MOXTEK Polarizing Beamsplitters for HMD and HUD Applications

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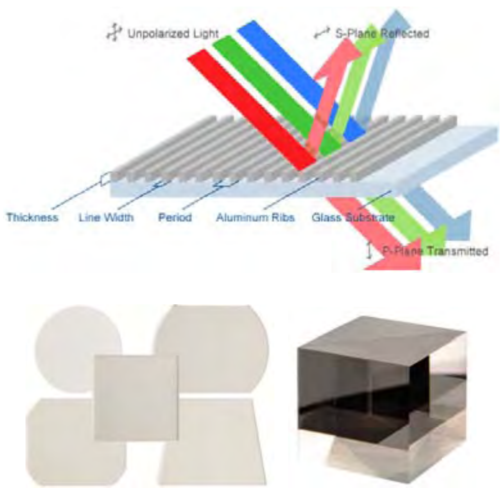
Introduction

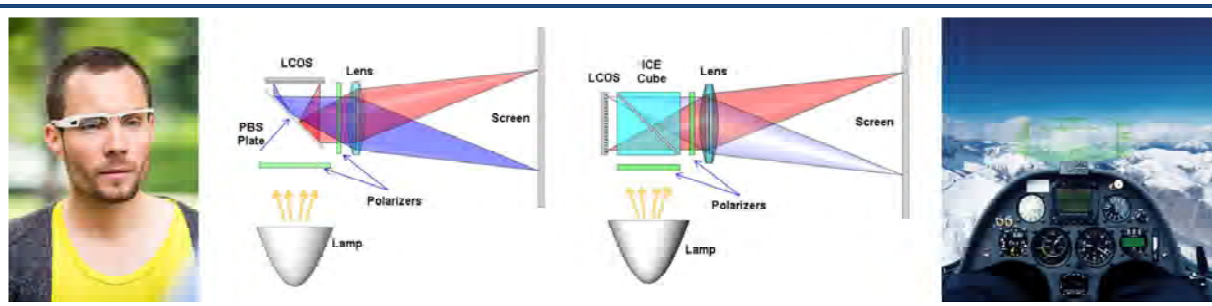
Moxtek's wire-grid polarizing beamsplitter (PBS) cubes and plates provide high transmission, high contrast, and high temperature durability resulting in bright, beautiful images. Moxtek's polarizing beamsplitter plates use patented aluminum deposited Nanowire® technology. These nano-wires are deposited on glass substrates and are extremely small providing high purity polarization and high contrast. Moxtek also applies thin film coatings to optimize performance and durability characteristics. Polarizing beamsplitters separate natural light into two orthogonal, linearly polarized components: the P-polarized light which is transmitted while the S-polarized light is reflected at a 90˚ degree angle. In principle, roughly half of the incident light is reflected and the other half is transmitted.



Moxtek PBS Plates and *ICE Cubes*™

Moxtek's PBS products are designed for use over a wide angular range while maintaining color uniformity and image contrast over the entire visible wavelength spectrum. Moxtek's PBS plates and *ICE Cubes*™ enable engineers the flexibility to design optical systems optimized for performance, size, and weight. Moxtek's PBS Plates and *ICE Cubes* are superior choices over MacNeille Cube designs and allow optical engineers to design smaller systems while maintaining excellent optical performance. Figure 1 shows a PBS plate used in reflection mode and a cube in transmission mode. When deciding on a system design, considerations such as astigmatism, back focal length, contrast, brightness, etc., are important in determining which configuration and components are the best for the application.

Moxtek PBS products are chosen by optical designers for use in projection display, virtual and augmented reality Head Mounted Display (HMD), and Head-Up Display (HUD) systems providing truly amazing visual experiences for consumer, commercial, and defense applications. Moxtek technology is used at the heart of these systems, and provides users with clear dynamic vision to perform critical functions with increased safety. This whitepaper details performance and durability advantages of Moxtek's polarizing beamsplitters compared to alternative polymer film and MacNeille cube designs.



HMD Applications | HUD Applications

Figure 1. PBS plate and cube beamsplitter application examples.

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Advancements in polarizing beamsplitter technology

Polymer film and MacNeille cube PBS products have been commonly used in projection display systems but due to performance and durability limitations, they have been replaced in many applications by wire-grid polarizing beamsplitter options. Both polymer film and MacNeille cube PBS designs have color balance and contrast ratio issues when used at low f/# (large cone angle). Also, polymer film PBS products do not tolerate high temperature and high luminous flux conditions.

Wire grid polarizers (WGP) are known for excellent broadband performance, especially for low f/# applications as well as being extraordinarily durable because of their inherent inorganic design. Moxtek's WGP PBS products are optimized for 45° angle of incidence (AOI) and offer superior broadband performance in low f/# (large cone angle) applications where both high efficiency and excellent contrast are required. Moxtek's PBS products also do not have the associated dramatic angular performance variations evident in MacNeille cubes and reflective polymer film polarizing beamsplitters.

