THE FRESNEL LENS

I. *Early Lighthouse Illumination*

When Augustin Fresnel's lens was first introduced in 1822, there was an immediate and dramatic improvement in the illumination that a lighthouse could deliver. To understand the significance of this change, we must look at the limitations and handicaps which burdened lighthouse keepers in earlier times.

Although there was probably some system of **signal fires** as long as ships sailed at night, the first lighthouse documented in history was the Pharos of Alexandria, one of the seven wonders of the ancient world. The 250-foot structure was completed about 300 B.C. It was topped by a metal container which held a wood fire. This lighthouse remained functional for the next 1,000 years.

The Romans maintained a series of lighthouses, and, as shipping increased during the Middle Ages, many of the maritime nations around the Mediterranean also established lighthouses. For many centuries the only fuel for the open signal fires was wood. Because wood burns rapidly, maintenance of the light was very labor-intensive. Furthermore, difficulty maintaining the light was greatest during storms, just when its brightness was needed most. As the years went by, surrounding forests were stripped, and the fuel supply became progressively more difficult. Coal gradually replaced wood as the preferred fuel; it burned more slowly but was brighter, although it too required fires open to the elements. Efforts to enclose coal flames in lanterns were foiled by heavy deposits of soot which promptly coated the window panes.

By the 1600s some lighthouses employed banks of extra-large **candles** as their light source. They offered the advantage of easier maintenance, and more significantly, they could be used in an enclosed structure. The most famous lighthouse to employ candles for its beacon was the first Eddystone lighthouse in south-west England, featuring a bank of sixty one-pound candles. The main limitation curtailing the use of candles was their inadequate illumination compared to other light sources. Nevertheless, some lighthouses continued to use candles well into the 18th century.

The 1700s brought the first significant improvement in illumination, with the introduction of **parabolic mirrors**. Place behind the lamp, they captured an extra portion of its light energy and reflected the light toward the target. To be effective this system required a series of lights, each with its reflector, with each needing its own maintenance. These mirrors were heavily silvered and tarnished rapidly in the presence of the lamps' fuels. This in turn led to very frequent polishing to preserve the reflective capability, so frequent that polishing rags were often collected to extract the silver!

About the same time better fuels began to make their appearance, mostly vegetable and animal fats. These were combined with various forms of lamps. One of the earliest of these, the spider lamp, consisted of four wicks standing in a pan of oil. They produced such acrid fumes that the keeper could only remain in the lantern room for a few minutes at a time. Despite the drawbacks the spider lamp was employed in all U.S. lighthouses until 1812.

A great advance in lighthouse technology was realized with the introduction of the **Argand lamp** in 1789. It was a chimney lamp with a hollow wick; oxygen was drawn up both sides of the wick, producing a bright flame, and just as importantly, a smokeless flame. When combined with parabolic reflectors behind it and a convex lens in front, the Argand lamp produced a focused beam roughly equivalent in intensity to an automobile headlight. However, to achieve that effect multiple sets of lamps and mirrors (up to 30) were required, each needing its own fuel supply and maintenance.

This was the state-of-the-art 33 years later when the **Fresnel lens** was first introduced. In a short time first-order lenses were producing beams that could be seen 20 miles away. Moreover they were achieving this with a system which was far more economical and easier to maintain than any of its predecessors.

II Fresnel Optics

The shortcoming of all devices before Fresnel was their inefficiency; most of the light that was generated was wasted, with only a fraction directed towards the intended target. If only a lens could be placed in **front** of the light, then more of the light rays could be captured and redirected in a parallel beam. The problem, previously insurmountable, was the size such a lens would have to be in order to be useful. The lens would need to be several feet tall and extremely thick. Such a lens would be impossibly heavy and bulky. Even if it could be placed in a lighthouse, there was no way such a device could be optically ground.

