Seeing the Light:

Optical Gels and Fluids Support Innovations in Photonics and Microscopy

By Jay Weikel

When reflection and refraction threaten to compromise light-based technologies, index-matching optical gels and fluids can help the light get through.

Index-matching gels were first formulated in the mid-1980s to solve a problem in the telecommunication industry. As networks turned to fiber optics to speed data transmission, fibers often needed to be spliced in the field. Unlike metal wires, splicing strands of glass requires precise cleaving, polishing, alignment, and an electric arc to fuse the strands — a painstaking process that called for extensive technician training and expensive “fusion splicer” gear. A new mechanical splice was invented to skirt the cost and complexity. Cleaved fibers are inserted into either end of the splice. Light travels into the splice on one fiber, jumps the micron-size gap between the fibers in the center of the splice housing to the other fiber, and continues on its way. The problem: reflection in the gap.

Reflection is like an ocean wave passing over a sandbar, where the wave is the light and the sandbar is the air between the fiber ends inside the splice housing. The velocity of the wave suddenly changes when it hits the sandbar, and a small portion of the wave is reflected from the sandbar while the remainder continues onward past the sandbar in the original direction of travel. Inside the splice (*See Figure 1*), the incoming light wave reached the end of the fiber, where the refractive index changed from 1.46, the

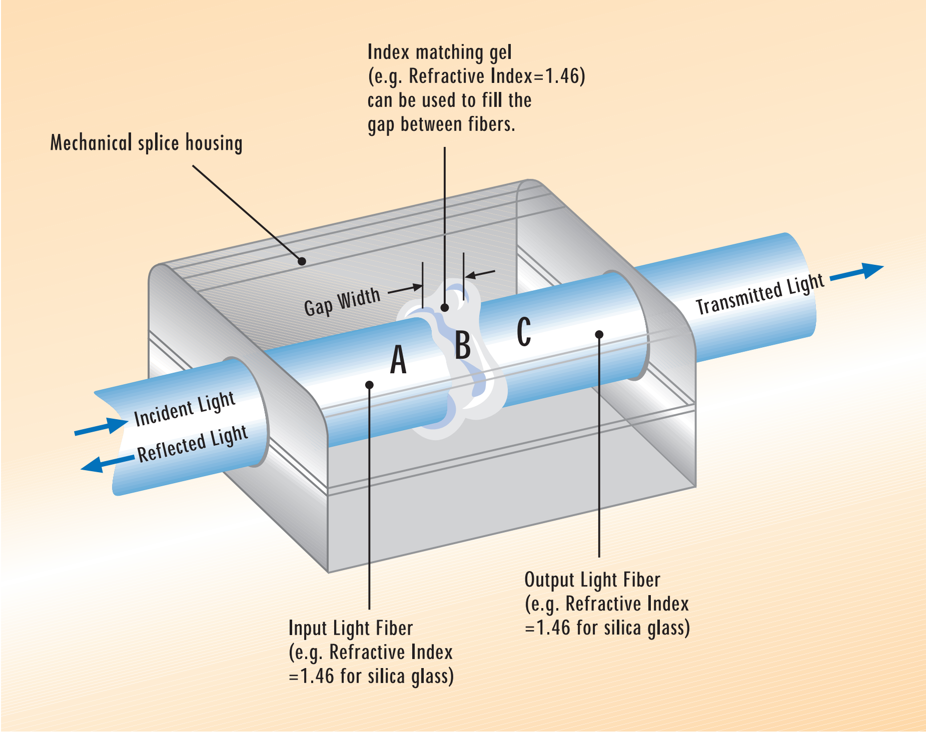

Figure 1: Basic Configuration of a Fiber Optic Mechanical Splice
An incident light wave reaches the gap at the end of the silica fiber (A:B interface). At this point, the index changes from 1.46 to its value in the gap, B. If the gap contains air (index of refraction = 1), a fraction of the light is reflected back to the left while the balance of the light signal continues on through the gap to the right. Here it encounters the second fiber (B:C interface) and undergoes a second reflection. Although there is some “rattling back and forth” of the signals reflected at each fiber endface, when the light signal emerges from the splice at the right hand side, it has suffered a significant net reflection. Since the amount of signal reflected depends on the difference in refractive indices between the gap and the fiber, an index-matching gel in the gap, which “bridges” the refractive indices of the two fibers, is very effective at minimizing reflections.

Courtesy: Video Scope International, Maxicam 3000

The Maxicam 3000 by Video Scope International is a digital intensified CCD camera for use in very low-light imaging. It is used mainly in microscopy, astronomy, and other special scientific and military applications. The camera uses a curing optical gel by Nye Optical Products to couple fiber optic components to maximize light transmission.

refractive index of fused silica glass, to 1, the approximate refractive index of air in the gap. As the light wave moves from the gap into the output fiber, the index of refraction changes back to 1.46. Reflections are introduced at each interface: input to gap and gap to output. For fused silica glass, the typical reflection from an unintended air gap is about 7%, or -11.5 dB reflectance or return loss. In telecommunications, light loss is data loss and industry standards required much lower levels of reflection.