Beamsplitter performance comparison results

As depicted in figure 2(a), a white light LED source was collimated and passed through an iris followed by a high contrast pre-analyzer to select an input polarization state. The beam was then focused into MacNeille (top row) and Moxtek (bottom row) cube beamsplitters and the blocking state transmittance was minimized on a screen. The blocking state reflectance (R_s) and transmittance (T_s) were then imaged using a camera (fig. 2b, 2e). After rotating the pre-analyzers 90°, the passing state transmittance (T_p) and reflectance (R_p) were then imaged (fig. 2c, 2f). Finally, the pre-analyzer was rotated approximately 45° to give equal intensity in the reflected and transmitted beams to approximate a PBS configuration. As shown in figure 2, the *ICE Cube* has improved color balance and a reduced leakage in the blocking state (T_s) when compared to the MacNeille Cube. The images represent about f/1.5 cube input cone angle, though the aperture was also varied to change the f/# (images not shown). Both cubes were also characterized at variable angles with well collimated light from the UV to the SWIR and the Moxtek PBS cube showed marked improvement, accommodating angular deviations from normal incidence of ±20° in the azimuthal direction and ±10° in the polar (elevation) direction with minimal performance variation.

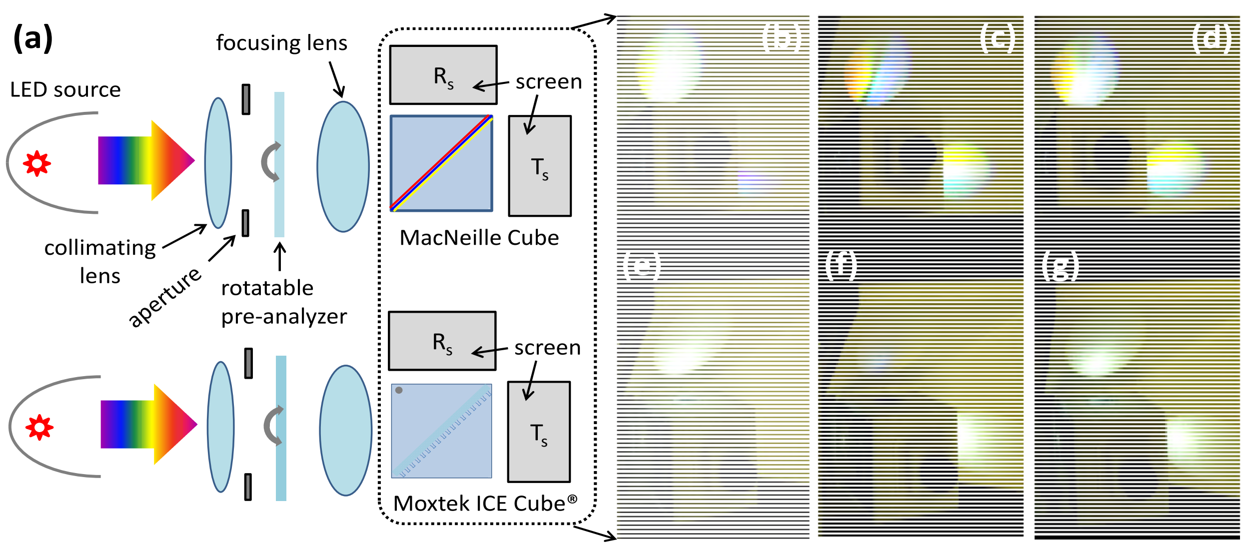

Figure 2. Low f/# performance comparison between polarizing beam splitter cubes. Measurement schematic (a) and results for MacNeille cube (b-d) and Moxtek *ICE Cube* (e-g) showing blocking state (b, e), passing state (c, f), and beamsplitting (d, g) configurations. Notice the poor color shift when using a MacNeille cube (c-d).

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Transmittance and reflectance measurements using the figure 2 setup were also made by replacing the screen with a detector (ThorLabs 5120C). For a cone angle of ±16° (f/# of 1.74), the Moxtek *ICE Cube* had a contrast ratio between passing and blocking state transmittance (T_p/T_s) of 1470, while the MacNeille Cube only had a measured contrast ratio of 23. Passing state transmittance (T_p) for the Moxtek and MacNeille cubes were about 74.8% and 78.6% respectively when compared to the raw transmittance without the cube. By placing a second aperture after the focusing lens, performance at a much smaller cone angle of ±4.4° (f/# of 6.45) was also examined, and the contrast ratio and T_p for the MacNeille Cube improved to 3390 and 78.3% respectively, while the *ICE Cube* contrast ratio and T_p improved to 4400 and 79.8%. The cool white LED light source used for the f/1.74 measurements showed a strong peak at about 450 nm and broadband emission in the red and green wavelengths, while a warm white LED with much lower intensity at 450 nm was used for the f/6.45 setup. Both LED transmission spectra were taken with an AvaSpec ULS3648 portable fiber spectrometer and are presented in figure 3. The pre-analyzer utilized was a Moxtek UVD240A and the MacNeille Cubes characterized were purchased from a standard optical catalog supplier.

The same f/6.45 measurements were also made for Moxtek's WGP plate (PBS02C) and for an off-the-shelf reflective PBS polymer film designed for brightness enhancement. The contrast ratio and T_p were 676 and 87.7% respectively for the Moxtek WGP plate but only 10.1 and 76.8% for the polarizing polymer film.

