Technical Note: Stress-Induced Birefringence in Vacuum Systems

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Even scientific grade optical glasses show birefringence when small external forces are applied to the sample. Stress-induced birefringence can be particularly detrimental to the state of polarization of light when a laser beam is transmitted through the glass. This is especially the case for glass windows of a vacuum chamber. Since compensation of spatially inhomogeneous birefringence is extremely challenging, it should be prevented by proper design of the vacuum chamber. Birefringence below 0.2 nm/cm can be achieved by thoroughly choosing glass material with low stress optical coefficient and mounting geometry. Applications strongly depend on light polarization are quantum technologies such as precision metrology, quantum computation and quantum simulations based on ions or atoms.

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The field of quantum technologies has recently been boosted by international and national initiatives, such as the flagship initiative of the European Commission, the British national program on quantum technologies, the Quantum Valley Investments in Canada and the Chinese effort for a secure quantum satellite channel. The goal of these initiatives is to strengthen fundamental science and and to advance the technology utilized in proof of principle experiments one step closer to commercial products.

Many experimental apparatus based on cold atoms or ions find applications for precision metrology, time keeping, inertial navigation, quantum computation and quantum simulation. These experiments are typically performed in a well-isolated environment to suppress unwanted interactions of single quanta with surrounding particles, i.e., they are operated in an ultra-high vacuum chamber. The interaction of particles with precisely polarized laser beams allows one to manipulate and prepare the internal states. However, care must be taken to propagate the precisely prepared polarization of light into the vacuum chamber since the window material itself can distort the light polarization state.

SOURCES OF BIREFRINGENCE

Unlike in crystals, such as calcite, where the birefringence is caused by the atomic lattice structure itself, ideal glasses are isotropic and do not exhibit birefringence. However, mechanical stress induces inhomogeneous birefringence in the glass material, as shown in figure 1. In general, the amount of birefringence is a function of the glass annealing conditions, external forces, and glass type. Commercially available optical glasses[1] undergo an annealing process that reduces temperature gradients in the material to a minimum in order to suppress the internal stress.

External forces originate from mounting screws, the pressure difference between the inside and outside of the chamber as well as unmatched expansion coefficients of the glass window and the metal flange of the vacuum system. Properly annealed gaskets made of copper or indium in combination with low clamping forces should be used to match the thermal expansion coefficients of the glass and the viewport flanges. While indium has the advantage of requiring lower clamping forces than copper, its melting point around 150 °C limits its application to systems that do not depend on high bake-out temperatures. In addition, the thermal expansion coefficients of flange material and window should be matched. If necessary, this can be done by inserting intermediate materials of different thermal expansion coefficient.

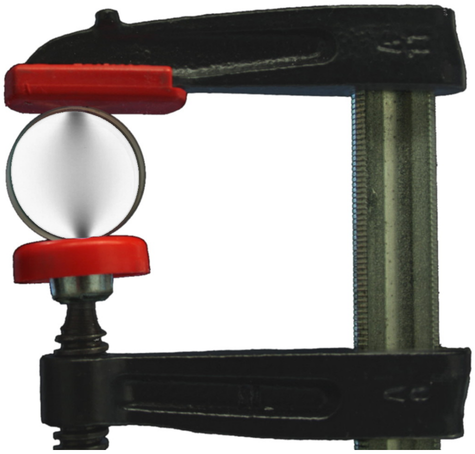

Figure 1. Picture of stress birefringence inside a N-BK7 glass window. The image recorded using homogeneous linear polarized light which passes through the sample and an analyzer. Dark areas in the glass correspond to regions of strong birefringence whereas bright areas indicate low birefringence.

The differential mechanical shear stress $\sigma = \sigma_\mathrm{o} - \sigma_\mathrm{e}$ within the glass converts into a birefringence Δn by a material dependent proportional constant called stress optical coefficient K

$$\Delta n = K \times \sigma$$

Here, the birefringence $\Delta n = |n_\mathrm{o} - n_\mathrm{e}|$ is defined as the difference in refractive index of the ordinary and extraordinary beam, which correspond to the normal and collinear direction of the stress tensor and can be identified with the two polarization axes of uniaxial crystals. Typical values for K are in the order of $1 \times 10^{-6}\,\mathrm{mm}^2/\mathrm{N}$ and show a weak dependence on wavelength and temperature. Hence, a suit-

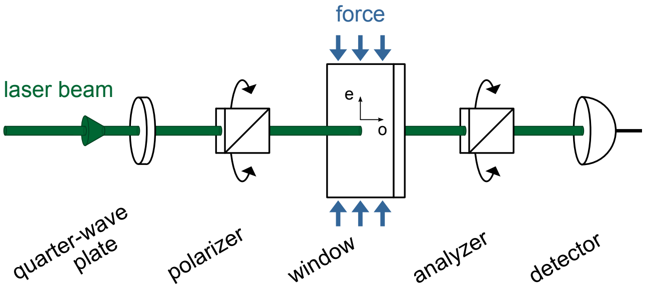

Figure 2. Setup to determine the birefringence.

able glass type with lowest K should be chosen.