The gap in the splice housing was filled with an optical fluid whose refractive index matched the silica glass. Since the difference in refractive indices determines the amount of signal reflection, displacing air in the gap with an index-matching optical fluid allowed light to flow from one cable to the other with minimal reflection. Fluids, however, are prone to leakage, evaporation, and entrained dust, which can absorb light, so their long-term effectiveness was compromised.

"Non-curing optical gels" developed at Nye replaced the optical fluid. These gels are made by combining optical-quality synthetic fluids with insoluble microscopic powders — precisely formulated to yield a specific index of refraction. Their consistency is similar to petroleum jelly, but similarity to conventional grease ends there. Non-curing optical gels are clear and clean. They are designed for high optical clarity with absorption loss less than 0.0005% per micron of path length in the splice, and they are ultrafiltered so that they contain no particles larger than 34 µm, nor more than 300 particles larger than 1 µm per cubic centimeter — standards originally developed for spacecraft lubricants.

The viscosity of non-curing optical gels is shear-dependent. They have a measurable apparent viscosity but when motion is introduced to the gels, they become more fluid-like. This enables the gel to be pumped into small assemblies. Toothpaste exhibits the same rheological property as it is squeezed from a tube. Once in the splice, when the shear rate is reduced to zero, non-curing optical gels assume the properties of an elastic solid and can stay in place indefinitely. They are chemically stable from -40°C to above 200°C, have an evaporation rate of less that 0.1% (ASTM D-972, 24 hrs. @ 100°C), and have become the industry standard for fiber optic splices (Bellcore GR-2919).

GELS, ADHESIVES, AND EPOXIES

Today, index-matching optical gels are used in a growing number of electro-optic devices, including optical sensors, photodiodes, laser packaging, medical instruments, and flat panel displays. Sometimes they replace more traditional optical adhesives and epoxies. While optical adhesives and epoxies provide excellent dimensional stability, adhesion, and tensile strength, their rigidity can literally be the undoing of an optical device. Optical adhesives and epoxies can trap stresses within an optical assembly. At low stress levels, birefringence can be induced in nearby optical glasses and plastics, degrading performance of polarization-sensitive designs. Over wide temperature ranges or under thermal shock or excessive vibration, adhesives and epoxies can fracture or delaminate from glass or plastic and decrease light output, reduce sensitivity, increase reflection, or even cause catastrophic electronic failure. Under similar operating conditions, optical gels can be a rugged alternative — or a complementary technology. While optical gels cannot assure high dimensional stability, their viscoelasticity can provide strain relief between precision optical parts. When high dimensional stability is mandated, optical gels can be used in concert with the adhesives and epoxies. Gels can provide stress relief, while the adhesives and epoxies provide structural integrity.

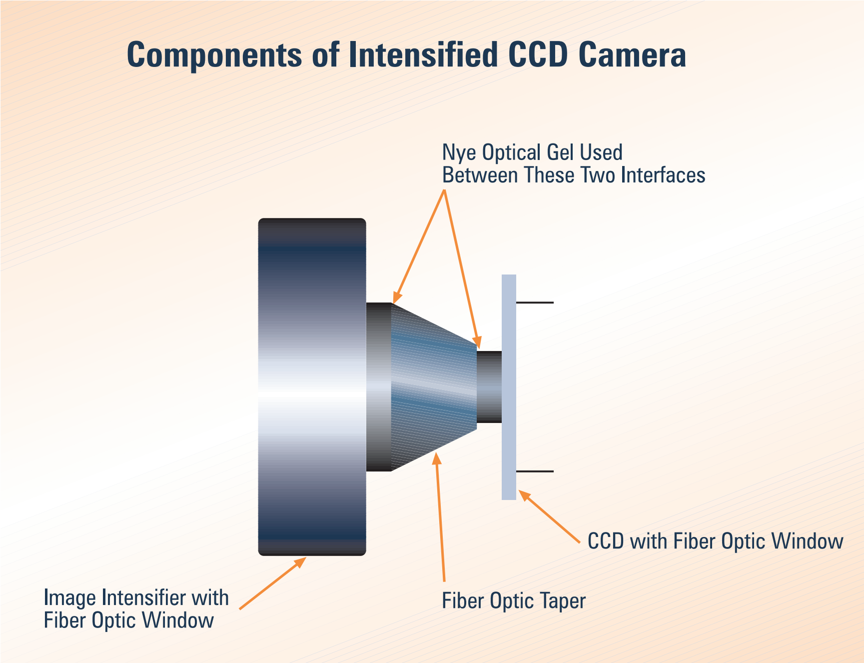

Figure 2: **Non-Curing Optical in Image-Intensified CCD Camera**
By applying a curing optical gel from Nye Optical Products between the taper and the windows on the CCD and image intensifier, Video Scope International eliminates the Newton's Ring effect in its intensified CCD camera.

