supply limitations (e.g., a set voltage), the control of sheet resistance of the heating layer is fundamental. Typically, the larger the window, the lower the sheet resistance required. There is a fundamental trade-off between sheet resistance and transparency. When the sheet resistance drops, the optical transmission will decrease. This is true for both TCOs, such as Indium Tin Oxide[1] (ITO), and metallic grids[2]. The choice of using a TCO or metallic grid will depend on the transmission required and the waveband(s) of interest. Generally speaking, a TCO is limited to the visible through MWIR bands and sometimes just the visible, depending on the required level of sheet resistance. The benefit of using a metallic grid is that it is usable over all optical wavelengths, though the amount of obscuration due to the metallic structures will impact the transmission at normal incidence and at angle[2]; in addition the diffraction effects may also need to be accounted for[3].

2. APPROACH

2.1 Design considerations

The size of the window (lateral dimensions and thickness) will also be a contributing factor to the sheet resistance required. For example, for a given sheet resistance on a rectangular geometry, the design may benefit from placing the electrodes along the longer dimensions rather than the shorter, since the electrode-to-electrode resistance would be effectively decreased and thereby increasing the power (i.e., $P=V^2/R$). Thus, to achieve the same power the sheet resistance may be reduced, which will typically increase the optical transmission. The power density is often a preferred quantity to use to determine the necessary heating, since it is based on the window environment and the window thickness rather than the lateral dimensions. The total power required, on the other hand is based on the power density and the lateral dimension. (i.e., Total Power=Power Density x Area).

Since power is related to the temperature by the Stefan-Boltzmann law, the *distribution* of power across the window surface will have a direct impact on the window temperature uniformity. There are several parameters that will influence the temperature uniformity. The substrate material is of particular importance, since the distribution of heat will depend on the thermal conductivity of the material. In addition, choosing a material with a low dn/dT will also improve wavefront error. For illustrative purposes in this study, fused silica was chosen based on its low thermal conductivity and high dn/dT.

Once a material is selected, specific design details can be worked out and the other temperature uniformity parameters considered. The location and size of electrodes is one such factor. As will be shown in the analysis section, if the electrodes extend too close to one another, the effective resistance is reduced locally and, therefore, the power is increased in that region. This is particularly challenging for non-symmetric window geometries. Related to the electrodes is the resistive path that the electric current takes. This will also depend on the uniformity of the conductive film or grid. The window dimensions and operating environment are other parameters to consider, since the convection of air and the rate at which the heat dissipates from a relatively large or small window surface will impact the overall temperature distribution. Other considerations are the amount of delivered power and the degree to which the window is elevated above ambient temperature. This will also increase the delta temperature across the window. With all these factors in mind, it is best to think of the power density as an average number and consider the temperature variations as deviations from this number, being highly influenced by one or more of the parameters mentioned above.

The clear aperture or usable area of the window is another important factor to consider when designing a window heater. Localized hot/cold zones may be unavoidable in some cases, so adjusting the design parameters that are alterable may become necessary to achieve suitable temperature uniformity in the zones of interest. This paper will focus on temperature uniformity of the entire clear aperture.

2.2 ANALYSIS

The LWOS team has developed a software tool capable of quantitatively modeling the thermal distribution of a heated window in operation using design guidelines based on the temperature variation parameters defined above. Often

iterative adjustments to the model are necessary to account for the many variables found in any given window to ensure accurate model-to-hardware correlation and for improving the design performance.

Two basic window configurations were selected for this aspect of the study – a trapezoid and a circle. The windows were analyzed by applying a voltage across the electrodes of a conductive coating on a fused silica substrate until the coldest temperature region on the window reached about 15°C above ambient (~22°C). The convection of air impressed upon the window was assumed to be 20 W/m°K based on previous experimental testing.

