

Beam manipulation: prisms vs. mirrors

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Designers of beam manipulation and imaging systems often encounter the need to fold their optical layout into a more compact form, or to redirect light to the next component. In either case, the choice inevitably arises between mirrors, or alternatively, prisms. Solutions may often be found either way, but making the best selection up-front could save the designer from potential problems later.

The general concept of using a reflective surface to reflect light needs no explanation. For discussing mirrors and prisms in beam steering applications, one mainly just needs to understand the Law of Reflection: it essentially shows that the angle of light incident on a plane surface is equal to the angle of reflection (**figure 1**). Combining several reflective planes with each other yields a higher number of potential applications. For example, two plane mirrors oriented at a given angle α to each other will reflect an incident beam of light by twice that angle, 2α , as long as the plane of incidence is perpendicular to the line of intersection of the mirror planes. This can also be seen in **figure 2**: The angular sum within the yellow triangle is $\theta_1 + \theta_2 + (180^\circ - \alpha) = 180^\circ$, and thus $\theta_1 + \theta_2 = \alpha$. Therefore, a beam deflection of $2\theta_1 + 2\theta_2$ equals 2α . From this, one can see that the special case of two mirrors oriented 90° to each other will return a beam oriented 180° (anti-parallel) to its original direction as shown on the right hand side in figure 2.

By adding a third reflective surface to create a right angle "corner" of three plane mirrors, it can be shown that a beam will be returned upon itself no matter what the angle or plane of incidence, as long as the beam hits all three mirrors successively as in **figure 3**. Such a configuration is called a corner cube retroreflector (**figure 4**) and is extremely useful in laser-based alignment applications. Retroreflectors can be found in either mirror or prism form. A mirror-based retroreflector would likely be

optimal for weight sensitive applications, or where material absorption or chromatic aberration could be of concern. A prism retroreflector would likely be optimal where thermal effects may be a concern (more on this later).

Both mirrors and prisms can also be used to split or combine beams of light, or simply to "fold" optical systems into physically smaller spaces. Every reflecting prism actually has a mirror-based equivalent. In theory, these different approaches are mostly interchangeable methods for bending paths of light. In reality, however, the performance characteristics and benefits of these two approaches can be appreciably different.

Whether to use mirrors or a prism largely depends on the complexity and purpose of the layout in question.

Using mirrors

For many simple layouts, a mirror-based solution may save cost and reduce the weight of a given system (assuming that off-the-shelf mirrors can be used). A mirror system might also make sense when system size is not a constraint, e.g. on a large bench. Mirrors are favorably used for wavelength ranges that are strongly absorbed by most types of glass. High power laser applications where even partial absorption may be a concern could be another strong case for using mirrors rather than prisms. Any bubbles or inclusions in the glass of a prism could lead to preferential

absorption and heat build-up, which could permanently damage or ultimately even crack the prism. Mirrors are also preferable in applications where flexibility and quick changes are more important than other system parameters. One major disadvantage to a mirror-based layout, however, is the need for mounting fixtures for each mirror. With multiple mirrors and mounts, positioning issues and alignment complexity can quickly become worrisome.

Using prisms

Instead of using multiple mirrors in a number of potentially cumbersome and costly mounting fixtures, one could often simply use a prism. Prisms are solid pieces of glass (sometimes other materials) with polished faces that have been worked into optically meaningful shapes. Their effect depends on the position, number, and angles of faces. Prisms work similarly to mirrors in that they are able to redirect light into different angles or around obstacles, based on reflection. As a monolithic component, an appropriately tolerated prism can often avoid common alignment problems that plague a similar mirror-

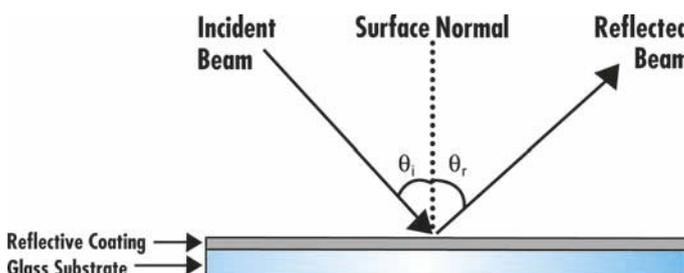


Figure 1: Angle of Incidence (θ_i) = Angle of Reflection (θ_r)