THE END OF THE RAINBOW

A second type of index-matching gel is called a "curing gel," which consists of an optical fluid and soluble thickening agents. Mixing the two components polymerizes the fluid molecules, which harden and immobilize as a soft cured elastomeric gel. Temperature can affect the rate of cure. Once fully cured, these gels are chemically stable to temperatures in excess of 200°C.

An advantage of curing optical gels is that they wick into tight spaces within small optical assemblies and can be dispensed easily on an automated production line. Prior to cure, curing optical gels have a viscosity of 100 to 1000 cP — about the viscosity of motor oil or about 30 to 40 times less viscous than non-curing optical gels. They can be designed to cure in place in an optical device through exposure to ambient or various elevated temperatures, or by the physical mixing of separate gel components. The degree of hardness can also be varied across a viscoelastic spectrum from a gelatin-like consistency to a hard rubber-like elastomer. Once fully cured, these materials are as mechanically and chemically stable as non-curing optical gels.

Video Scope International, a manufacturer of low-light video systems, uses curing optical gels in its image-intensified, black and white CCD cameras (*See Figure 2*). An image intensifier consists of a light-sensitive electron emitter or Photocathode that forms an electron image; a "microchannel" plate that amplifies the electron image; and a phosphor screen which converts the electron image back to light — about 80,000 times brighter than the incoming image. A fiber optic taper couples the output of the intensifier, which has a fiber optic window, to the fiber optic window of the CCD. Though the window surfaces and taper ends are precision-ground and polished, neither is perfectly flat. The small micron-size ripples on their surfaces are just enough to cause Newton's Rings, a phenomenon in which concentric bands of colored light are seen where two transparent surfaces are not quite in contact. The optical gel, whose index of refraction matches the windows and the taper, fills the tiny gaps, maximizes light transmission, and eliminates the refraction that causes the rainbow.

NIGHT INTO DAY

Curing optical gels are a key component in an innovative medical device to treat Sleep Phase Disorders (SPD), Seasonal Affective Disorder (SAD), and Jet Lag. Each condition is linked to a disruption in circadian rhythm, a natural, 24-hour cycle of bodily processes, including waking and sleeping. Circadian rhythm is controlled by an internal "body clock," the suprachiasmatic nucleus (SCN), a group of cells located in the hypothalamus. Light receptors in the retina have a direct pathway to the SCN, making the light-dark cycle an important regulator for body clocks. When an elderly person experiences ongoing sleep problems due to medications, psychological or physical conditions (SPD); or persons with SAD suffer bouts of depressions as days shorten during winter months; or when a jet traveler takes days to recover after crossing many time zones, the cause — and cure — are related to light and circadian rhythms.

To date, the most common light-related therapy for these disorders has been a light box with full-spectrum fluorescent bulbs that simulate sunlight. The downside to light box therapy is lack of patient mobility. The light box has to be plugged in and the patient needs to sit in front of it — sometimes for hours. Enlightened Technologies Associates addresses this drawback with Somnavue™, a unique pair of prescription eye glasses that gives patients with SPD and SAD light-to-go.

Each pair of glasses has 12 acrylic fibers cut at 45° angles and coated with a reflective material. Six fibers are strategically embedded about 60° apart into each polycarbonate lens. The other end of each fiber is connected to a light-emitting diode (LED) in the frame. Light travels from the LEDs to the lenses and floods the photoreceptors in the retina without interfering with acute vision. Patients get plenty of therapeutic light, but can read, use a computer, watch TV — generally follow their normal routine.

The LEDs are wired to a small, hand-held, battery-powered control box that gives patients complete mobility. It has a built-in microprocessor that displays elapsed therapy time and sets off an alarm when therapy should start and stop. In the near future ETA forecasts that jet travelers who cross time zones and datelines will enter their itineraries into the Somnavue™ control box, which will automatically deliver the doses of light they need to keep their circadian rhythms in sync with destination time zones — and virtually eliminate Jet Lag.

ETA uses a curing optical gel at the fiber-to-lens interface to minimize refraction and reflection. When coupling similar materials, the index of refraction of the optical gel is the same as the index of refraction of the material. When coupling dissimilar materials, the geometric mean determines the index of refraction of the optical gel. In the Somnavue™ glasses the refractive index of the lens is 1.6 and the fiber is 1.49, making an optical gel with a refractive index of about 1.5 the best match. The curing gel fills in micron-size irregularities on the surface of the materials, holds the fibers in place, and minimizes reflection and refraction. An index-matching gel that couples the fiber to the LED also helps to maximize light transmission.

