Reinterpreting Brewster's Law

3M™ Enhanced Specular Reflector or ESR, reflects more than 98 percent of the light that hits it, which is pretty remarkable. It's especially remarkable because it's one of the most reflective materials on the planet. It's even more reflective than silver or aluminum. Yet it's made of transparent polymers. There are several hundred layers of these polymers, and together they cause light waves to interfere with each other, preventing them from traveling through the film. As a result, virtually all the light is reflected.

Its most common application is here in the backlight of a display. This film takes any misdirected light back and bounces it back toward the viewer. It also plays a key role in recycling light from any brightness enhancing films in the backlight.

When we developed this film more than 20 years ago, this extreme reflectivity was even more remarkable to scientists, because it seemed to contradict a 200-year-old rule of optics called Brewster's Law.

Brewster's Law starts with a beam of light. Like a wave, it is vibrating in two directions, which we call the s- and p-polarizations. Usually, when that light hits the interface between two transparent materials (such as air and water) some of it is reflected and some is transmitted. At each angle of incidence, some light with the s-polarization and some with the p-polarization is reflected, and some is transmitted.

Sir David Brewster, a pioneer of optics who - among his other achievements, invented the kaleidoscope - found that there is one angle of incidence at which only the s-polarization is reflected, and all of the p-polarization is transmitted.

We call this Brewster's angle or...because it effectively polarizes the light...the polarization angle. Because of this effect, the reflection of light off an interface is very dependent on the angle of incidence.

Or so we thought.

The Moment of Discovery

There's a romantic idea about the moment of discovery, when a scientist suddenly realizes something new and amazing. The discovery that our mirror film didn't have an angle of polarization was actually kind of a "eureka" moment/

The scientists who figured out how to make this film were in a long meeting about it. People in long meetings get bored, and they look for other things to do.

One of them rolled the film into a tube and then, for no special reason, he pinched one end of it. The light entered, and rattled around inside until it bounced out. All of it. The end of the roll looked like it was glowing...like it was lit from the inside.

And someone said, “Wait a minute. That shouldn’t be that efficient. It looks like it doesn’t have a Brewster’s angle.”

As the light rattled around in the tube, they expected that eventually some of it would have hit the film at its Brewster’s angle and been transmitted out. Because none of it seemed to do so, they wondered if it was possible that the film didn’t have a Brewster’s angle.

They went back to the textbooks and ran the calculations and it didn’t make sense. Then someone else realized there was a typographical error in the textbook. They went around the lab and found a scientist who is an expert on Fresnel equations, which govern optics.

In about 10 minutes, he derived the correct equation from scratch. He gave the team two hand-written pages that confirmed that, yes, given the indices of refraction of the materials in the many layers of this film, there should be no decrease in reflectivity, regardless of the angle of incidence.

Why did no one expect this?

When Brewster developed his law, people were focused on how light interacts with materials that are isotropic, such as air and water. That means they have the same optical properties in all directions, regardless of the direction that light is traveling or vibrating inside the material. People knew that some crystals weren’t isotropic. They were, instead, anisotropic or birefringent, which means that light in one direction has different properties than light moving in the other direction.

That’s an important exception to Brewster’s Law, but one that people didn’t often think about because they rarely worked with birefringent materials.

However, it turns out that many plastics are birefringent. Plastics are made of long, stringy molecules called polymers. In most plastic objects, including many consumer electronic displays, those long strings are jumbled together like a plate of spaghetti. But if you stretch them, they become aligned in one direction, and you get a material that has different optical properties depending on the direction of the light or its polarization.

Further, when you create a special multilayered stack of these birefringent materials, as we do with our mirror films, there is no angle at which the light is polarized, with one state being reflected and the other transmitted. Because there is no angle of polarization, there is the potential for near-perfect reflectivity. We don’t say it contradicts or eradicates Brewster’s Law, because the equations that underlie Brewster’s Law actually did capture this situation...but no one realized it because these stacks of birefringent materials hadn’t existed until we made them.

You can actually watch the change in properties happen before your eyes when you stretch these films and make them birefringent. We start by extruding many layers of transparent polymers into a single film. Then we stretch it, aligning the polymer molecules, and it turns from a clear film to a perfect mirror.

The mirror film was only the beginning. Once you extend Brewster’s Law to accommodate these new materials and you understand what’s happening, there’s quite a bit more you can do.

By stretching them in the right way, you can create films that reflect only one polarization of light. Unlike Brewster's Law, which says there's one angle where you get that reflection of one polarization, these birefringent multilayered films can be engineered to do this at essentially all angles. This film is called a reflective polarizer.

Consumer electronic displays only use one polarization of light, so about half of the energy delivered to the display can be wasted. A reflective polarizer, such as 3M's Dual Brightness Enhancement Film (3M DBEF) made those early displays at least 50 percent more efficient by reflecting light with the undesired polarization back into the backlight cavity, where it hits this highly reflective mirror film. The mirror film, and other components, convert some of the light to the desired polarization, which is then fed back to the viewer. This process repeats to maximize the amount of light delivered to the display with the desired polarization.

These films are pretty efficient right now, but there's a big payoff for making even tiny improvements. Because they recycle the light over and over, a 1 percent improvement in the film performance is multiplied, and quickly becomes a 2 percent or 5 percent or greater improvement in performance. So our goal today is to continue to refine and improve them with better processing and better materials.

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