Finding the Optimal Polarizer

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"I have an application requiring polarized light. What type of polarizer should I use?" This is a question that is routinely asked in the field of polarization optics. Many applications today require polarized light, ranging from semiconductor wafer processing to reducing the glare in a periscope. Polarizers are used to obtain polarized light. A polarizer is a polarization selector; generically a tool or material that selects a desired polarization of light from an unpolarized input beam and allows it to transmit through while absorbing, scattering or reflecting the unwanted polarizations. However, with five different varieties of linear polarizers, choosing the correct polarizer for your application is not easy. This paper presents some background on the theory of polarization, the five different polarizer categories and then concludes with a method that will help you determine exactly what polarizer is best suited for your application.

I. POLARIZATION THEORY - THE TYPES OF POLARIZATION

Light is a transverse electromagnetic wave. Every light wave has a direction of propagation with electric and magnetic fields that are perpendicular to the direction of propagation of the wave. The direction of the electric field oscillation is defined as the polarization direction. In the most general case, this direction is random; i.e. unpolarized light. Light can be polarized linearly, elliptically and circularly. Linearly polarized light has the electric field in one specific direction or it can be analyzed as a linear combination of two vectors, vertical and horizontal, with the same phase. Elliptical polarization can be described as a combination of two orthogonal linear polarizations that are added together with a phase difference. Elliptical polarization is described by the major axis direction, eccentricity and handedness of the ellipse. Circular polarization is a special case of elliptical polarization where the horizontal and vertical electric fields are added together in equal amounts of the two and have ninety degrees of phase difference.[1]

II. LINEAR POLARIZER TYPES AND SPECIFICATIONS

Linear polarization of light is achieved by passing light through a linear polarizer which absorbs, scatters or reflects the unwanted polarization direction. Linear polarizers come in five main varieties, dichroic polymer, dichroic glass, wire grid, beamsplitting and crystalline polarizers.[2] Polarizers are primarily characterized by two main specifications: transmission and contrast ratio. Transmission is the percentage of light that passes through the polarizer. One hundred percent transmission means that all of the light goes through the polarizer. This can only happen when the incoming light is polarized. An ideal linear polarizer transmits 50% of unpolarized light through or all of the light in the direction of polarization that is aligned with the polarizer axis and none of the orthogonal direction.[2] Since polarizers are not ideal, they transmit less than 50% of unpolarized light or less than 100% of optimally polarized light; usually between 40% and 98% of optimally polarized light. Polarizers also have some leakage of the light that is not polarized in the desired direction. The ratio between the transmission of the desired polarization direction and the undesired orthogonal polarization direction is the other main specification: contrast (or extinction) ratio.[2] For linear polarizers, the contrast ratio is the ratio of the maximum amount of light that passes through a polarizer to the minimum as the polarizer is rotated. The maximum transmittance occurs when a polarizer is placed so that the polarization axis of it is parallel to the polarization of the incoming light.[2] The minimum transmission is when the polarization axis is perpendicular to the input polarization. This is described by the Law of Malus which states that transmission is proportional to the square of the cosine of the angle between the plane of polarization of the input light and the transmission axis of the polarizer.[3] The contrast ratio for polarizers varies depending on the polarizer, ranging from around 10:1 to over 10 million to 1.

Past these two main specifications, other secondary specifications also need to be taken into account when selecting a polarizer. These include transmitted wavefront quality, the laser damage threshold, and mechanical specifications of the physical polarizer.[2] Transmitted wavefront quality is the measure of how much distortion there is when a plane wave passes through an optic. This also includes beam deviation. Beam deviation is an angular measure of how much the light direction is changed when passing through the polarizer.

The laser damage threshold is also another key point to consider, especially when dealing with a laser power source that has a high power density. Certain absorptive polarizers absorb the light and convert it to heat. This limits the amount of power that the polarizer can handle. When a massive amount of light is converted to heat, the polarizer will "burn."