According to ISO 10110-2[2], stress birefringence for optical components is specified by

$$\Delta n = \mathrm{OPD}/L$$

in units of [nm/cm], where OPD is the relative optical path difference between ordinary and extraordinary beam and L the thickness of the sample. The technical standard also defines classes of permissible stress birefringence values for typical applications such as polarization or interference instruments ($< 2\,\mathrm{nm/cm}$), precision or astronomical optics ($< 5\,\mathrm{nm/cm}$) and photographic or microscope optics ($< 10\,\mathrm{nm/cm}$).

DETERMINATION OF BIREFRINGENCE

The measurement of the extinction ratio η allows a precise determination of the birefringence as well as of the orientation of the optic axes[3]. This ratio is defined as $\eta = P_{\mathrm{min}}/P_{\mathrm{max}}$, where the minimum ($P_{\mathrm{min}}$) and maximum ($P_{\mathrm{max}}$) power of a transmitted laser beam are recorded for a full rotation of the analyzer. This measurement is based on a setup where the device under test is placed between a polarizer and an analyzer as shown in figure 2.

The extinction ratio is expected to vanish when the polarizer, and thus the linear input polarization, is exactly aligned to one polarization axis of the material. The maximum value of the extinction ratio is instead observed when the polarizer is aligned under 45°, which corresponds to an equal splitting of the input power onto the two axes. The birefringence is given by the amplitude variation $\Delta\eta$ of the extinction ratio for different angles of the input polarizer whereas the axes are given by the angle at which the extinction ratio is minimum or maximum. In case of small birefringence, we have

$$\Delta n \approx 2\sqrt{\Delta\eta}/(kL)\,,$$

where $k = 2\pi/\lambda$ is the wave vector of light showing the quadratic dependence of the signal amplitude $\Delta\eta$ on the birefringence[3]. Measured extinction ratios are in most cases limited to 10^{-7} due to imperfections of the polarizers and inhomogeneities in the substrate material.

Typical values for the birefringence of commercially available vacuum windows are 10^{-6} ($20\,\mathrm{nm/cm}$) and 10^{-7} ($2\,\mathrm{nm/cm}$) for well annealed vacuum glass cells[4]. The latter barely reaches the value recommended by ISO 10110-2[2] for interference instruments. Some dense flint glass show a value for the stress optical coefficient that are two orders of magnitude smaller than the corresponding value of commonly used glasses: N-BK7 or Pyrex. Using these glass types, it is possible to enter the regime of ultra-low birefringence below 10^{-8} ($0.2\,\mathrm{nm/cm}$) even for complex geometries of the vacuum cell, such as the twelve-sided glass cell shown in Figure 3. Note that these glasses are more brittle and demand for special handling procedures during manufacturing[3].

EXAMPLES

What does this amount of stress birefringence mean for practical purposes? Assume that we want to transmit a perfectly right-handed circularly polarized light beam through a standard vacuum viewport exhibiting a birefringence of $\Delta n = 20\,\mathrm{nm/cm}$ and a thickness of $L = 5\,\mathrm{mm}$ at a wavelength $\lambda = 852\,\mathrm{nm}$. Because of the bifringence, the polarization acquires a slight change in ellipticity. A widely used figure of merit to quantify the distortion from pure circular polarization is the polarization purity

$$\Pi \equiv \frac{P_{\mathrm{rh}}}{P_{\mathrm{lh}}},$$

defined as the power ratio between right-handed (P_{rh}) and left-handed polarization (P_{lh}). In case of an initially circular polarization, it can be shown that

$$\Pi = \frac{1}{\Delta\eta} \approx \left(\frac{\lambda}{\pi\,\Delta n\,L}\right)^2,$$

which yields a value of $\sim 3 \times 10^3$ for our example.