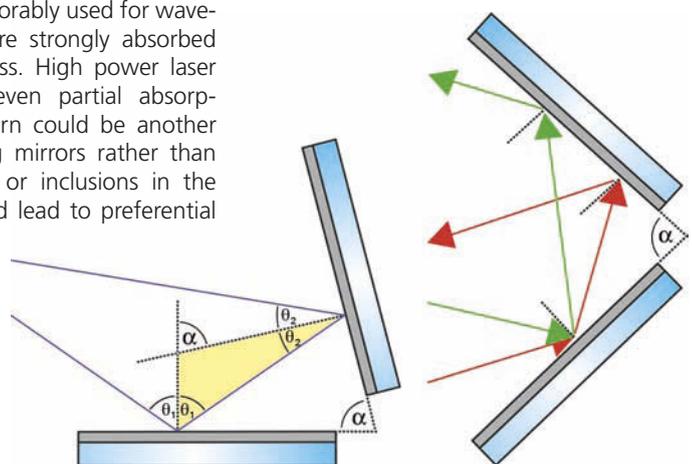


Figure 2: Two mirrors oriented at angle α will turn a beam by an amount twice that angle. In the special case shown on the right hand side, a 90° orientation will turn the beam 180°

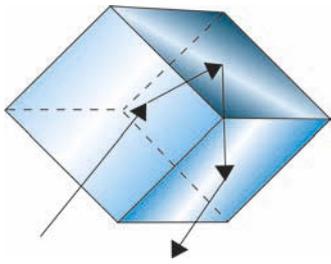


Figure 3: Three mirrors arranged in a right angle "corner" configuration will return a beam back to its source (with some offset) from any incident angle as long as all three mirrors are hit successively

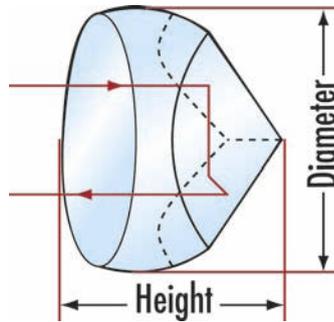


Figure 4: A corner cube retro-reflector prism

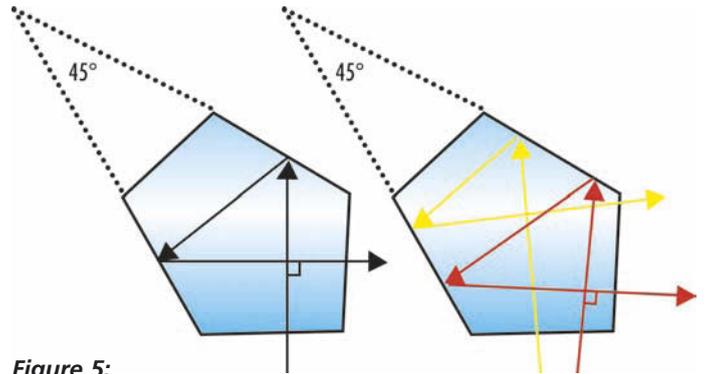


Figure 5: A penta prism has two reflective surfaces oriented at 45°, which produces a 90° beam deviation regardless of the input angle

based approach. For example, consider the case of using a penta prism instead of one or two plane mirrors in order to bend a laser beam by 90° (see **figure 5**). A penta prism will yield a resultant beam at 90° with respect to the incident beam, in the plane shown, regardless of minor alignment errors of the prism or input beam. Conversely, it is easy to picture the difficulty of aligning a mirror (or mirrors) at exact angles in order to yield the same result. Note that any alignment error with a mirror is doubled on account of the Law of Reflection.

Besides the aforementioned retroreflector prism and penta prism, other prisms that are commonly used in beam manipulation applications include: the right angle prism, the dove prism, the rhomboid prism, and wedge prisms (see **figure 6**). The right angle prism is quite a versatile component. Depending on orientation, a right angle prism can either be used to turn a beam 90° by reflecting it off of the hypotenuse, or to turn a beam 180° by reflecting it off of the orthogonal faces, with a predictable amount of beam displacement. In both cases, reflection occurs internally. A dove prism is essentially a right angle prism that is truncated for weight and size concerns. Both the dove and right angle prism can be used for beam displacement, by translating it in the plane of incidence, or for beam rotation, by rotating the prism about an axis parallel to the incoming beam. A rhomboid prism is useful for displacing the optical axis without changing the beam direction.