As mentioned earlier, when the electrodes are placed closer together, the resistive path is shorter (less resistive), so a higher amount of power is delivered to this region. For example, in Figure 1 (left) the distance between electrodes varies, following the shape of the trapezoid sides. The clear aperture is defined by the dashed line. The temperature map was taken of the clear aperture and is shown in Figure 1 (right). A significant delta temperature is seen across the window surface (~14°C) corresponding to the resistance gradient.
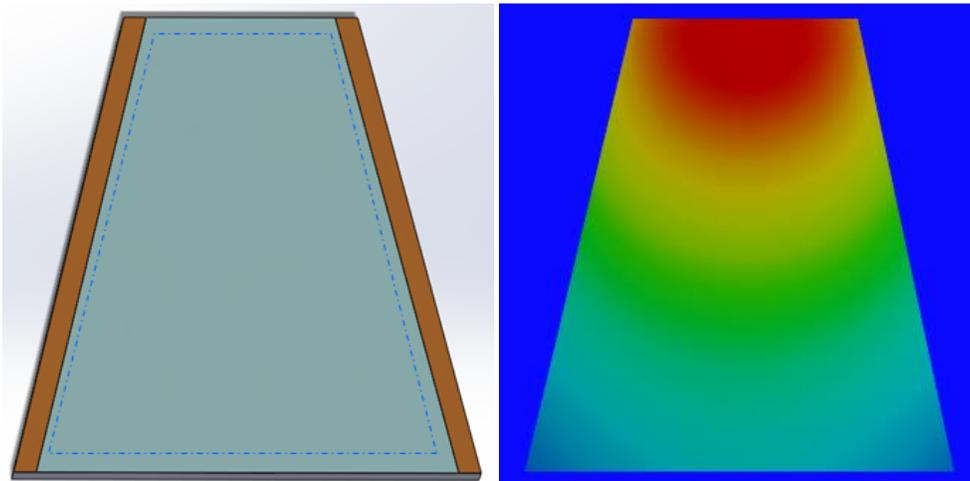

Figure 1   Trapezoidal window shown with electrodes and clear aperture within the dash lines (left) and the corresponding thermal image (right).

For a circular window, the electrodes must be carefully positioned to optimize the temperature uniformity. For example, if the electrodes are either too short or too long, the temperature uniformity will be significantly impacted with a delta temperature as much as 30°C (see Figure 2). When the electrode lengths are optimized, the temperature uniformity is significantly improved with a delta temperature of only 10°C (see Figure 2, right). Note that hot and cold zones have been reduced in absolute terms and are no longer isolated to 2 respective regions, but evenly distributed to 4 respective regions instead.
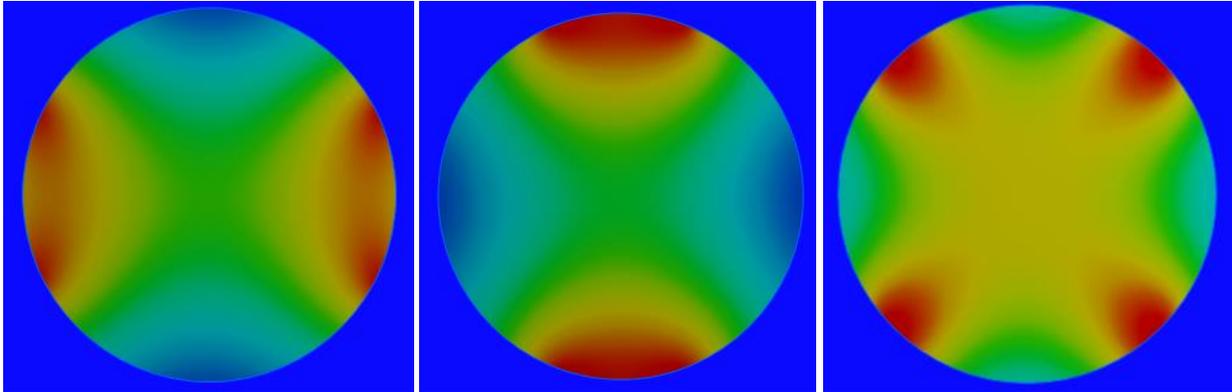
Figure 2   Thermal images of a circular window with electrode lengths that are too short (left), too long (center), and properly optimized (right).

The benefit of performing this type of analysis is that it allows one to determine an optimized heater design before any hardware is fabricated, saving significant time and cost. For particularly difficult configurations, this approach reduces the number of test samples required to ultimately optimize the window heater design.