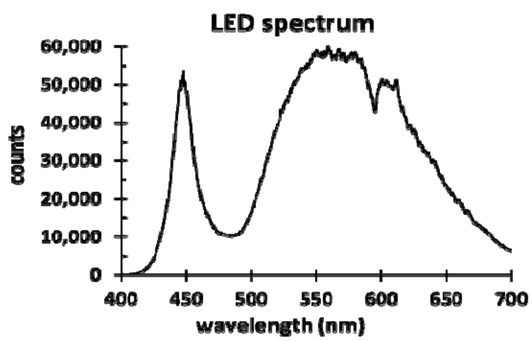

Figure 3(a). LED spectrum for f/1.74 measurements.

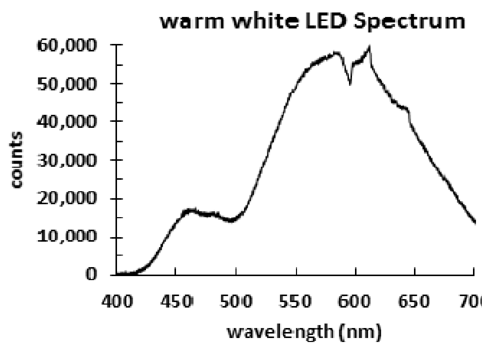

Figure 3(b). LED spectrum for f/6.45 measurements.

General Performance Considerations

Figure 4 depicts the general beamsplitting function of the Moxtek *ICE Cube*, where the prism hypotenuse plane defines the s- and p-polarization states. The passing state transmittance is p-polarized with very high purity (T_p), while the reflected beam has both s-and p-polarization states (R_s and R_p). The weak p-polarized reflectance can be eliminated using a pre-analyzer or clean-up polarizer, depending on the application requirements.

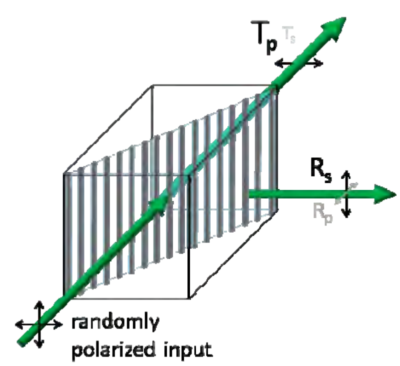

Figure 4. Moxtek *ICE Cube* beamsplitter schematic showing embedded wire grid polarizer as well as passing state transmittance (T_p) and blocking state reflectance (R_s). The weaker passing state reflectance (R_p) and blocking state transmittance (T_s) can be further removed using clean-up polarizers.

Detailed spectral and angular performance results for each of the polarizers examined are presented in the following section. Cube beamsplitters are found in a variety of applications where matching path lengths, reduced ghosting, and limited beam shift are important, and can be especially beneficial when a compact form factor or reduced mechanical vibration are required. The *ICE Cube* opto-mechanical design and environmental performance details are summarized below in Table 1. The broadband performance and large angular field of view are important criteria in emerging near-eye display applications while the maximum luminous flux and operating temperature are more critical in HUD and traditional projection display applications. Also listed are transmitted wavefront distortion (TWD) and angular deviation measurements, which are important in interferometry applications. Optional assembly of optics in plate or film form (e.g. pre-analyzers, clean-up polarizers, waveplates), directly onto the cube face is also possible. This could be advantageous to reduce interfacial reflectance losses and effects from mechanical vibration.

Table 1. *ICE Cube* Features

Feature	Detail
Size	1” cube (inquire for other dimensions)
Beamsplitting Component	embedded wire grid along hypotenuse
Spectral Range	400-800 nm*
Angular Field	±20-30° azimuthal ±10-20° polar (elevation)
TWD	λ/3
Angular Deviation	<3 arcmin
Material	N-BK7 glass
Restrictions	90°C and 6 W/cm^2 max, ≲1.5 kW/cm^2 LIDT (see table 3)

* Performance can be extended into short wavelength infrared (SWIR) by omitting the AR-coating on the cube faces.

Variable Angle Performance

Experimental Setup:

Figure 5 depicts simplified schematics of an Agilent spectrometer with variable angle Universal Measurement Accessory. Part (a) depicts the grating-based, source-side monochromater with rotatable polarizing pre-analyzer, which allows characterization of the sample using both s- and p-polarized light (as defined from internal wire-grid-coated hypotenuse of cube or plate). The beamsplitter sample is clamped on a central stage, which can rotate around a full 360 degrees. The detector sits on an extended arm, which can either park at the home position (labeled A), for measuring normal-incidence transmittance, or swing around to the 90° position (labeled B) for measuring reflectance.

As depicted in figure 5 (c), when the sample is rotated clockwise (+θ) or counter-clockwise (-θ), the detector remains in the home position (A’) for the variable angle transmittance measurement, but moves to the 90-2θ position or the 90+2θ position (B’) for clockwise or counter-clockwise rotations respectively. The detector is large enough that beam shifts due to refraction through the cube do not significantly impact measurements for moderate angles (θ<30°). The nomenclature used in the variable angle performance results of the following section refer to the incoming beam angle with respect to the cube face. For example, an incoming angle of -θ is depicted in figure 5(c) and the detector positions are labeled accordingly at positions A’ and B’. For the plate and film beamsplitter measurements, the reflecting surface was placed in the same orientation, (i.e. where the cube prism hypotenuse was located), and the same notation is utilized. For these variable angle performance measurements, the instrument beam

