Wire-Grid Polarizing Beamsplitter Cube

PBS ICE Cube™ Series Data Sheet

Moxtek *ICE Cube*

Applications

- Head-Mounted Display (HMD)
- Head-Up Display (HUD)
- 2D & 3D Projection Display
- Interferometry
- Spectroscopy

Introduction

The Moxtek *ICE Cube*™ polarizing beamsplitter provides superior performance in broadband, low f/# applications where both high efficiency and excellent contrast are required. The Moxtek *ICE Cube* designs utilize an embedded aluminum Nanowire® polarizing element, enabling a wide field acceptance angle, minimal performance variation with wavelength, and with none of the dramatic angular performance variations that are evident in MacNeille beamsplitters.

Variable Angle Performance

Experimental Setup:

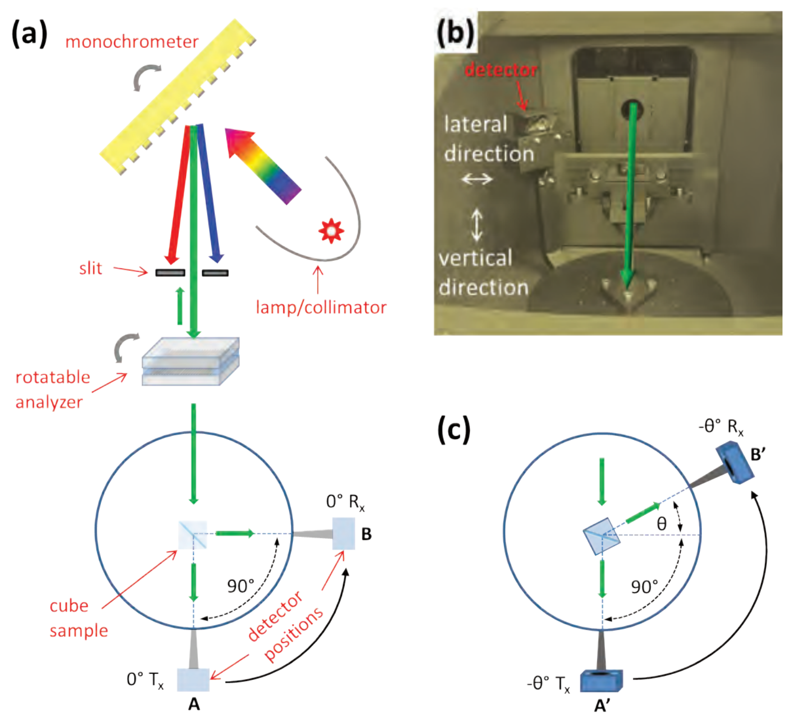
Figure 1 depicts a simplified schematics of an Agilent spectrometer with variable angle Universal Measurement Accessory. Part (a) depicts the grating-based, source-side monochrometer with rotatable polarizing pre-analyzer, which allows characterization of the sample using both s- and p-polarized light (as defined from internal wire-grid coated hypotenuse of cube). The beamsplitter sample is clamped to a central stage, which can rotate 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 1 (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-θ position or the 90+θ position (B') for clockwise or counter-clockwise rotations respectively.

Figure 1.

(a) Simplified measurement schematic in normal incidence (0°) configuration.

(b) Inside view of Agilent Universal Measurement Accessory.

(c) Measurement configurations for an azimuthal sample angle of -θ°.