3.   MEASUREMENT

3.1 Setup

The windows under test were made of fused silica (~6 inches in diameter and ~0.25 inches thick) with a conductive layer of ITO covering the clear aperture on one side of each window. Window A was made with the optimized electrode design shown in Figure 3 (right).   Window B was made using a novel electrode design to further improve the temperature uniformity. Electrical wires were bonded to the electrodes and the wires were then attached to a variable DC voltage source. The voltage was gradually increased until the coldest area on the window was 15°C above ambient and a steady-state temperature was reached.

A FLIR A320G thermal video camera was used to measure the temperature distribution across each test window. The window was placed about 2 feet away from the camera (see Figure 3).   The surrounding area was shielded from background radiation that may reflect off of the window surface. In the thermal imagining software, the emissivity was adjusted for each window surface by comparing the apparent temperature to a direct measurement on the window surface using a calibrated thermocouple. A mask was made of a thermally insulating gasket followed by black cloth with a hole cut to the size of the clear aperture that was placed on top of each window surface to mimic a window in a frame as shown in Figure 3. The clear aperture was assumed to be greater than 80% of the surface area.
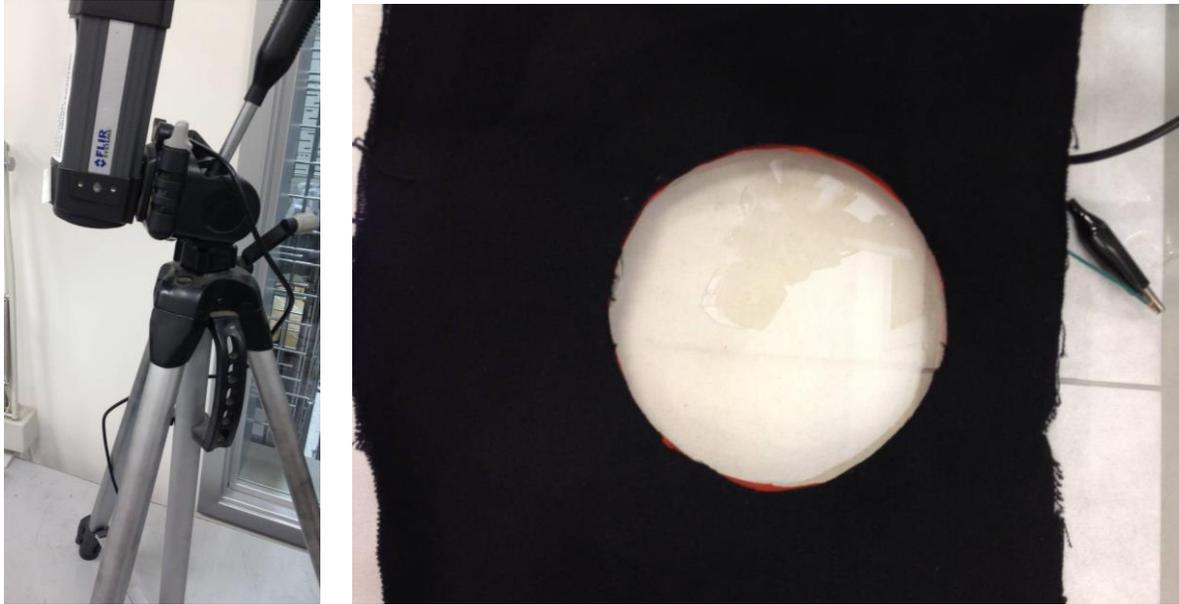
Figure 3   Test setup showing the FLIR A320G thermal video camera (left) and the window under test with the area outside the clear aperture masked (right).

3.2 Window results

Windows A and B were heated and tested per the setup above. The delta temperature was calculated by subtracting the maximum and minimum temperatures for both the front and back window surfaces of each window. The measurement results were compared to the modeled analysis for the same window configurations and are shown in Table 1 below. The measurement results show good agreement to the analysis and are 0.5°C to 4°C higher than the calculated data. While not a perfect correlation, the 2X improvement in thermal homogeneity of Window B to Window A, is clearly evident and consistent with both analysis and measurement. Challenges in correlating the proper convection value to the model, possible inaccuracies in the measurement emissivity value, and properly reaching a steady-state condition are all likely contributors to the differences.

Table 1   Temperature uniformity for Windows A and B for the front and back surfaces.