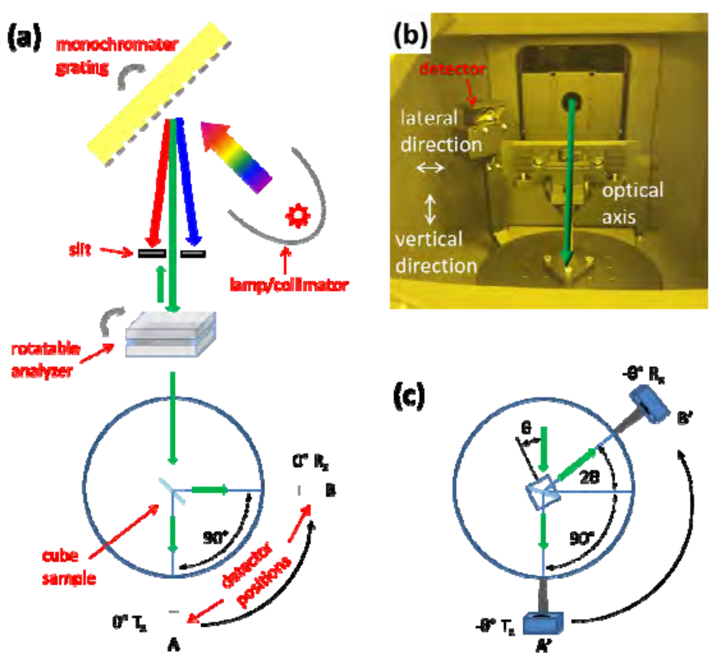

Figure 5. (a) Simplified measurement schematic in normal incidence (0°) configuration. (b) Inside view of Agilent Universal Measurement Accessory. (c) Measurement configuration for an azimuthal sample angle of -θ°

was fairly well-collimated, with ±1° and ±2° cone angles in the lateral and vertical directions respectively, which are denoted in figure 5(b). The situation depicted in figure 5 (c) shows the azimuthal rotation of the cube by an angle of -θ.

For polar (elevation) angle behavior, the cube is rotated 90° clockwise about the optical axis such that the reflected beam is shooting up in the vertical direction in figure 5(b), or equivalently, out of the plane of figure 5 (a), hence only the transmitted beams can be captured for polar rotations. There is also a slight asymmetry between the azimuthal and polar variable angle measurements since the beam collimation (cone angle) of the spectrometer is not the same in the lateral and vertical directions. In addition, the beam size (patch size) can be slightly different in the vertical and lateral directions, and the beam may not be perfectly-centered on the cube hypotenuse, which can impart additional slight shifts in the polar and azimuthal spectra, even for normal incidence measurements.

The Agilent spectrometer, with Universal Measurement Accessory, has two sets of matched stacked detectors. A three stage chopper directs the beam to the rear detector one-third of the time for a baseline drift correction, completely blocks the beam another third of the time for a dark reference correction, and directs the beam to the sample and front detector the rest of the time for the measurement of interest. The fixed rear beam has a mixed polarization state that depends on the source distribution and the internal mirrors and grating of the spectrometer but the front beam has a different beam path and a different polarization state. The pre-analyzer is used to choose one orientation at a time, usually s- or p-polarization, and a baseline is taken beforehand for each polarization state. There can be large jumps in the source's raw baseline spectra (ratio of front and rear detector responses) at the grating and detector crossover points (usually set around 700 nm and 1050nm respectively), presumably due to different detector responsivity for s- and p-polarization and/or slightly different beam positions for the UV-Vis and IR gratings. This jump was reduced by placing a Hanle depolarizer in the front beam path in the regular Agilent auto-polarizer (pre-analyzer) position; however for larger beam angles a small jump in the cube spectra is still evident at the detector crossover. Since its normal slot was taken, the 18 x 18 mm auto-polarizer (pre-analyzer) was placed at the entrance of the main sample compartment (the dark hole in figure 5b), which should actually improve the polarization purity of the system.

Variable Angle Performance Results:

For many commercial beamsplitter applications, the source is extended and is broadband so beam collimation is far from ideal. This gives a mix of rays from various polar and azimuthal angles interacting with the beamsplitter. MacNeille beamsplitting cubes have a complex stack of thin films coated along their hypotenuses in order to enhance a Brewster-like asymmetry in reflectance between s- and p-polarization states. This type of arrangement cannot simultaneously provide both broadband performance and large angular field of view. Meanwhile, the Moxtek *ICE Cube* and plate products utilize our ProFlux® sub-wavelength aluminum nanowire grid design, which separates the beam polarizations at the wire grid surface by an anisotropic reflection and absorption mechanism, providing excellent contrast and consistent passing state transmittance for broadband applications with large angular field requirements. See figures 6-8 for broadband performance comparisons at varying angle of incidence for a typical Moxtek *ICE Cube* and PBS plate and for competing film and MacNeille Cube beamsplitter designs.

Figure 6 compares variable angle passing state transmittance (T_p) from 0° to ±20° azimuthal angle of incidence. The Moxtek products have a much more consistent performance for varying angle of incidence than the polymer film or MacNeille Cube, which eases design considerations and allows for a much greater utilization of the available luminous output from broadband, extended sources. The dip in *ICE Cube* spectra in the violet wavelengths at more glancing angles is caused by a plasmonic grating resonance, but has minimal impact in most display applications.