The mechanical specifications are something else to consider when choosing a polarizer. This includes the outside diameter, thickness, and the clear aperture of the

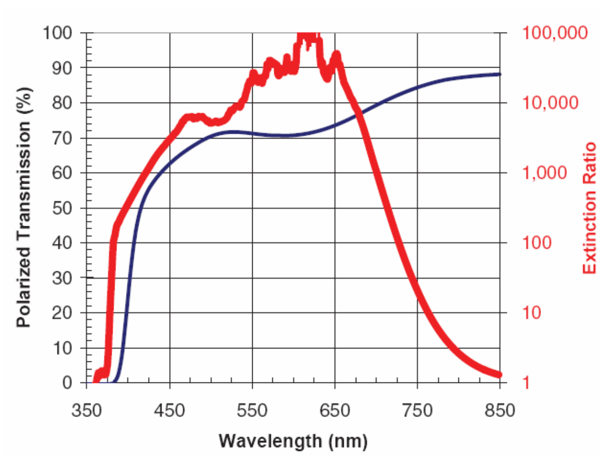

FIG. 1: A polarizer's transmission and contrast ratio can be shown graphically against wavelength. The contrast ratio is determined by dividing the maximum transmission by the minimum transmission. By looking at the graph at different places, it can be seen that both specifications are wavelength dependant.

polarizer. Some polarizers can only come in smaller sizes due to the manufacturing process of the polarizer while others are made in larger sizes and can be fabricated down to the smaller sizes. Also the aspect ratio, or the ratio between thickness and diameter needs to be considered as some polarizers have a thickness the same or greater than the diameter. The acceptance angle for polarizers is an important specification when uncollimated light is incident on the polarizer.

The final specification that needs to be considered is the cost of the polarizer. Polarizer costs can range from a few dollars to more than ten thousand dollars. Certain applications require high specifications and this will drive up the cost. Certain types of polarizers cost more due to the manufacturing procedure or a rarity in raw materials. This is less appealing if you are on a tight budget or an original equipment manufacturer attempting to keep the cost down. For many applications that do not need the precise specifications, a polarizer can be found that will meet your requirements at a reasonable cost.

III. DICHROIC POLYMER POLARIZERS

Dichroic polarizers are absorptive polarizers. Dichroism is the selective absorption of the unwanted polarization direction. Dichroic polymer polarizers are the most inexpensive variety of polarizer on the market. Dichroic polymer, or sheet, polarizers are made out of a thin stretched polymer sheet that is then doped with microcrystals that align parallel to the stretch direction. The electromagnetic waves perpendicular to this alignment pass through and electromagnetic waves parallel to it are absorbed.[4] These polarizers have the added benefit in that they can be easily customized in terms of size and shape because many types of polymer come in large rolls. Visible versions of dichroic sheet polarizers have been developed extensively over the last decade as television and monitor manufacturers use them in flat panel displays and this has helped drive their cost down. Dichroic polymer polarizers also come in other varieties that are useful for wavelengths ranging from the ultraviolet to the near infrared.

Usually, dichroic polymer polarizers have around 45-90% transmission with polarized light and a contrast ratio in the hundreds to thousands to one. When the sheet is used by itself, the transmitted wavefront quality is usually on the order of several waves. However, this can be improved when the polymer is laminated between glass substrates, usually made from BK7 or Fused Silica, and index matched adhesive is used.[2] The index matching adhesive decreases the differences in optical path length seen by light when going through the polymer and improves the transmitted wavefront distortion down to a fraction of a wave. However, this increases the cost of the part from a couple of dollars to the hundred dollar range.[1] It also makes the part thicker, from a couple of millimeters to as thick as an inch on large diameter polarizers. Finally, dichroic polymer polarizers also have an acceptance angle on the order of ten or twenty degrees.[2]

The two main concerns for a dichroic polymer polarizer are low damage threshold and thermal performance. Dichroic polymer has a low damage threshold before the polymer starts decomposing or "burning". This usually occurs with a laser density on the order of 1 W per square centimeter. Dichroic polymer polarizers are also susceptible to "bleaching." Bleaching occurs when the polarizer is damaged from too much exposure to light, usually ultraviolet light. This causes the polarizer's transmission increase but at the cost of the extinction ratio. Also at temperatures greater than 120 to 150 degrees, the polymer melts.[1] These are the primary drawbacks to using dichroic polymer polarizers.