Courtesy of Enlightened Technology Associates, Inc.

Somnavue™, a personal light therapy system from Enlightened Technologies Associates, directs light through fiber optic elements to the wearer's eyes to treat sleep disorders, seasonal affective disorder, and Jet Lag. It uses a curing optical gel by Nye Optical Products at the fiber/lens interface.

OPTICAL FLUID HITS THE SPOT

Optical fluids have long been used in microscopy as immersion oils. They are typically applied between the objective lens and a specimen to get better image quality. Recently, a scientist at Intel used a high-refractive-index optical fluid to achieve a laser spot size of 0.5 µm inside a silicon integrated circuit (IC) — not with visible light but with an infrared laser imaging through the silicon substrate. Flip-chip technology set the stage for this innovation in optical probing.

Flip-chip technology is an advancement in the miniaturization of IC packaging. Flip-chips use an array of solder bumps across the active area of the die, which eliminates the inactive perimeter of wire-bond pads common to socketed CPUs. The die is "flipped over" and bonded to a grid of solder pads on the carrier. With all wiring in intimate contact with the carrier, probing the internal circuitry of the chip became a challenge. However, if the silicon is thinned to less than 150 µm, it becomes partially transparent to infrared light. Using this knowledge, the Probe Systems Group at Schlumberger Technologies built the first "back-side" optical probing system.

Schlumberger's IDS 2500, which is used at Intel and many other semiconductor device manufacturers, relies on infrared lasers to "see through" the silicon and measure waveforms on device transistors inside operating flip-chip ICs.

Though Schlumberger's see-through probing technology is less than five years old, it is already feeling the pressure of Moore's Law, the prediction that the number of transistors per integrated circuit would double every 18 months. In a paper presented in November 2001 at the 27th International Symposium for Testing and Failure Analysis, Intel's Travis Eiles summarized the problem and the solution. The IDS 2500 has been critical in the analysis of Intel microprocessors since the introduction of 0.25 µm process technology. The current IDS 2500 objective lens yields a spot size of approximately 0.76 µm and performs well when probing transistor drains fabricated in the 0.18 µm generation, where the distance between the gate edges in a stacked transistor device is approximately 0.5 µm long, about the length of a bacterium. The 0.76 µm spot overlaps the distance between the gate edges but differentiates transistors well. However with 0.13 µm process technology arriving and 0.09 µm not far behind, the problem is how to extend the life of the optical probing system without specially designed-in probe points. Eiles' solution is a liquid immersion lens that uses a high-refractive index optical fluid.

It's all about resolution. In general, resolution can be improved by shortening the wavelength of the light or by increasing the numerical aperture of the objective. Using a shorter wavelength, as in a lithography system, to get a smaller spot size isn't an option with the IDS 2500. Shorter wavelengths won't work with silicon because IR light, with a wavelength near 1.06 micrometers, is the only light that can penetrate highly doped silicon. Move toward the visible range and light will be absorbed. That leaves increasing the numerical aperture (NA) of the objective lens as the only option.

NA is a number that expresses the ability of a lens to resolve fine details. It is defined by the formula: NA = n sin q, where n is the index of refraction and q is one half of the angular aperture of the lens. Since q for the objective lens currently used in the IDS 2500 is already optimized, the greatest benefit is gained by increasing the refractive index of the medium through which the light travels. Eiles spearheaded the development of a new liquid immersion lens which uses an optical fluid with a refractive index of 1.6, the highest index available for a non-toxic fluid. The old objective lens has an 0.85 NA. The new liquid immersion objective lens has a 1.3 NA. Because of the optical fluid, refraction is decreased, rays are more readily focused, and the objective achieves a 0.5 µm spot size and resolution, that is, two objects 0.5 µm apart can be clearly distinguished — a 33% improvement. Eiles reports the new immersion lens greatly improves images of transistors on a 0.13µm chip and will very likely continue to deliver good flip-chip probing results even on 0.09 µm technology. Intel has licensed the new lens to Schlumberger, which is now offering an immersion-lens version of the IDS 2500. ■

Courtesy: Schlumberger Probe Systems, San Jose, CA

The Schlumberger IDS 2500 uses a focused infrared laser to probe through the back side of an active flip-chip IC and measure waveforms on the device transistors with a 10 GHz bandwith. With a new lens designed to work with the IC immersed in a high-refractive-index (1.6) optical fluid by Nye Optical Products, the system achieves a spot size of 0.5 µm, making it suitable for 0.13 µm and even 0.9 µm technologies.