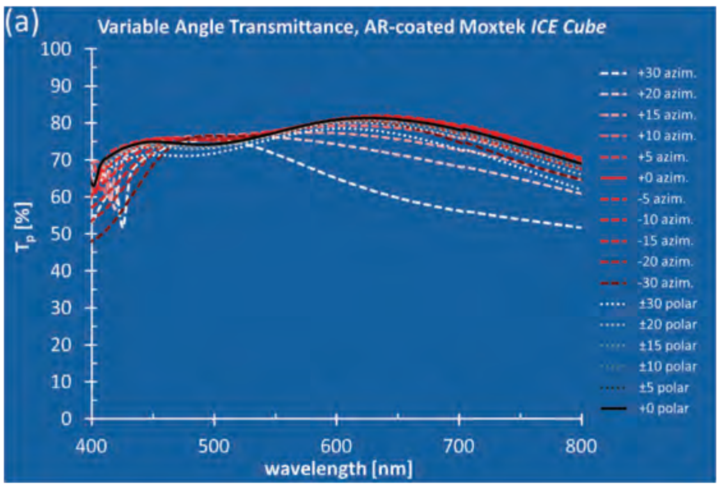


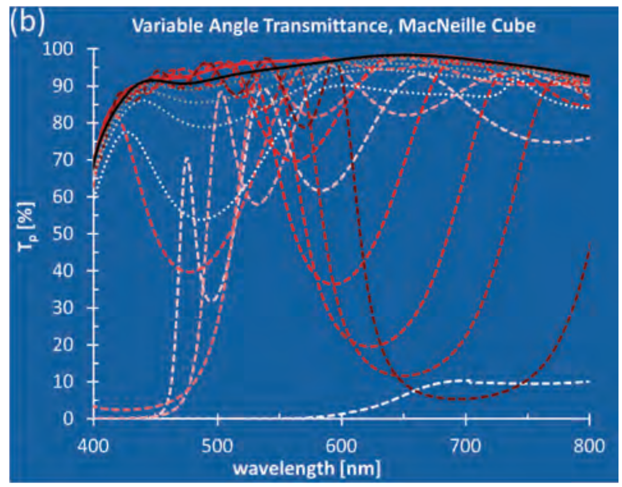
The detector is large enough that beam shifts due to refraction through the cube do not significantly impact measurements for moderate angles. For these variable angle performance measurements, the instrument beam was fairly well collimated, with ±1° and ±2° cone angles in the lateral and vertical directions respectively, which are denoted in figure 1(b). The situation depicted in figure 1 (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 shoots up in the vertical direction, out of the plane of figure 1 (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.

Variable Angle Performance (continued)

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 around 700 nm and 1050 nm 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 (dark hole in figure 1(b)).

Variable Angle Performance Results





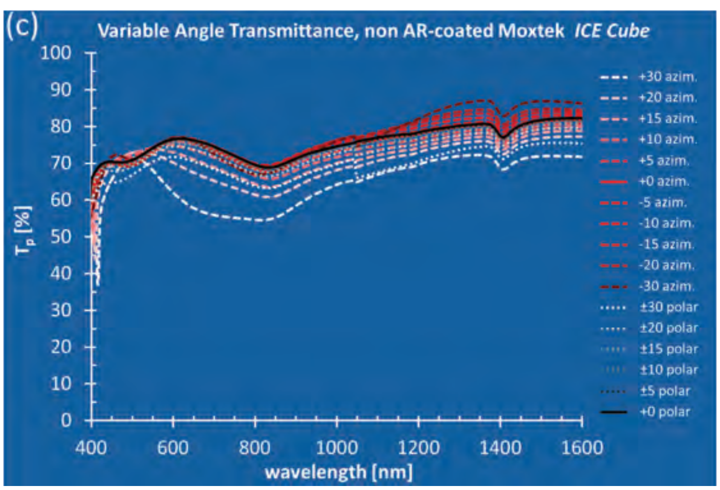


Figure 2. Variable angle passing state transmittance (Tp) performance comparison for a typical Moxtek *ICE Cube* and competing beamsplitters for 0° to ±30° angle of incidence.

(a) AR-coated Moxtek *ICE Cube* performance.

(b) MacNeille Cube performance.

(c) Broadband non AR-coated Moxtek *ICE Cube* performance.

For most commercial beamsplitter applications, the source is extended and 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* product utilizes 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 figure 2 and figures 4-6 for broadband performance comparisons at varying angle of incidence for a typical Moxtek *ICE Cube* and competing beamsplitter designs.