Fresnel's contribution was to devise a system where the same focusing power was achieved, but with thin optics. He observed that an appropriately-selected prism could, at any point on a lens surface, bend light rays in the same way as the lens itself. By combining an elaborate system of prisms he was able to mimic the effect of a large convex lens. (See Figure 1.) The completed Fresnel lens employed a central convex lens (the bullseye), surrounded above and below by banks of prisms that refracted the light rays. The power and placement of the prisms, as well as the lens, were selected to redirect light rays into a parallel beam, when the light source was at the focal point.

Fresnel added another innovation for the most peripheral prisms, utilizing the principle of **total internal reflection**. This is demonstrated in Figure 2. Light rays passing through glass are bent, or refracted, and normally emerge on the opposite side. But if the angle at which the ray strikes the glass exceeds a critical level, the refracted light can't escape and are reflected back into the prism and emerge in a totally different direction. Fresnel arranged the outermost prisms so that light was so reflected and refracted, finally joining the other parallel beams. By using this technique he could tilt the top of the lens towards the light source, capturing even more of the stray light.

Figure 3 shows the entire lens schematically. The central lens and the surrounding prisms refract the light, while the outermost internally reflect, then refract the light. The end result was to produce a very powerful beam from a weak light source not by "magnification" but by efficient light ray gathering and redirecting. Figure 4 shows that the Fresnel lens collected upwards of 70% of the lamp's output, a several-fold improvement over the best of its predecessors. Even with the light sources of the day, the Fresnel lens enabled a beam to be seen well over 20 miles away.

III The Completed Fresnel System

The complex of lenses described above will transmit a single, uni-directional beam of light. In order for it to be seen over the breadth of the horizon, the lens system has to be rotated, and to attain a continuous signal, a series of lens arrays surrounding the lamp is needed. So the final Fresnel system looks like a beehive, with up to twenty or more banks of lenses, and over 1,000 individual prisms. Each bank of lenses is called a **flash panel.** Viewed from above, the array would appear as a series of beams of light, radiating form the center like spokes of a wheel.

By occluding some of the panels, a pattern is created, with timed periods of light, interrupted by moments of darkness. Each lighthouse has its own distinct pattern, or **signature**, by which a mariner can identify that particular station.

The commonest method of rotating the lens was to rest it on a platform which turned on brass chariot wheels. The movement was achieved by a grandfather clock-like mechanism. Until electricity arrived in lighthouses, the mechanism had to be rewound by hand every four hours. The very largest lenses required a mercury float to support their weight of up to eight tons and still permit easy rotation.

The Fresnel lenses were made in several sizes, referred to as **orders**. There were seven orders—one through six, as well as 3 ½ . The first order lens (such as at Point Sur) was the largest size. It and the second order lenses were used for major landfalls, where the greatest range was needed. Intermediate sizes were placed in bays and estuaries. The smallest is only 18 inches in height, while the biggest can be 18 feet tall, with a six-foot diameter.

IV U.S Lighthouses and the Fresnel Lens

In the early 1800s lighthouses were under the jurisdiction of the Treasury Department. The specific individual in charge was the fifth auditor, Stephen

Pleasanton. He was an accountant, with minimal knowledge of lighthouses. He came to rely more and more for advice on Winslow Lewis, and unemployed sea captain. Lewis had patented his version of the Argand lamp, advised its use and produced it for the government, consistently winning bids over competitors. His devices were later found to be shoddy in design and construction.

After Fresnel's lens was introduced in Europe in 1822, a steady stream of foreign and American sea captains touted its superiority. Whether because of Lewis' influence or not, Pleasanton consistently resisted implementation of the Fresnel lens, calling it a "fad", and stating that it was too expensive. Even when two lenses were purchased and unanimously judged as superior, Pleasanton called for "more study".

Ultimately Congress took matters into its own hands, appointing an investigative board. As a result of its blistering criticism the lighthouse service was reorganized under a Lighthouse Board with competent leadership. By 1860 every lighthouse in the country boasted a Fresnel lens.