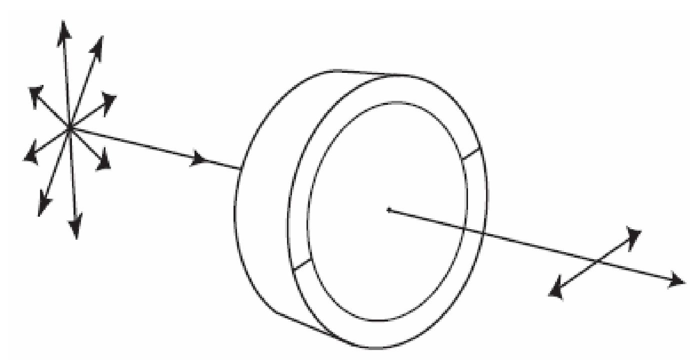

FIG. 2: A Dichroic polymer polarizer transmits only the desired polarization direction and absorbs the rest.

IV. DICHROIC GLASS POLARIZERS

Dichroic glass polarizers are similar to dichroic polymer polarizers. Dichroic glass polarizers are thin glass polarizers with metal particles in them, usually silver or copper. The manufacturing process is same to dichotic polymer polarizers in principle, the glass is seeded with metal particles and stretched, turning the metallic spherical particles into elongated ellipsoids, aligned along the stretch direction.[5] This is also an absorptive polarizer and can work at many wavelengths including the ultraviolet-down to 350 nm-visible and infrared, going out as far as five microns in some cases. There is one exception: the blue wavelength range (approximately 410-470 nm). The silver particles used in dichroic glass polarizers absorb blue light and cause low transmission and contrast ratio in this wavelength range.

Dichroic glass polarizers do have several benefits, especially the high contrast ratio that can be achieved, in some cases going higher than ten million to one as well as having high transmission in the near infrared, over 80-90% of polarized light. Just like its dichroic polymer counterparts, dichroic glass polarizers have wide acceptance angles, going as high as twenty degrees in some cases.[2]

Dichroic glass polarizers can also be laminated, decreasing the wavefront distortion of the part from over a wave to around one quarter of a wave.[2] Also, dichroic glass polarizers become less fragile when laminated as the unlaminated polarizer is extremely thin glass on the order of hundredths of an inch thick. The laminated polarizer will be over one tenth of an inch thick. Lamination increases the price because the manufacturing process sandwiches the dichroic material between two substrates of BK7 or fused silica. The cost of these polarizers is significantly more than dichroic polymer polarizers, usually over one thousand dollars for a polarizer with a one inch diameter. The size of the polarizer drives this price up as well. Unlike dichroic polymer polarizers, which can be made several inches in diameter, the largest diameter dichroic glass polarizers can achieve is on the order of two inches. Sizes larger than that cannot be manufactured at this time, but may be available in the future. One significant difference between the unlaminated dichroic glass and both laminated dichroic glass and dichroic polymer polarizers is the operating temperature. When unlaminated, dichroic glass polarizers can be used up to 400 degrees Celsius which greatly exceeds the range of either polymer or laminated dichroic glass polarizers.[6]

Finally, since this is an absorptive polarizer, it converts the unwanted light into heat, and the maximum power density that can be handled by this polarizer is similar to the polymer polarizer. It is approximately one watt per square centimeter.

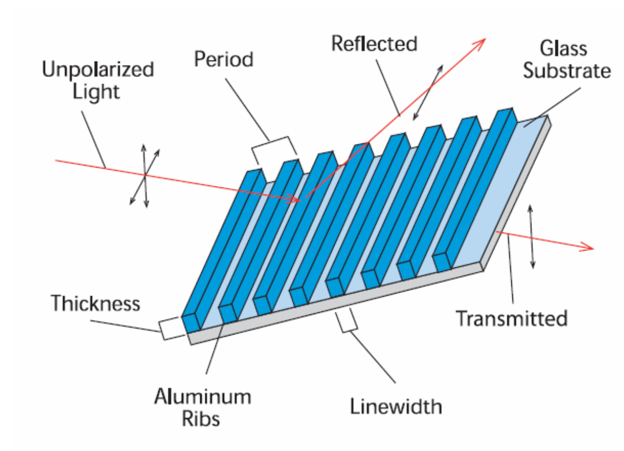

FIG. 3: A Wire Grid Polarizer transmits the P-polarized light and reflects the S-polarized light.