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Figure 2 compares variable angle passing state transmittance (Tp) from 0° to ±30° angle of incidence. The AR-coated Moxtek product has a more consistent performance for varying angle of incidence than the 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 the blue wavelengths at more glancing angles is caused by a plasmonic grating resonance. The small jump in the spectra at the IR detector crossover (1050 nm) is due to a shift in beam position on the detector at increasing angles caused by refraction through the glass cube.

Unwanted leakage through the polarizing beamsplitter cubes (Ts) was measured using both the Agilent Universal Measurement Accessory depicted in figure 1 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 an ultra-high contrast pre-analyzer (tripled Moxtek UVT240 polarizer) in order to measure the blocking state transmittance (Ts). The contrast ratio (inverse of the extinction ratio) for transmission is a measure of how pure the outgoing polarization state will be for an unpolarized input beam. It is calculated as the ratio of the passing state transmittance (Tp) to the blocking state transmittance (Ts), which assumes a perfect pre-analyzer. Figure 3 depicts 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.

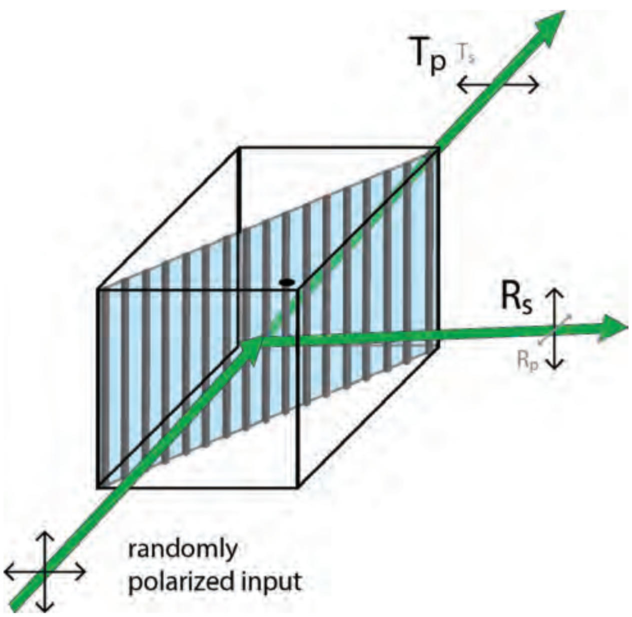
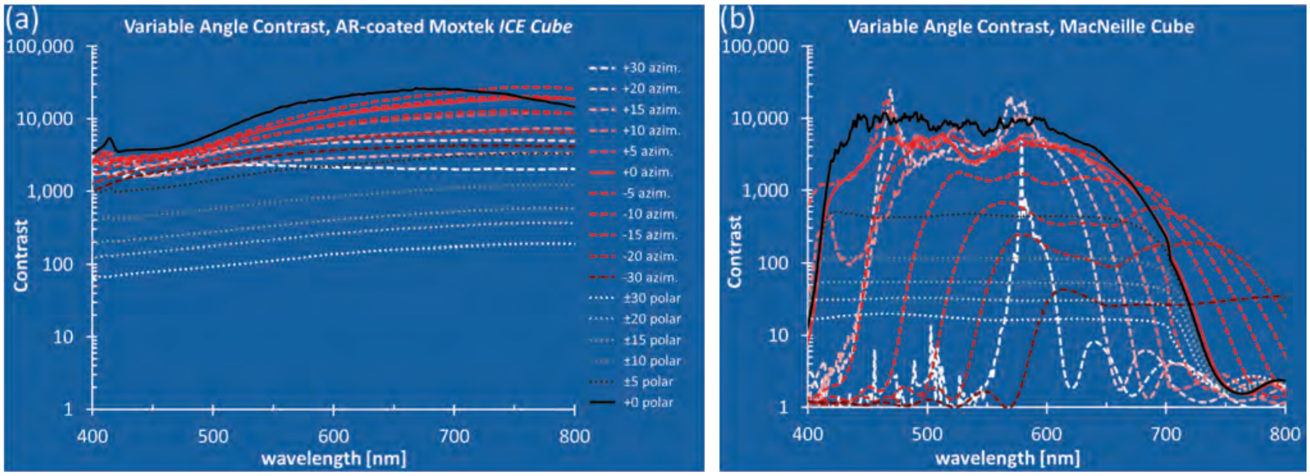


Figure 3. Moxtek *ICE Cube* beamsplitter schematic showing embedded wire grid polarizer as well as passing state transmittance (Tp) and blocking state reflectance (Rs). The weaker passing state reflectance (Rp) and blocking state transmittance (Ts) can be further removed using clean-up polarizers.