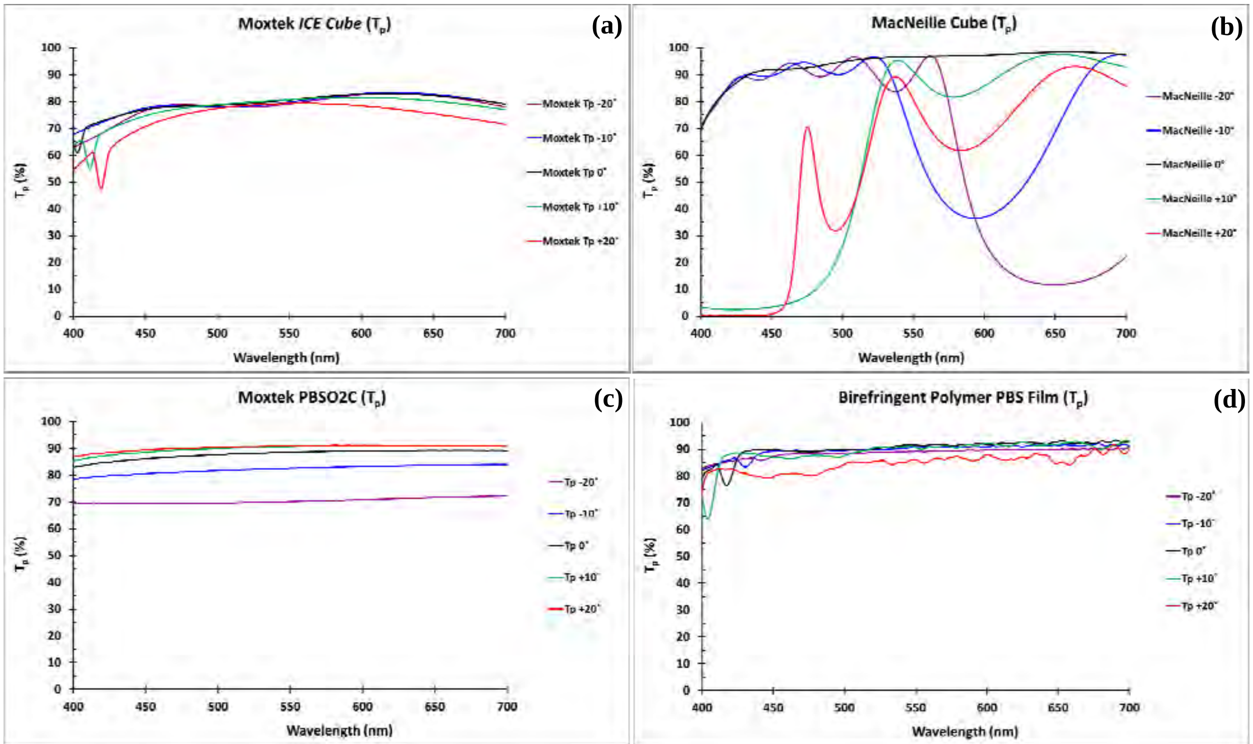

Figure 6. Variable angle passing state transmittance (T_p) performance comparison for a typical Moxtek *ICE Cube* and PBS product and for competing beamsplitters for 0° to ±20° azimuthal angle of incidence. (a) Moxtek *ICE Cube* performance. (b) MacNeille Cube performance. (c) Moxtek ProFlux PBS02C wire-grid PBS plate. (d) Birefringent Polymer PBS film.

Unwanted leakage (T_s) through the polarizing beamsplitters was measured using both the Agilent Universal Measurement Accessory depicted in figure 5 as well as the Harrick variable angle transmittance accessory mounted in a CARY 5000 UV-Vis-IR spectrometer. The latter accessory yielded reduced noise because of a reduced number of reflections along the instrument beam path, more optimized detectors, and an increased beam cone angle (±2.7° and ±4.9° horizontal and vertical cone angles respectively). Each beamsplitter's transmission axis was crossed with that of a super high contrast pre-analyzer (tripled Moxtek UVT240A polarizer) in order to measure the blocking state transmittance (T_s). The contrast ratio (inverse of the extinction ratio) for transmission is a measure of how pure the outgoing polarization state will be for an un-polarized input beam. It is calculated as the ratio of the passing state transmittance (T_p) to the blocking state transmittance (T_s), which assumes a perfect pre-analyzer. Figure 4 depicted the orientation of s- and p-polarized light with respect to the cube hypotenuse and wire grid as well as the beamsplitting function of the Moxtek *ICE Cube*. The contrast ratio is typically a function of both wavelength and angle of incidence, although Moxtek wire grid polarizers are known for their broadband performance with large angular field of view. Figure 7 compares variable angle contrast ratio performance (T_p/T_s) from 0° to ±20° angle of incidence for azimuthal angles. Again, the Moxtek products have much more consistent performance with varying angle of incidence than the MacNeille Cube, which should improve achievable contrast from broadband extended sources.