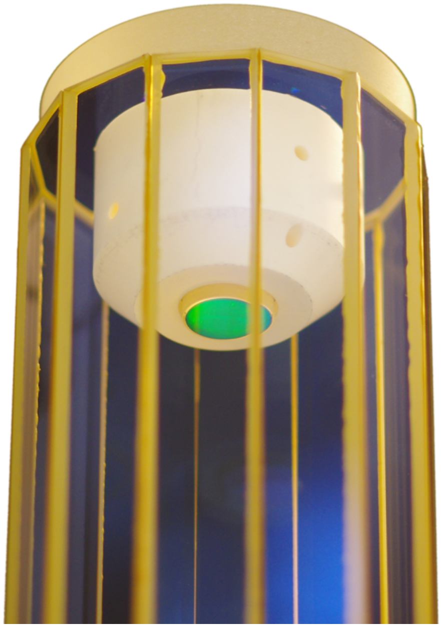

Figure 3. Image of a dodecagonal glass cell[3] with ultra-low birefringence for ultra-high vacuum systems. The cell further features a double-sided optical coating on each window and it is capable of hosting further scientific components, such as a high numerical aperture objective lens.

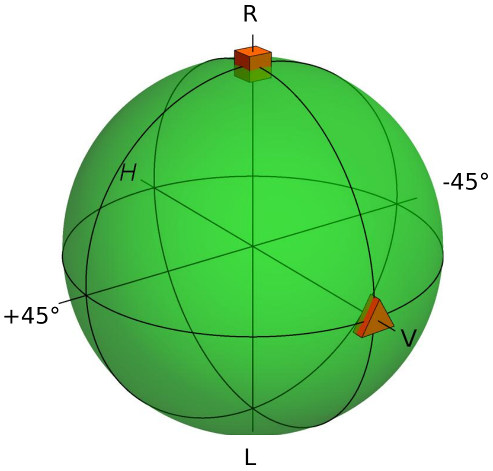

Figure 4. Graphical representation of polarization states on the Poincaré sphere.

Thus, a perfectly circular polarized input beam with 1 mW power exhibits an unwanted circular component of 330 nW after the window. In quantum optics, this amount of power in the wrong polarization mode is already sufficient to considerably reduce the fidelity of quantum state manipulations. In contrast, using the ultra-low birefringence vacuum glass cell respectively, this value is correspondingly reduced to 0.033 nW.

Another way often employed to characterize circular polarization is to measure the contrast

$$C \equiv \frac{P_{\max} - P_{\min}}{P_{\max} + P_{\min}} = 2\frac{\sqrt{\Delta\eta}}{1+\Delta\eta}$$

by determining the minimum $P_{\min}$ and maximum power $P_{\max}$ behind a rotating analyzer, likewise as for the extinction measurement of linear polarization.

The effect of a retardance due to stress birefringence can also be visualized on the Poincaré sphere, see figure 4, where circular polarization is geometrically represented by points at the poles and all possible linear polarizations are mapped onto the great circle at the equator. A small birefringence rotates a circular polarization (cube) closer to the equatorial plane bestowing a slight change in ellipticity on the polarization state. For thin vacuum windows (i.e., no optical activity), the corresponding rotation axis is located in the equatorial plane with an angle which is given by the direction of the stress tensors. The same effect occurs in the case of linear polarized light (triangular), where the rotation results in a movement out of the horizontal plane which also indicating a slight change in ellipticity. For small birefringence the rotation angle α is given by

$$\alpha \approx 2\sqrt{\Delta\eta}\ .$$

Spatially inhomogeneous stress birefringence results in different amount of rotations depending on the position, which obviously cannot be compensated by additional homogeneous wave plates. While it is in principle possible to compensate spatially inhogeneous birefringence, it is highly demanding under realistic conditions, since the vacuum viewports or cell windows need to be individually characterized over the desired area. In case of vacuum system, this becomes prohibitively challenging since the stress tensor has to be measured after the cell is evacuated, to account for mechanical stress resulting from the outside atmospheric pressure. Furthermore, this measurement cannot be performed for two opposing windows at once, but has to be carried out individually for each window. In an extreme scenario scenario, two relatively large birefringence of the two windows might even cancel, resulting in an erroneously small birefringence estimated for each window. Thus, an in-situ measurement of the birefringence of a single window requires placing a rotatable analyzer into the vacuum system, which is a demanding task and not compatible with most practical situations.

CONCLUSION

Stress birefringence in vacuum glass viewports needs to be considered during the design phase of an experiment when high polarization purities are required. A later compensation of the birefringence is not feasible under realistic conditions due to the inherent inhomogeneity of the stress tensor and to the demanding requirements for its accurate determination under vacuum. However, a residual birefringence below 1 nm/cm can be achieved by a proper choice of the flange and sealing as well as a window glass possessing a low stress optical coefficient. An example is the ultra-low birefringence vacuum cell made of Schott glass.

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