Figure 4 compares variable angle contrast ratio performance (Tp/Ts) from 0° to ±30° angle of incidence for both azimuthal and polar angles. Again, the AR-coated Moxtek product has a much more consistent performance with varying angle of incidence than the MacNeille Cube, which should improve achievable contrast from broadband extended sources.

In display and imaging beamsplitter applications, any unwanted reflectance from the p-polarized state (Rp) can be easily removed using a clean-up polarizer; however a flat response in s-polarized reflectance (Rs) over a broad range of wavelengths and angles is an important requirement for maintaining uniform brightness and color balance. Figure 5 compares blocking- and passing-state reflectance (Rs and Rp) from 0° to ±30° azimuthal angle of incidence. The Moxtek products have much more consistent performance with varying angle of incidence than the MacNeille Cube, resulting in reduced color shift. The non-AR coated Moxtek product depicted in figure 5 (c) has excellent broadband performance extending into the short wavelength infrared and is ideally suited for broadband interferometry and hyperspectral imaging applications. The small jump in the spectra at the IR detector crossover (1050 nm) for large angles is a measurement artifact caused by shifting beam position on the detector and is a result of refraction through the glass cube that cannot be accommodated for by the Agilent Universal Measurement Accessory.

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 (Tp x Rs). Figure 6 compares this efficiency for 0° to ±30° 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. The non-AR coated Moxtek product depicted in figure 6 (c) has excellent broadband performance extending into the SWIR.



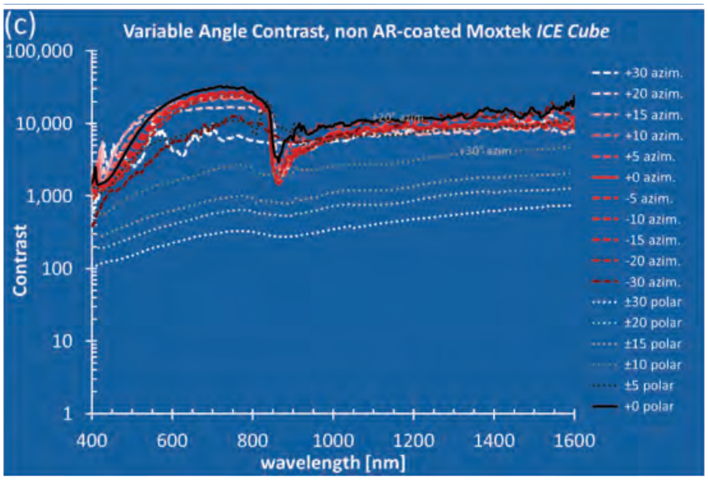


Figure 4. Variable angle contrast ratio (Tp/Ts) performance for a typical Moxtek *ICE Cube* and competing beamsplitters for 0° to ±30° angle of incidence.

(a) AR-coated Moxtek *ICE Cube* performance.

(b) MacNeille Cube performance.

(c) Broadband non AR-coated Moxtek *ICE Cube* performance.

Environmental and Form Factor Considerations

The *ICE Cube* contains an embedded plate wire-grid polarizer that utilizes all inorganic materials similar to Moxtek's standard visible spectrum 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 reliability results suggest a recommended temperature use condition of 90°C or less and a luminous flux of less than 6 W/cm2 (Hg-arc lamp source with UV and IR glass filters). 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. Table 1 summarizes design and environmental differences between the Moxtek *ICE Cube* and competing polarizing beamsplitter cube designs.