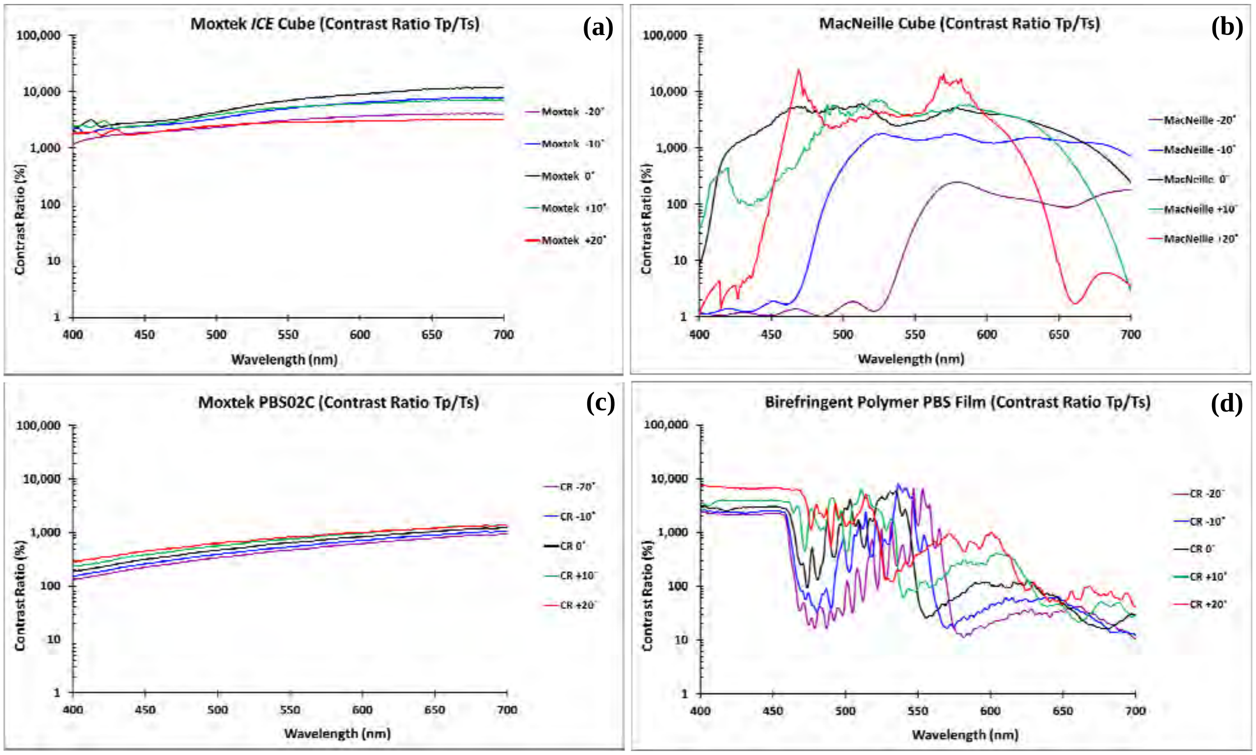

Figure 7. Variable angle contrast ratio (T_p/T_s) performance for a typical Moxtek *ICE Cube* and competing beamsplitters for 0° to ±20° angle of incidence. (a) Moxtek *ICE Cube* performance. (b) MacNeille Cube performance. (c) Moxtek ProFlux PBS02C wire-grid PBS plate. (d) Birefringent Polymer PBS film.

An important figure of merit for a polarizing beamsplitter is the overall efficiency, which is usually represented by the product of passing-state transmittance and blocking state reflectance ($T_p \cdot R_s$). Figure 8