	Window A front surface ΔT (°C)	Window A back surface ΔT (°C)	Window B front surface ΔT (°C)	Window B back surface ΔT (°C)
Analysis	10	8	5	3.3
Measurement	13	12	5.5	5

Thermal images of window surfaces are directly compared to the analyses for windows A and B in Figures 4 and 7 below, respectively. In these figures, the color scales were adjusted linearly based on the delta temperature of the window surface in order to qualitatively highlight the relatively warmer and cooler temperature locations. The measurement results clearly show good agreement to the analyses. The warmer and cooler zones are in consistent locations, particularly evident when initially heating the window. As the windows warm and reach steady-state, they are allowed to soak for several minutes at the desired, stable temperature. At this point the warmer zones become less evident at steady-state for both windows. It is important to note that actual hardware will not have the ideal parameters of the model, such as a perfectly uniform ITO or exact placement of the electrodes. However, even these variables can be captured in the model to establish a tolerance for delta temperature and determine the qualitative impact through the thermal image.
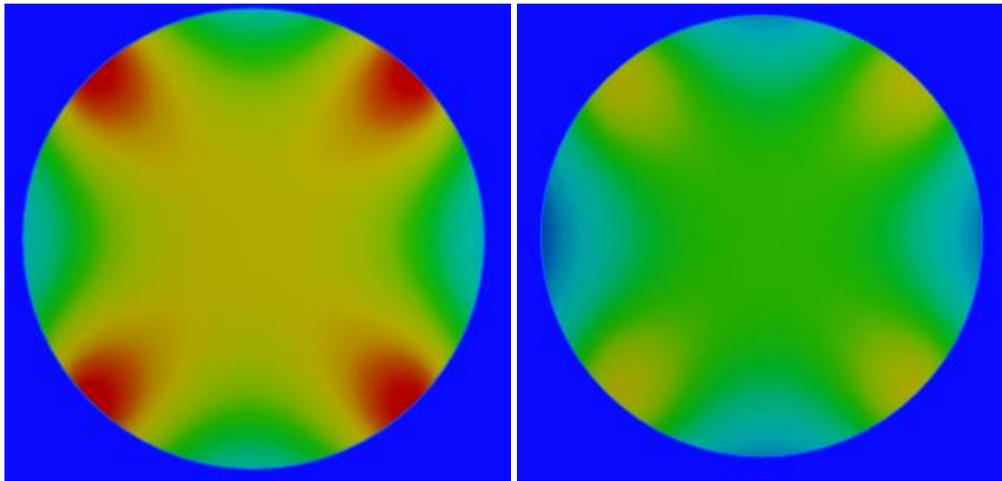
Figure 4   Modeled thermal image of Window A for the front (left) and rear (right) surfaces.
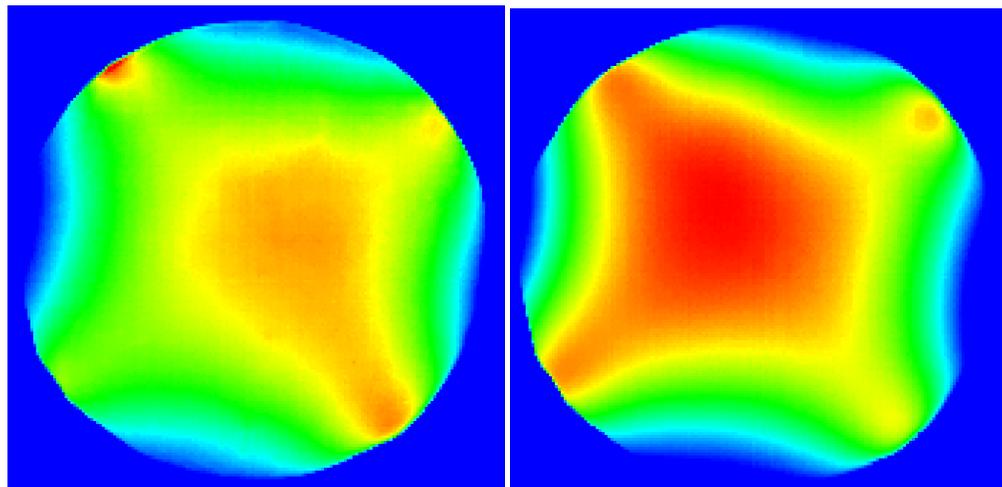