V. WIRE GRID POLARIZERS

Absorption is not the only way polarization selection mechanism used in polarizers. Other polarizers use reflection to reject the unwanted polarization. This includes the wire grid polarizer. Wire grid polarizers, since they are reflective, can withstand more power from a laser than the dichroic polarizer. This can be as high as tens of kilowatts per square centimeter. The wire grid transmits polarization that is perpendicular to the wire grid and reflects the polarization that is parallel to the wire grid and has a large acceptance angle, on the order of forty five degrees.[2]

Wire grid polarizers are made through a manufacturing process in which the wire grid, usually made of thin aluminum wires or gold is coated and patterned on a glass substrate. This is done on large pieces of glass that can be easily cut down to any smaller custom size or shape. Wire grid polarizers also work over a large wavelength range, from the ultraviolet, through the visible and into the near infrared. Certain types of the wire grid polarizer are optimized for a smaller wavelength range by adding an antireflection coating.[2] When used in the ultraviolet, there is no antireflection coating over the wire grid.[2] They also have lower contrast and transmission than those used in the visible and near infrared, but are still viable for many ultraviolet applications.

Concerns for the wire grid polarizers are the transmitted wavefront distortion and surface quality. Wavefront distortion varies depending on the substrate used and can go as high as several waves per inch when a material such as a precision float glass is used. By changing the substrate material to polished fused silica, this problem can be avoided but the cost increases.[2] The surface quality is somewhat poor due to the intrinsic manufacturing process decreases the scratch - dig standard to around 80-50 for larger parts but in some cases, smaller parts can be held to a 60-40 standard.

Finally, cost of wire grid polarizers must also be considered.While not as expensive as some other varieties of polarizer, such as dichroic glass and crystalline, wire grid polarizers are more expensive than unlaminated dichroic polymer polarizers for similar sizes. When the parts exceed several inches in size, and coatings are required, then the cost can go up as high as five to ten thousand dollars per part.

VI. BEAMSPLITTING POLARIZERS

Dielectric beamsplitting polarizers are another type of reflective polarizer. These can come in two different varieties. Beamsplitting plates operate in a manner similar to wire grid polarizers although the principle of operation is different. Instead of a wire grid on the surface of the substrate, they have a thin film coating that has a similar function to the wire grid in that it splits the beam into two polarizations.[2] Beamsplitting cubes, or MacNeille cubes-named after Stephen Macneille who invented them-are manufactured by cementing two right angle prisms together with a multilayer dielectric coating along the hypotenuse that transmits p-polarized light and reflects s-polarized light.[5] The outside faces of the cube usually have antireflection coatings to minimize loss. Beamsplitting polarizers come in two main varieties: laser line and broadband. Broadband beamsplitting polarizers work over a couple hundred nanometers in wavelength while laser line works at only one wavelength but have exceptional performance at that one wavelength.[2] Broadband beamsplitting polarizers include beamsplitting polarizers with a wire grid along the hypotenuse. By using a wire grid there instead of a dielectric coating, the acceptance angle and wavelength range can be increased.[7] Laser line beamsplitting polarizers have all of the coatings, both along the hypotenuse and on the legs tuned for the specific wavelength to improve the performance for that single wavelength.

Beamsplitting polarizers have two output beams, each with its own transmission and contrast ratio. The transmission for both beams is high, over ninety to ninety five percent for cubes with a dielectric coating on the hypotenuse. The contrast ratio is usually on the order of hundreds to one for the transmitted beam and less than one hundred to one for the reflected beam.