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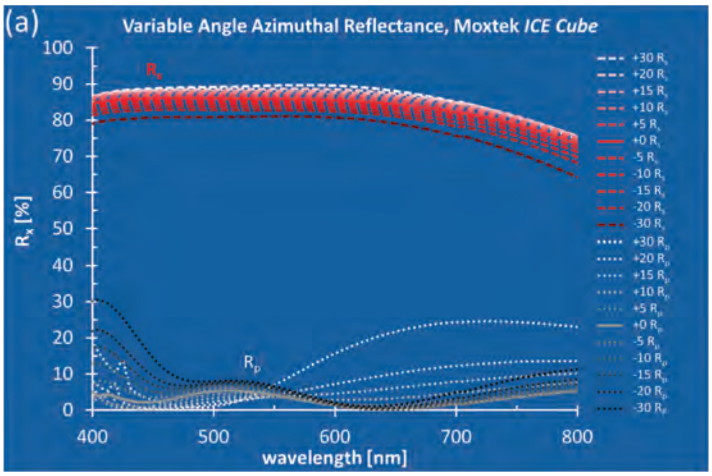
Table 1. Comparative Summary

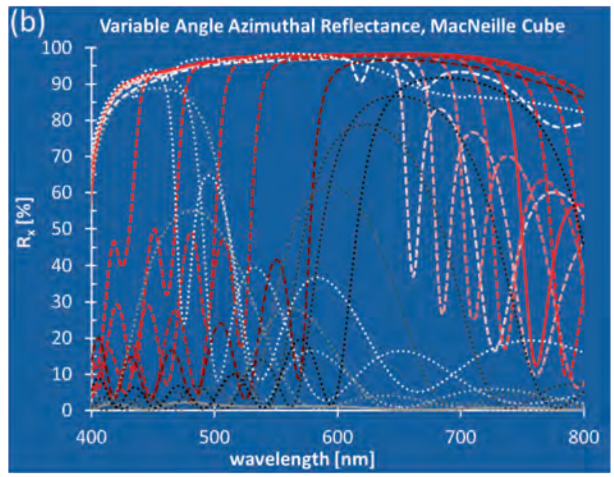
Feature	Moxtek ICE Cube	MacNeille Cube
Angle of Incidence	±20° to 25° azimuthal	±5° to 10° azimuthal†
	±10° to 20° polar‡	±5° to 10° polar‡
Spectral Range	400-700 nm*	410-700 nm
Durability	90°C and 6W/cm2 max	Requires polymer waveplate (degrades over time) to give correct polarization in display applications

† Excluding blue wavelengths.

‡ Contrast limited.

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





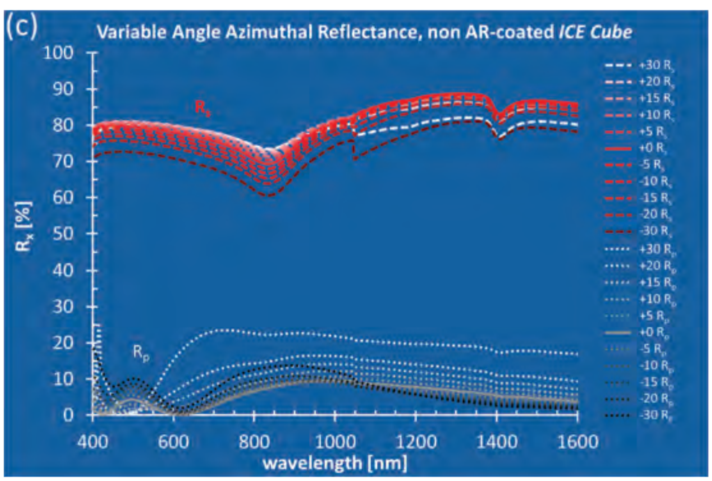


Figure 5. Variable angle reflectance (Rp, Rs) for a typical Moxtek *ICE Cube* and competing beamsplitters from 0° to ±30° azimuthal angles of incidence.

(a) AR-coated Moxtek *ICE Cube* performance.

(b) MacNeille Cube performance.

(c) Broadband non AR-coated Moxtek *ICE Cube* performance.