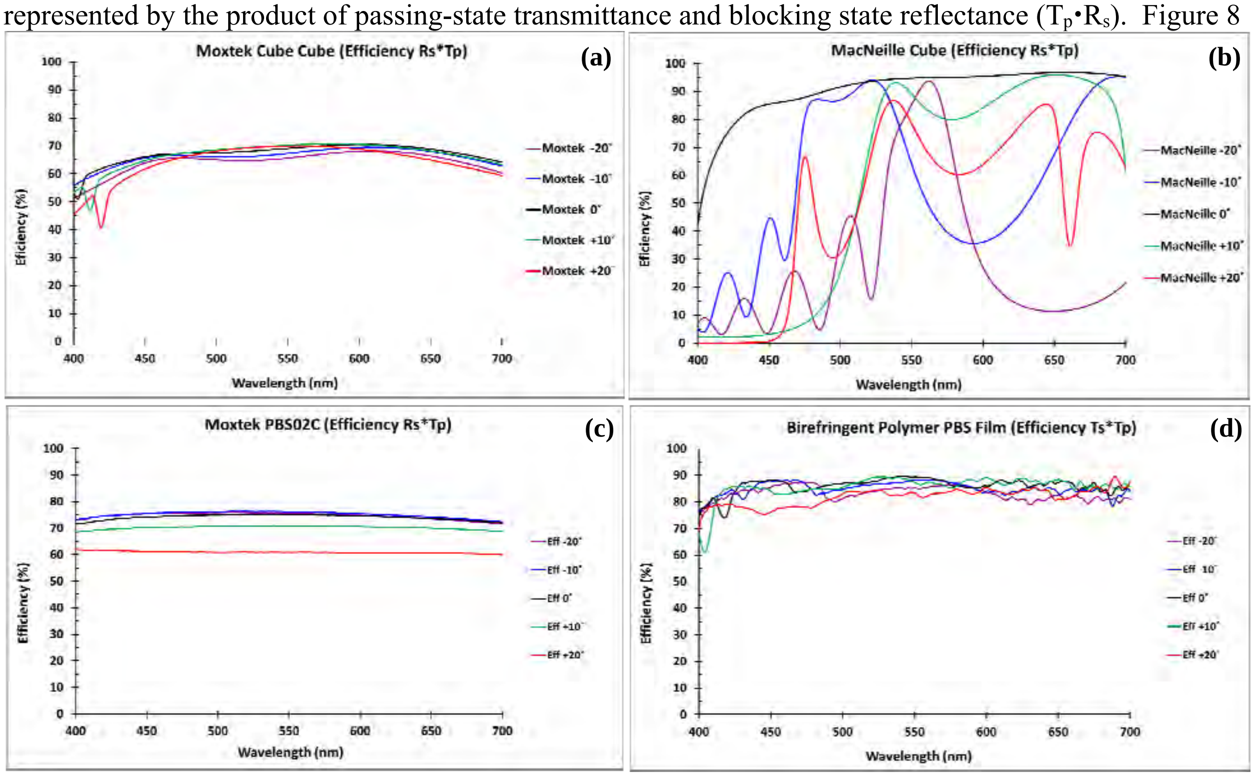

Figure 8. Variable angle efficiency ($T_p \cdot R_s$) for a typical Moxtek *ICE Cube* and competing beamsplitter from 0° to ±20° azimuthal angles of incidence. (a) Moxtek *ICE Cube* performance. (b) MacNeille Cube performance. (c) Moxtek ProFlux PBS02C wire-grid PBS plate. (d) Birefringent Polymer PBS film.

compares efficiency from 0° to ±20° azimuthal angle of incidence. The MacNeille Cube has poor spectral uniformity in beamsplitting efficiency for all angles excluding normal incidence, whereas the Moxtek ICE Cube shows flat spectral performance with varying angle of incidence. In display applications this should result in significant improvements in both color and contrast uniformity. This should also translate into greatly improved fringe visibility for the Moxtek product in broadband interferometric applications where the light source is not well-collimated.

Environmental and Form Factor Considerations

The *ICE Cube* contains an embedded wire grid polarizer that utilizes all inorganic materials similar to Moxtek's standard visible spectrum plate polarizer products, which are recognized for their excellent sustained performance in high temperature and high humidity projection display applications. In addition, the Moxtek *ICE Cube* contains two glass prisms, coupled to the wire grid plate by optical cement. This prevents the use of the *ICE Cube* in some high temperature, high flux applications. Current cube reliability results suggest a recommended temperature use condition of 90°C or less, and a luminous flux of less than 6 W/cm^2 for broadband Hg-arc lamp source (without IR filter). Laser induced damage threshold (LIDT) testing of the *ICE Cube* using a small beam spot showed stability to much higher luminous flux, however, for broadband high flux and high temperature environments we recommend our plate polarizers and beamsplitters.

The buried nanowire design of the Moxtek *ICE Cube* series beamsplitter helps protect against handling damage and environmental contamination and results in improved reliability in humid environments as any moisture has to diffuse through the optical cement. However, Moxtek plate beamsplittters can now be coated to protect against severe environmental factors (e.g. UV light, humidity, and condensation) and high luminous flux and operating temperature, which will be critically important to the growing field of HUD applications, where severe reliability stressors can be present. To demonstrate the impact of these coatings on part reliability, we tested and compared optical performance (T_p, Contrast) of various regular products with and without our latest protective processing (X-coat). Table 2 presents initial performance at 450, 550, and 650 nm wavelengths along with the changes after 2064 hours of environmental stress for both regular (PPL05C) and X-coated parts. The first table presents reliability testing under high temperature conditions, while the second table gives high humidity test results. The change in initial passing state transmittance (T_p) of the uncoated parts are minimal, while the contrast ratio is improved significantly and becomes much more stable to environmental stressors for the X-coated parts.

Table 2. Moxtek WGP plate reliability testing with and without X-coat for challenging environments.

	200° C for 2064 hours					
Product	**PPL05C**			**PPL05C + X-Coat**		
Wavelength:	**450**	**550**	**650**	**450**	**550**	**650**
Tp [%]:	91.1	93.1	93.6	87.87	91.54	91.72
ΔTp:	0	-0.15	0.27	-0.44	-0.16	0
Contrast Ratio	152	310	493	266	610	1147
Δ Contrast Ratio [%]	-15	-19	-17	-3	0	0

	60° C and 90% RH for 2064 hours					
Product	**PPL05C**			**PPL05C + X-Coat**		
Wavelength:	**450**	**550**	**650**	**450**	**550**	**650**
Tp [%]:	91.93	93.6	93.95	83.82	90.41	91.23
ΔTp:	-0.22	-0.01	-0.04	-0.74	-0.11	-0.11
Contrast	131	260	427	364	904	1825
Δ Contrast Ratio [%]	-7	-8	-4	-5	0	0

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For high light flux narrowband applications, laser damage threshold (LDT) testing of the Moxtek *Ice Cubes* was performed. A continuous wave laser emitting at 532 nm wavelength with a spot diameter ($1/e^2$) about 0.5 mm (TEM_{00}) was used for the testing. The following protocol was used: 9 sites were irradiated for 30 seconds at a given irradiance. If no damage was observed for the 9 sites upon inspection with a Nomarski microscope, then the 10th site was irradiated for 15 minutes or until damage occurred, whichever came first. If no damage occurred, then the laser irradiance was increased. Occasionally the highest irradiance tested had only the longer 15 minute exposure performed. Damage for each site during the 15 minute exposure was monitored by observing the increase in scattering from a low power He-Ne laser beam coincident on the same spot as the high power 532 nm laser. Visual damage was monitored as well, and the time of damage for a particular laser flux was determined based upon the first occurrence of either of these. Cubes were irradiated in various orientations while testing for laser induced damage, which included: passing preferred, passing non-preferred, blocking preferred and blocking non-preferred orientation, as depicted in the schematics of figure 9 below.