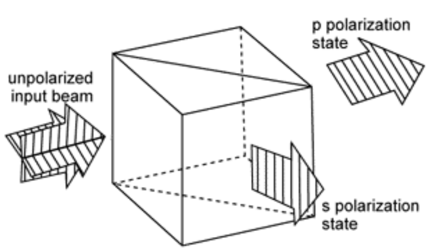

FIG. 4: A beamsplitting cube transmits the p polarization state through and reflects the s polarization state at 90 degrees.

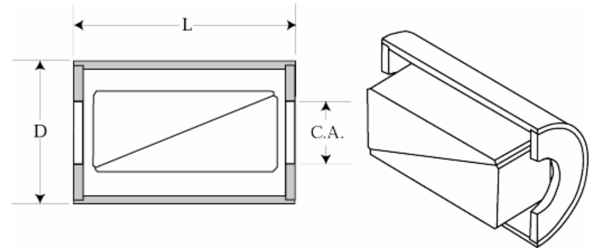

FIG. 5: A Glan-Thompson polarizer is an example of a crystalline polarizer.

Beamsplitting polarizers have high laser damage thresholds because of their sturdy construction. They are able to handle power on the order of hundreds of watts per square centimeter.[5] They also have low wavefront distortion because of their construction but unfortunately have small acceptance angles due to the nature of the dielectric coating on the hypotenuse. However, one of the main concerns of beamsplitting polarizers is mechanical. The aspect ratio of these polarizers is one to one, so without the room to mount these polarizers, they are impractical. Beamsplitting polarizers can usually be found only in sizes up to two inches. While at smaller sizes, they are neither the most inexpensive nor the most expensive polarizer, at larger sizes the price increases to over two thousand dollars for a two inch cube. The cubes must also be carefully mounted to avoid stress induced birefringence which degrades the polarizer performance.

VII. CRYSTALLINE POLARIZERS

The final type of reflective polarizer is crystalline polarizers. Crystalline polarizers are generally made from naturally occurring crystals that exhibit birefringent properties.[2] There are also synthetic options available. They have some of the best extinction ratios-often over 10,000:1 and can be used over wide wavelength ranges, usually from 200-300 nm to over two microns. The usable wavelength range is limited not by the crystal itself but the cement used to make the polarizer and any possible antireflection coatings that may be used also.[2]

These polarizers come in several different varieties such as Glan-Laser polarizers, Glan-Thompson polarizers, Glan-Taylor polarizers, Wollaston prisms and Rochon prisms.[8] All of these polarizers are comprised of two different pieces of birefringent crystal, usually calcite, that are either air spaced or cemented together. The calcite pieces are usually cut in such a way so that the reflected beam will come out at an oblique angle. The reflected beam can either then be stopped by the wall of the housing or in high power situations, there is one or two escape windows in the housing. This allows the

	Clear Aperture (mm)	Acceptance Angle	Part Cost	Contrast Ratio	Damage Resistance (per cm^2)	Mechanical Thickness (mm)	Transmission	Wavelength Range (nm)
Crystalline	5 – 10	± 5°	\$500 - \$5,000	10^5	25-30 W	22.5 – 38.1	85 – 95 %	320 – 2300
Dichroic Glass	1 – 30.4	± 20°	\$500 - \$5,000	10^6	1 W	0.5 – 6.9	39 – 98%	325 – 2000
Dichroic Polymer	10 – 50+	± 10°	\$1 - \$1,000	10^4	1 W	3.3 – 12.7	45 – 90%	325 – 1800
Dielectric Beamsplitting	10 – 20	± 2°	\$100 - \$5,000	10^3	500 W	12.7 – 25.4	95%	440 – 1600
Wire Grid	1 – 200	45°	\$100 - \$5,000	10^4	50 KW	0.7 – 1.5	70 – 85%	400 – 2000+

FIG. 6: A comparison between all of the five main categories of polarizers with all of their specifications.

reflected beam to escape and gives the user two usable beams.[9]

There are some drawbacks to crystalline polarizers though. One is that the transmission is not consistent across the entire wavelength range and decreases significantly when used in the ultraviolet. Also, the naturally occurring calcite crystals keep the price of calcite polarizers high as it is hard to acquire optical quality pieces, especially for larger clear apertures.[1] Crystalline polarizers are the most expensive type of polarizer. Mounting must also be considered as the aspect ratio is over one as crystalline polarizers have small apertures and are long, ranging in length anywhere from about half an inch to about three inches long.