At the time the Fresnel lens was introduced in this country, the preferred fuel for its lamp was whale oil. This soon became too costly and was replaced by lard, and later, kerosene. Finally electricity was introduced not only for the lamp, but to power the rotation of the lens. In many remote stations such as Point Sur there was no electrical supply, requiring local generators to produce the power. At Point Sur the lighthouse received its electric power from generators for many years, while the keepers and their families still got by with coal stoves and kerosene lamps.

V Modern Uses of the Fresnel Lens

Today, Fresnel's name is perpetuated in a host of applications of his lens. Tiny lenses are fashioned for optical and electronic work molded from plastic with grooves less than 1mm. apart, separating equally tiny prisms. Auto headlights, taillights and traffic signals all employ Fresnel lenses, as do searchlights, big screen TVs, camera range finders and the overhead projector used for these training classes. Modern technology allows the lenses to be fashioned from one piece of precisely molded plastic. But none can match the majesty of the mighty lighthouse Fresnel lenses!

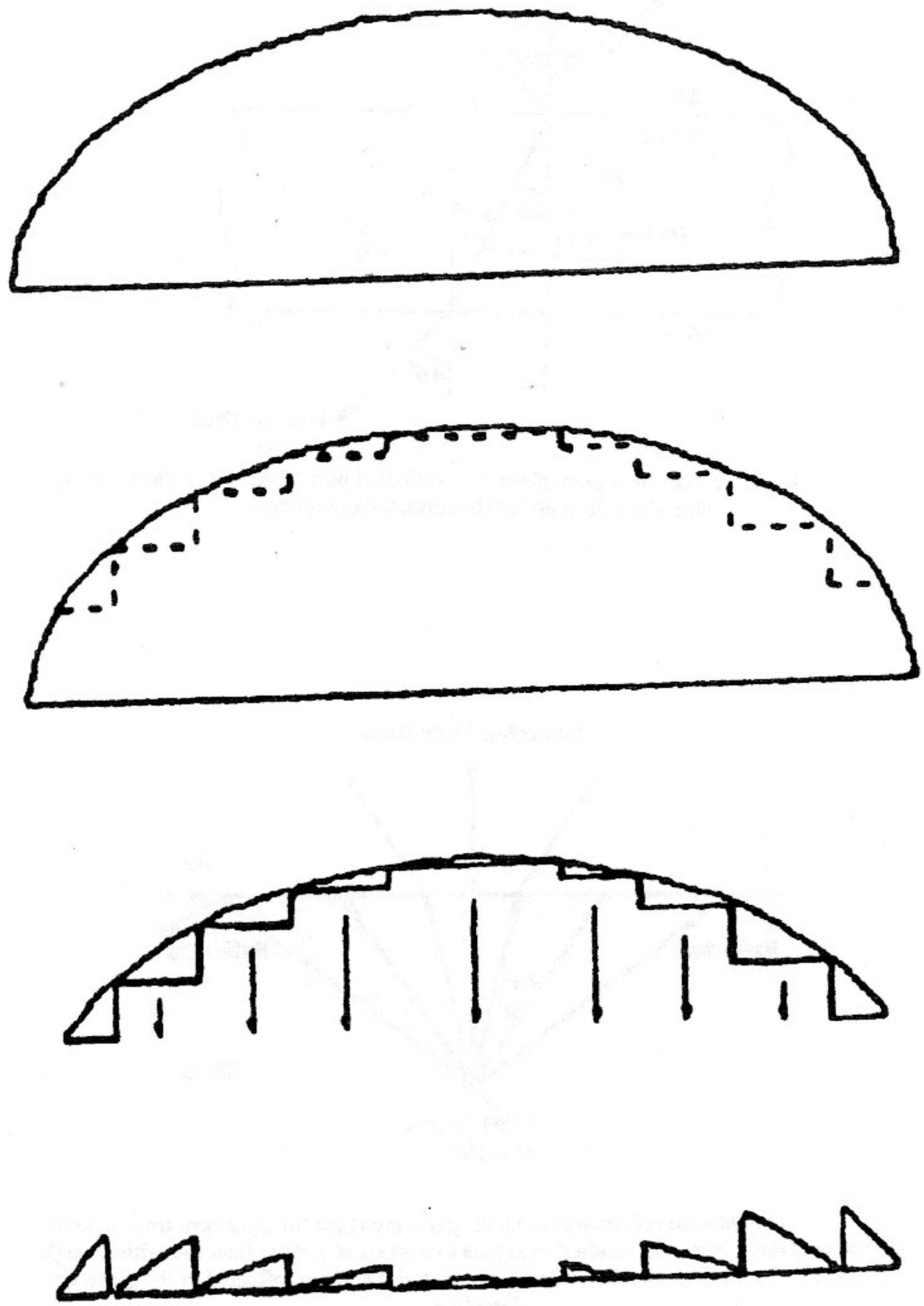
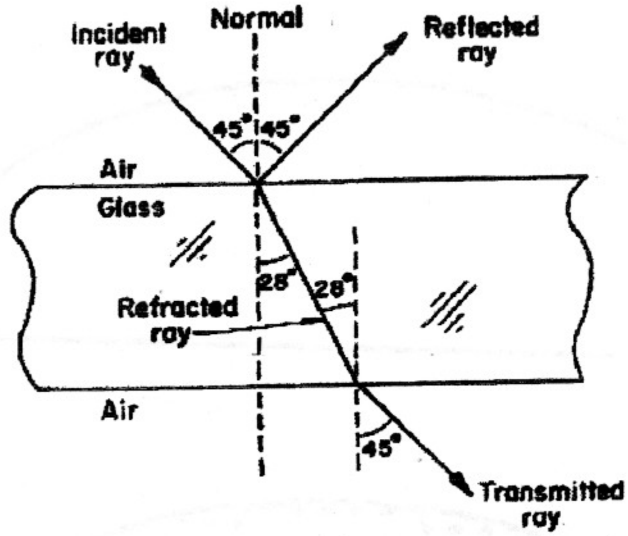
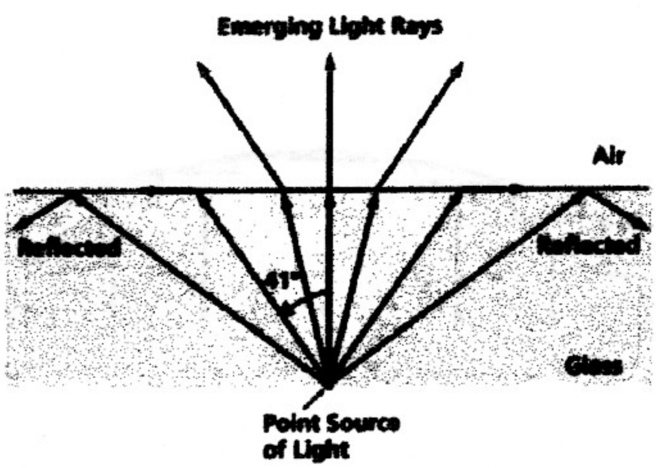