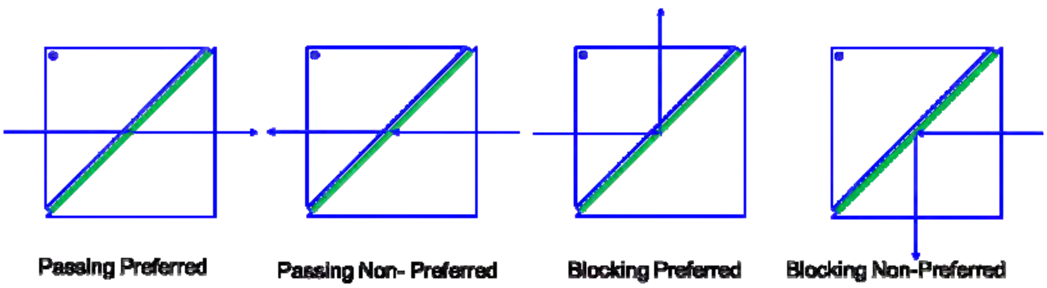

Figure 9. Schematics of *ICE Cube* orientations tested for LDT

The raw data was divided into two sections: the statistical section, where sites were expose for 30 seconds, and a section called “time to failure” where one site was exposed to the specified irradiance for 15 minutes or until damage occurred, whichever happened first. Using Reliasoft® Weibull Analysis, the mean time to failure (MTTF) was extrapolated down to various irradiance levels, which are presented in Table 3 below:

Table 3. Extrapolated Mean Time to Failure in hours for LDT testing of 1” *ICE Cube* parts at various irradiance levels.

MTTF (hrs) - *ICE Cube*-C	**Irradiance (W/cm^2)**			
Orientation	**1,500**	**2,000**	**2,500**	**3,000**
Blocking Non-Preferred	800,000	2,000	50	5
Blocking Preferred	3×10^{18}	7×10^{11}	7×10^{7}	200,000
Passing Non-Preferred	3×10^{8}	30,000	100	3
Passing Preferred	4×10^{7}	9,000	60	2

Table 4 summarizes several design and environmental differences between the Moxtek ICE Cube and competing polarizing beamsplitter cube designs. As shown, Moxtek cubes have superior angular performance across the visible spectrum over MacNeille cube designs. Moxtek recommends a maximum temperature of 90°C and a maximum laser fluence of 1.5 kW/cm^2 for the *ICE Cube*, however for broadband visible/near-IR lamp sources, luminous flux should be kept below 6 W/cm^2.

Table 4. Competitive Summary

Feature	Moxtek *ICE Cube*	MacNeille Cube
Acceptable angle of incidence	±20 to 30° azimuthal	±5 to 10° azimuthal†
	±10 to 20° polar‡	±5 to 10° polar‡
Spectral Range	400-700 nm*	410-700 nm
Durability	90°C 1.5 kW/cm^2 max LDT	Requires polymer waveplate (degrades over time) for correct polarization in display applications

† Excluding blue wavelengths.
‡ Contrast limited.
* Performance can be extended into short wavelength infrared (SWIR) by omitting AR-coating on cube faces.

Conclusions

When compared to MacNeille or polymer film polarizer designs, the Moxtek *ICE Cube* and plate polarizing beamsplitters provide superior broadband performance over a wide angular aperture, without the dramatic color shifts and angular performance variations evident in MacNeille Cube beamsplitters or reflective polymer film designs. The embedded aluminum nanowire® grid design in the Moxtek products are sub-wavelength, providing excellent contrast and good efficiency with consistent spectral response throughout the visible and even into to the short-wavelength infrared. The outstanding uniformity in performance over a large angular range helps maintain efficiency and ease system design in applications with demanding form factors.

The Moxtek *ICE Cube* and plate PBS can easily accommodate angular deviations from normal incidence of ±20° in the azimuthal direction and ±10° in the polar (elevation) direction with minimal performance variation. This corresponds to a field (cone) angle of 20-40°, which allows for dramatically improved light utilization and color uniformity when using poorly collimated sources. While competing polarizer designs can typically only tolerate a narrow angular aperture before performance deteriorates, the Moxtek *ICE Cube* and plate beamsplitters with embedded nanowire grid polarizer technology are the clear choice for applications requiring large angular fields. When ghost images and matching path lengths are not a concern, Moxtek recommends a plate-style wire grid polarizing beamsplitter such as our PBS and PBF products for even greater efficiency, extended broadband performance, and flatter angular response. Moxtek can also provide several wire grid coating options for extreme environments, such as those found in HUD applications.

Moxtek's state-of-the art polarizers and beamsplitters are the preferred choice for applications that demand high optical performance, large angular field of view, and temperature durability. Moxtek can customize our products to meet the demands of a wide range of optical applications.