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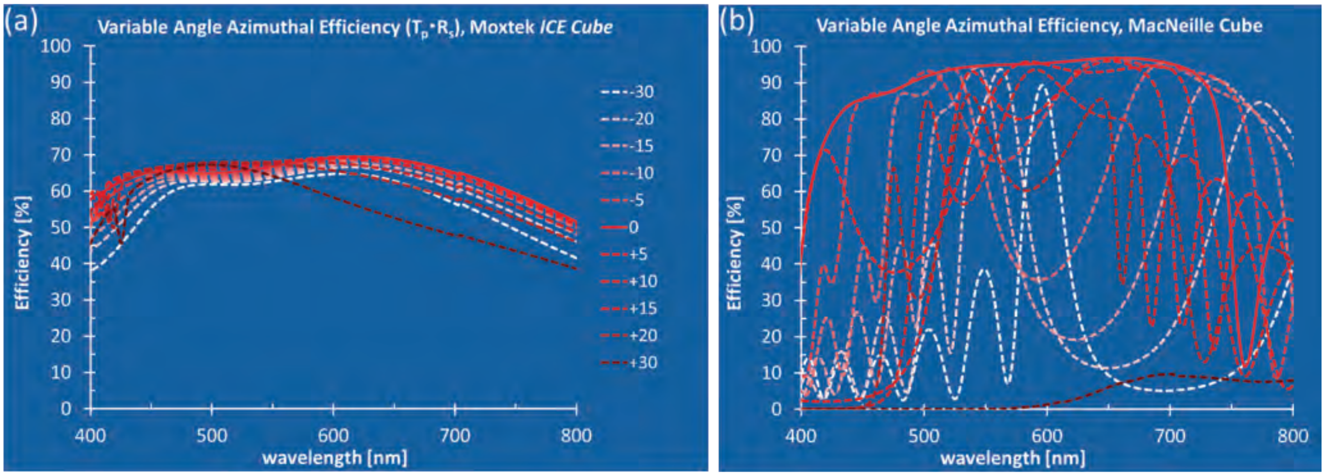
Environmental and Form Factor Considerations (continued)



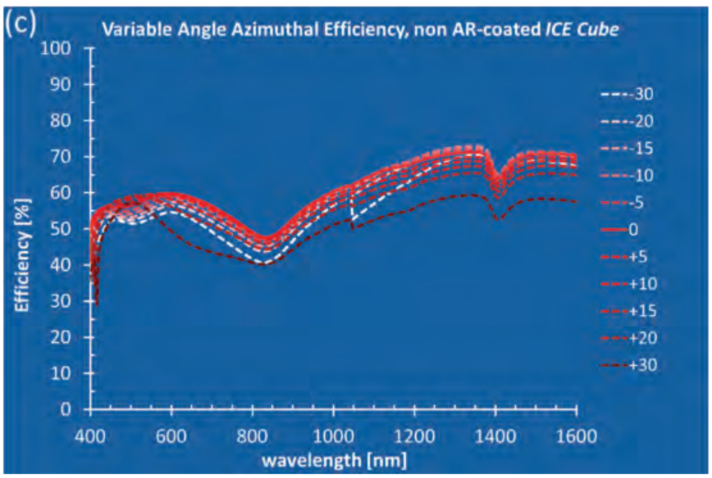


Figure 6. Variable angle efficiency (Tp x Rs) for a typical Moxtek *ICE Cube* and competing beamsplitters from 0° to ±30° azimuthal angles of incidence.

(a) AR-coated Moxtek *ICE Cube* performance.

(b) MacNeille Cube performance.

(c) Broadband non AR-coated Moxtek *ICE Cube* performance.

Conclusions

When compared to MacNeille polarizer designs, the Moxtek *ICE Cube* polarizing beamsplitter provides superior broadband performance over a wide angular aperture. The embedded aluminum Nanowire® grid design is 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* 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 when using poorly collimated sources. While competing polarizer designs can typically only tolerate a narrow angular aperture before performance deteriorates, the Moxtek *ICE Cube* with embedded Nanowire® grid polarizer is 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.

For warranty and ordering information, please visit www.moxtek.com.

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