Unique features of prisms

Prisms can also be used as refractive elements. An individual wedge prism as in figure 6 will deviate a laser beam at a set angle, while an anamorphic pair of two wedge prisms can expand a laser

beam in one dimension. This is achieved by adjusting the angle of tilt between the two wedge prisms, and is useful for making elliptical laser beams circular (see **figure 7**). A pair of wedge prisms, referred to as a Risley prism, can also "steer" a beam anywhere within a circle described by the full angle 4θ , where θ is the deviation from a single prism (see **figure 8**).

By applying special coatings between prisms that are to be cemented together, any number of potential beamsplitter and beam combiner assemblies can be created that would be very difficult to duplicate effectively with similar specialized plane mirror coatings. The simplest version of

a prism-based beamsplitter is the cube beamsplitter, which is composed of two right angle prisms cemented together at their hypotenuses. More complex prism-based beamsplitter and beam combiner assemblies are often used in certain laser targeting and laser range-finding applications.

It is necessary to add a note of caution when using prisms with either convergent or divergent light, or when the entrance or exit face of the prism is at an angle to the incident light. Any of these conditions will introduce aberrations (both monochromatic and chromatic). In the case of laser beam steering, convergent or divergent input light would suffer from spherical

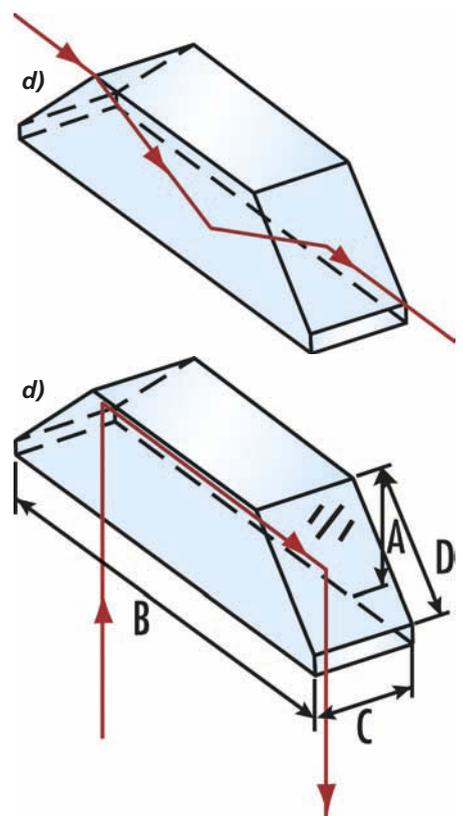
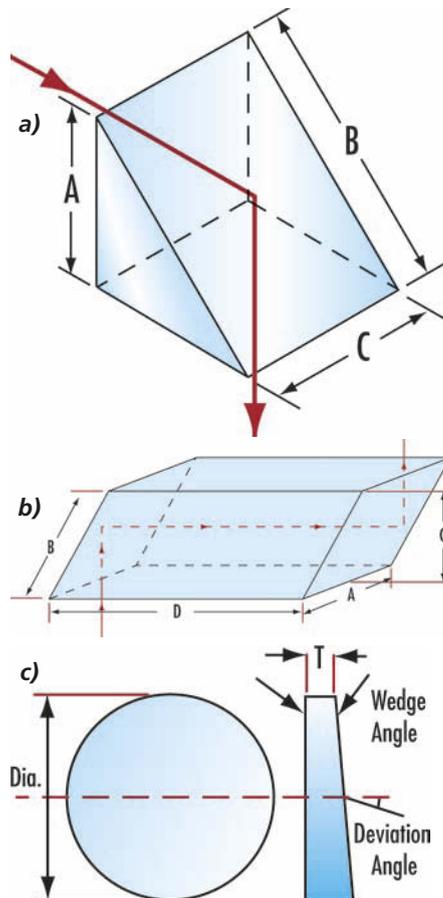


Figure 6: a) A right angle prism, b) a rhomboid prism, c) a wedge prism, and d) a dove prism

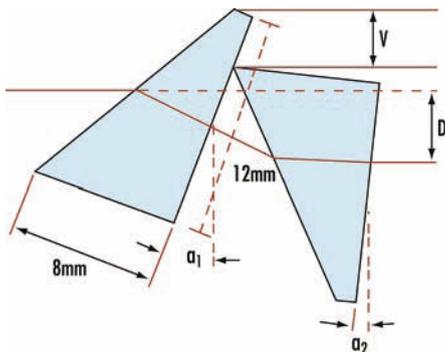


Figure 7: An anamorphic pair uses two tilted wedge prisms to expand a laser beam in one dimension or change its ellipticity

aberration, while tilted prism faces would likely lead to astigmatism.