VIII. POLARIZER SELECTION "GUIDE"

When choosing a polarizer for an application, one must take all of the aforementioned specifications into consideration. Usually, the customer knows several specifications of the desired polarizer. These may include: transmission, contrast ratio, price range, wavelength range, mounting considerations, and transmitted wavefront quality. This will provide a basis for a recommendation as to which polarizer will work best for the application. However, all specifications must be examined when choosing the ideal polarizer. Certain tradeoffs may have to be made to achieve a desired specification. For instance, if a customer wants a dichroic polymer polarizer with excellent wavefront quality, they cannot obtain an unlaminated polarizer.

Usually, identifying the application and the most important required specification is an ideal starting point for choosing a polarizer. Not all applications place the same emphasis on the same specification. One of the first specifications to consider may be the wavelength or wavelength range of use. This can easily limit the types of polarizers from which to select, especially in the ultraviolet. Many polarizers are either opaque in ultraviolet light or are damaged by it. The target price must also be considered. Customers on tighter budgets will probably want to stay away from the dichroic glass and calcite polarizer options as both of these options are significantly more expensive on the whole than the other three options. Going through the decision making process on the type of polarizer is a crucial step towards obtaining the optimal polarizer. When one correctly identifies the required specifications for the desired application, choosing the polarizer becomes much easier as each polarizer has its strengths and weaknesses and all of the polarizers already have known applications where they work well with proven results. A knowledgeable sales engineer can help you with your questions through this selection process.

Specification	Preferred Type(s) of Polarizer
Transmission	Dichroic Glass
Contrast Ratio	Dichroic Glass Crystalline
Clear Aperture	Wire Grid Dichroic Polymer
Transmitted Wavefront Distortion	Beamsplitting Wire Grid (with appropriate substrate)
Beam Deviation	Wire Grid
Laser Damage Threshold	Wire Grid
Thinnest	Dichroic Glass Dichroic Polymer Wire Grid
Cost (lowest)	Dichroic Polymer Wire Grid
Acceptance Angle	Wire Grid
Absorptive Polarizer	Dichroic Polymer Dichroic Glass
Reflective Polarizer	Wire Grid Beamsplitting Crystalline

FIG. 7: A listing of the preferred types of polarizers for several important specifications.[10]

IX. CONCLUSION

Polarization control or selection is required for a multitude of applications today. With a bevy of choices from which to choose from, it is easy to get confused as to which polarizer is the "ideal". Each polarizer category; dichroic polymer, dichroic glass, wire grid, beamsplitting, and calcite has its own niche in the world of optics with applications that it is best suited for. By looking at the key specifications of polarizers: transmission, contrast ratio, transmitted wavefront quality, surface quality, beam deviation, laser damage threshold, and mechanical specifications; one can easily close in the polarizer that will fit their application the best and be able to meet their polarization requirements.

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[1] T. Baur and S. McClain, in *Optical System Design*, edited by R. Fischer (SPIE press, McGraw-Hill, 2008), chap. 19.
[2] *Meadowlark optics inc., 2009-2010 polarization handbook and catalog*, Catalog (2009).
[3] T. Baur, *Understanding and Managing Polarization*, Meadowlark Optics Inc. (2001).
[4] J. Bennett, in *Handbook of Optics*, edited by M. Bass (McGraw-Hill, New York, 2005), vol. II, chap. 3.
[5] E. Kubacki, in *Photonics Spectra* (2006), pp. 74–78.
[6] *Codixx colorpol*, Advertisement (2008).
[7] T. Baur, *A New Type of Beamsplitting Cube*, Meadowlark Optics Inc. (2001).
[8] M. Griot, *Melles griot catalog*, Catalog (2008), vol. X.
[9] K. L. Corporation (2009).
[10] W. S. Barbarow (2008).