Figure 1

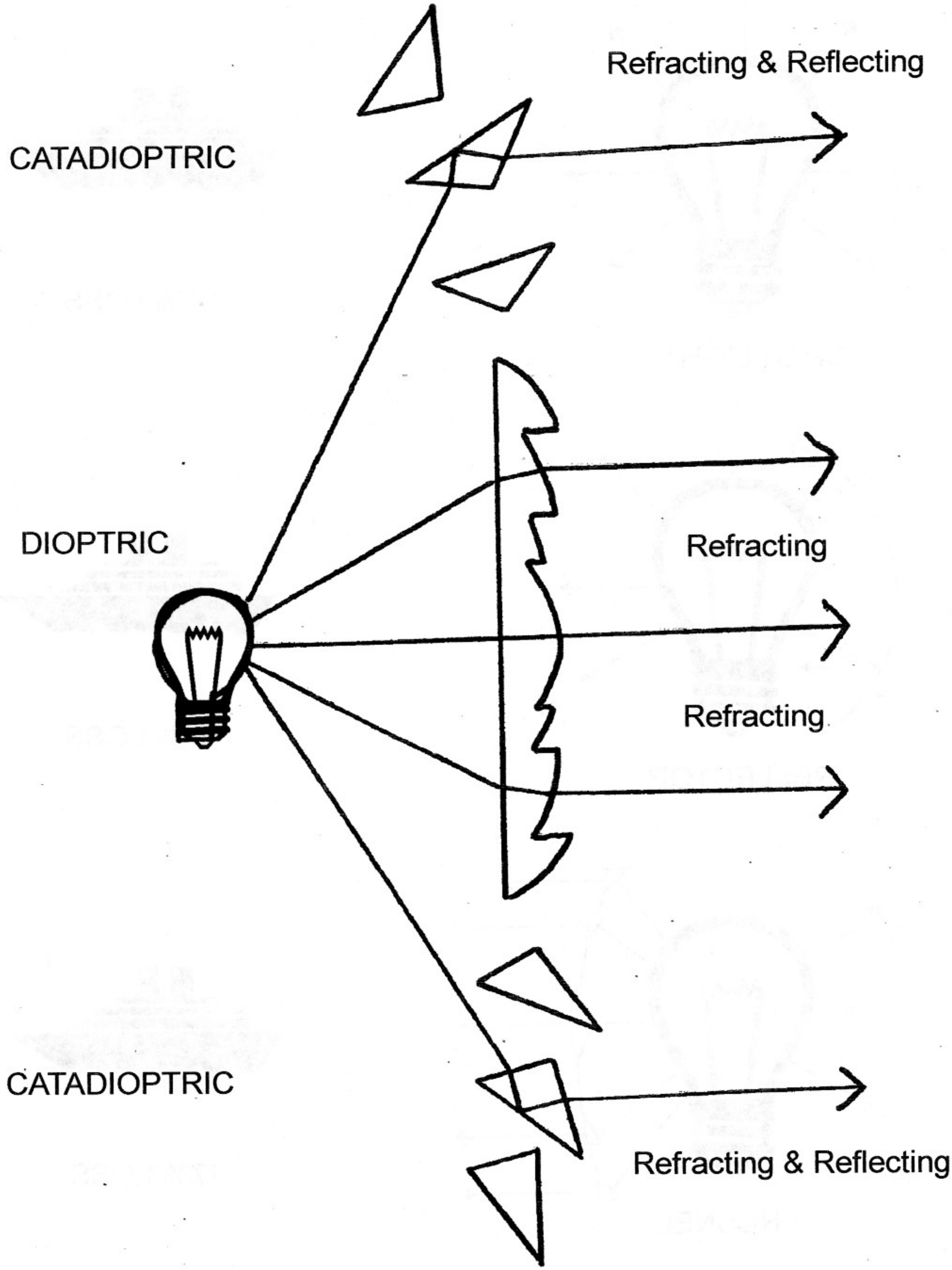


Light incident on a glass plate. The reflected part of the ray is shown along with the light path for the refracted component.



The internal reflectance at an air/glass interface for light rays from a point source in glass. Light rays incident at angles to normal at greater than the critical angle (here, 41° for glass to air) do not leave the material and are reflected at the glass/air interface.