Efficiency

A topic that should now be discussed is the relative efficiencies of prisms and mirrors, with regard to maximizing the amount of light put through a given system. It is desirable to have reflections of light inside of a prism happen as a result of Total Internal Reflection, or TIR. This occurs when the angle of incidence θ_i of a beam traveling from a material of higher index (i.e. glass, refractive index $n_1 = 1.5$) to a material of lower index (i.e. air, $n_2 = 1$) exceeds the critical angle θ_c required for the light to stay inside the prism, rather than refract out of the prism into the air (i.e., $\theta_r < 90^\circ$). According to Snells Law:

$$n_1 \cdot \sin(\theta_i) = n_2 \cdot \sin(\theta_r) \quad (\text{Eq. 1})$$

An angle of the refracted beam of $\theta_r \geq 90^\circ$ means that no light is escaping across that interface. Therefore, at $\theta_r = 90^\circ$, Eq.1 with $\theta_i = \theta_c$ turns into:

$$\theta_c = \arcsin(n_2/n_1) \quad (\text{Eq. 2})$$

For a typical glass-to-air interface, this requires θ_i to be greater than $\theta_c \approx 42^\circ$. TIR is 100% efficient provided the reflecting surface is clean and free of defects. Appropriate antireflection coatings on the entrance and exit faces of the prism would ensure that only a negligible amount of light is lost from unwanted reflections at each of the air-to-glass interfaces.

If TIR is not met, then a metalized mirror coating will need to be applied to the offending prism face to facilitate reflection. A downside of a metalized mirror coating – and standard mirror coatings in general – is that there is often a significant drop in efficiency. A standard metal mirror coating may not be much more than 90% efficient, for example, with the balance of the light being scattered or absorbed.

It is also possible to design and achieve very high reflectance mirrors, but they have to be tailored to specific wavelengths by using certain specialized dielectric coatings (i.e. “laser mirrors”), and the cost of such mirrors are often in the range of hundreds of dollars. At that point, there is often just a negligible cost difference between premium mirrors and precision prisms or prism pairs that are appropriately antireflective coated to minimize reflection losses at each air-to-glass interface.

Thermal stability

There are other benefits to using prisms rather than mirrors, where applicable. As a uniform piece of glass, a prism is fairly naturally athermalized. In other words, the entire prism would expand or contract with a given homogeneous temperature change. Such a uniform expansion or contraction is much more unlikely to have a detrimental effect to the optical system of which the prism is a part. Mirrors and their mounts made of various metal components would likely have much more severe reactions to changes in temperature. Prisms tend to be less affected than mirrors by other environmental variations as well, which is again due to the fact that they are solid blocks of glass rather than individual “exposed” components.

Conclusion

Although mirrors certainly have their uses in a variety of systems, especially in optical bench layouts with basic system folds, many designs switch to using prisms at the prototype stage and beyond because of the various benefits of prisms discussed above. Such a substitution can often result in a decrease in alignment issues, overall system size, and general maintenance. If specified correctly, an increase in accuracy and simplicity could also often be realized at this stage. Although the choice between using mirrors or prisms is application-dependent, having a rough understanding of which choice to make – and why – may save precious design, prototype, and maintenance efforts and costs in the long run.

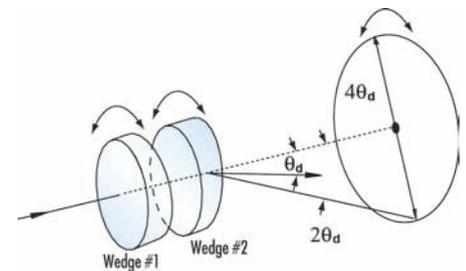


Figure 8: Beam steering in a Risley prism is accomplished by rotating the wedge prisms independently of each other

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