Figure 5   Measured thermal image of Window A for the front (left) and rear (right) surfaces.
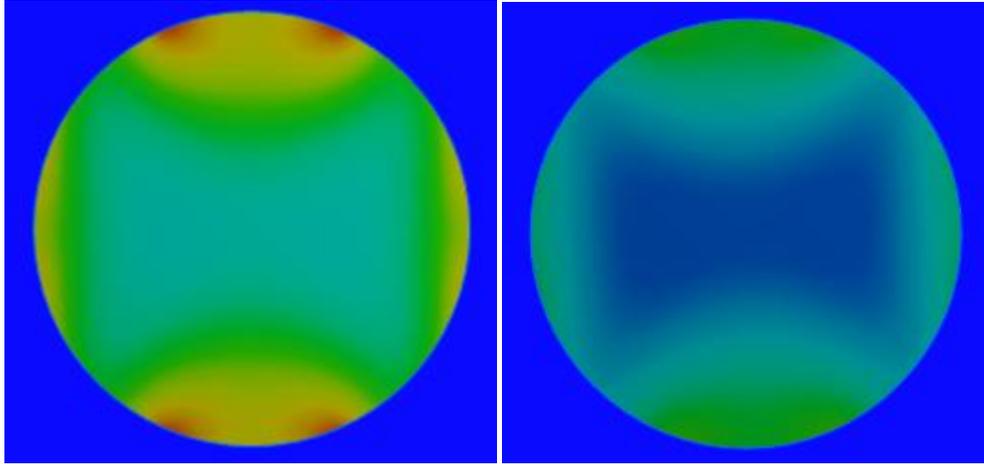
Figure 6   Modeled thermal image of Window B for the front (left) and rear (right) surfaces.
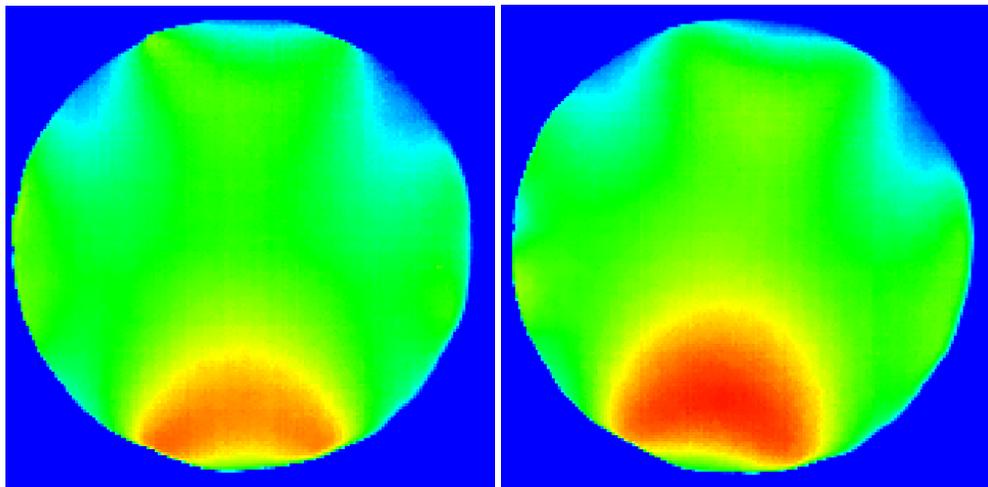

Figure 7   Measured thermal image of Window B for the front (left) and rear (right) surfaces.

4. CONCLUSION

LWOS has developed and demonstrated a software tool capable of quantitatively modeling the thermal distribution of a heated window in operation. This capability allows the design team to optimize the heater layer sheet resistance and the configuration of bus-bar connections to ensure maximum temperature homogeneity across a heated window and minimum thermally-induced transmitted wavefront distortion. Data was presented that demonstrates the validity of these models via comparison to actual heated windows observed under heated conditions. Good agreement was shown between the experimental data and the model, both quantitatively and in specific heating zones. Moreover, the team has demonstrated that heater configurations that marginally meet performance requirements can be improved significantly by employing thoughtful design techniques. Further work is under consideration that will more directly correlate the modeled temperature distribution of a window to its transmitted wavefront error.

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