Figure 2


Refracting & Reflecting
CATADIOPTRIC
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Refracting
CATADIOPTRIC
Refracting & Reflecting

Figure 3

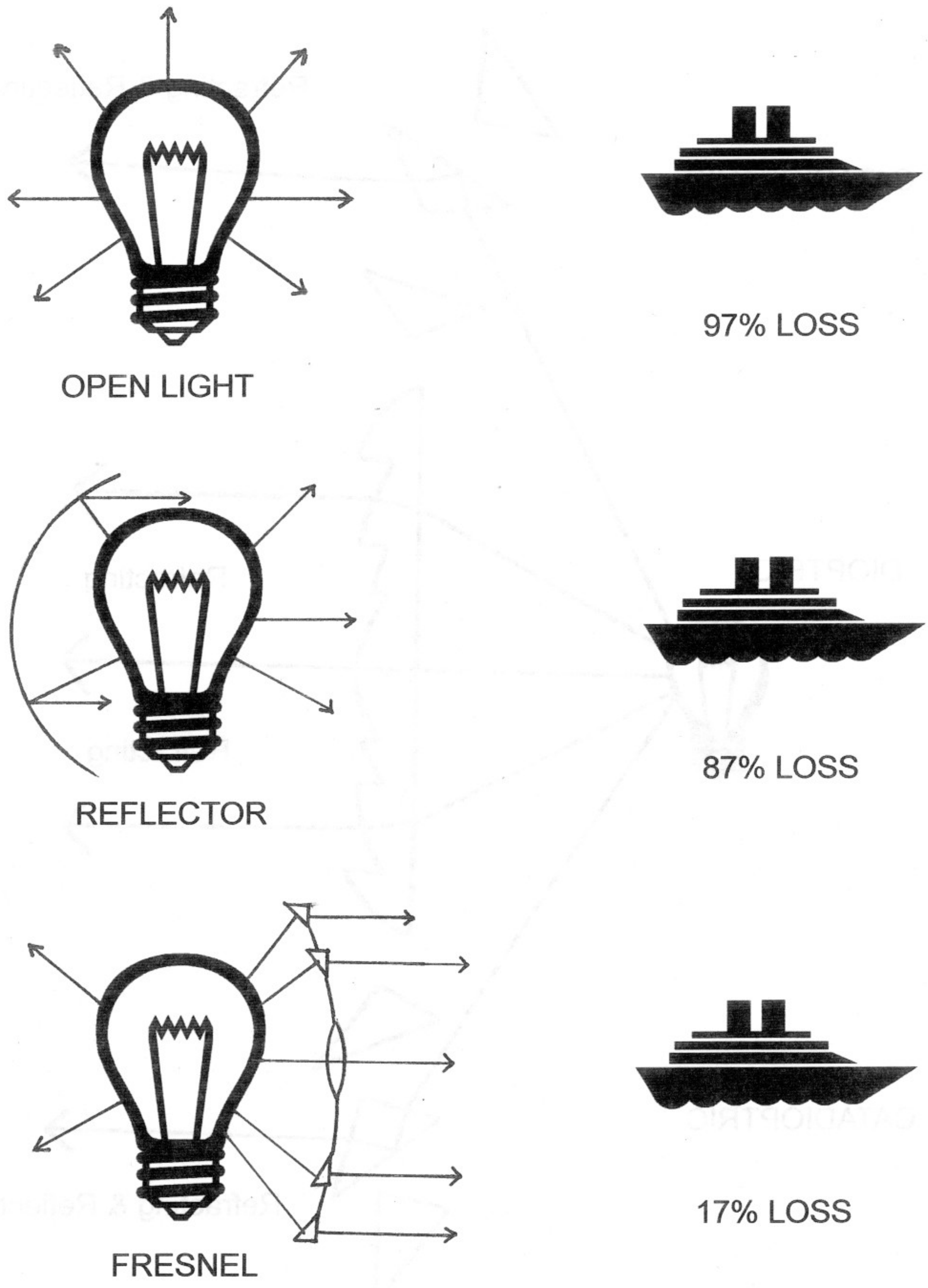

Figure 4