Optical Gels for Fiber-Optic Connectors and Splices – *A Tutorial*

The world's leading suppliers of fiber optic splices and connectors are using a new class of synthetic index-matching gels to simplify designs, lower costs, and improve ruggedness and reliability.

What Lucent, 3M, and other suppliers have discovered is that the secret to using index-matching gels is in the design of the gel itself. These are NOT the oil-bleedy, hazy, yellowing, petroleum-jelly-like buffer or temporary test jack gels. These optical gels are worthy of telecommunications hardware. They offer zero oil bleed, crystal clarity, wide-temperature serviceability, a 30-year service life — and cost and reliability benefits designers work hard to achieve.

This tutorial reviews optical gels, their parameters, the interconnect problems they address, and how some of the biggest names in the lightwave business are incorporating the new optical gel technology into their products.

A GEL PRIMER

Reflections in optical interconnects can be reduced in two ways: through "zero gap" design and "index-matching" gels. Zero-gap design requires precision mechanical mating of optical parts, typically achieved with a fusion splice or dry mechanical connector, "dry" meaning without an optical gel.

On the other hand, instead of closing the gap between the mating fibers the index-matching approach fills the gap with an optical gel that serves as a "light bridge" across the gap. The gel reduces the need for stringent mechanical tolerances on cleaving and polishing, expensive fusion equipment, and extensive technician training — which makes the index-matching approach a pragmatic alternative to zero-gap design.

To understand how an index-matching gel minimizes the reflection of light at the connection, consider the basic geometry of a fiber optic interconnect (See Figure 1). An incident light wave enters a splice or connector and encounters the end of the input light fiber, often fused silica glass, which has a refractive index of 1.46. At this point the index of refraction

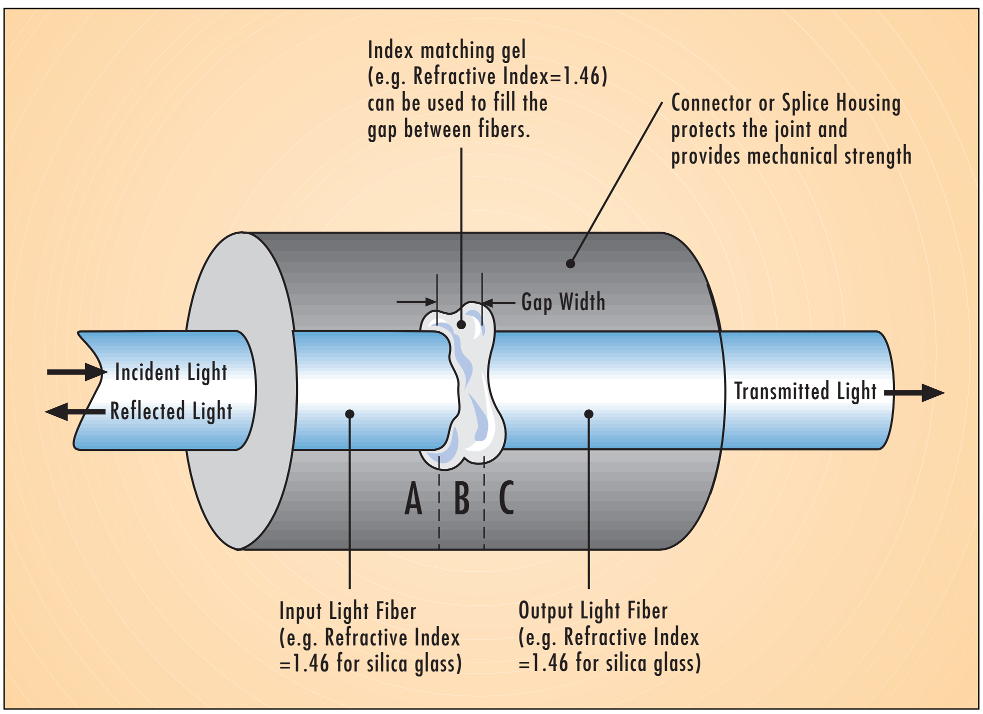

Figure 1 – Basic Configuration of a Fiber Optic Interconnect

A light wave, incident from the left, encounters the gap at the end of the input 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, the end result is that when the light signal emerges from the interconnect 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.

changes from 1.46 to the value of the air in the gap between light guides. A good estimate of air's index of refraction is 1, because the index of refraction of a vacuum is exactly 1 and the speed of light in air is very close to its speed in a vacuum.

As the wave moves from the gap into the output light guide, the index changes again. Reflections are introduced at each interface: input to gap and gap to output. The effect is analogous to an ocean wave as it passes over a shallow but hidden sand bar; the "sandbar" here is the air in the gap. The velocity of the wave is suddenly changed 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. For fused silica glass commonly used in fiber optic links, the typical reflection from an unintended large air gap is about 7%, or -11.5 dB reflectance or return loss. Industry standards require much lower levels of reflection on telecommunications interconnects. That's where optical gels go to work.

The refractive index of an optical gel is engineered to match the refractive index of the fiber (or lenses or other transparent materials in electro-optical devices) — virtually eliminating the large differential optical impedance between air in the gap and the signal carrying lightguides. Signal reflection is minimized.

Epoxies, Too Hard; Fluids, Too Runny; Gels, Just Right. Index-matching materials come in three forms: epoxies, fluids, and gels — and gels are best suited for interconnects.

While an epoxy has high strength, its rigidity does not allow the different materials in an interconnect, each with differing coefficients of thermal expansion, to expand and contract during temperature cycling. Thermally induced stress can be so high that the weak point in the interconnect can eventually become fatigued and fracture or delaminate — in effect inserting a large air gap smack in the middle of the interconnect assembly.

At the other extreme, an index-matching fluid has infinite ability to yield to any applied stress, but it can wick out of the assembly if it is not sealed tightly with o-rings or gaskets. Mechanical complexity must be added back into the interconnect design to provide a long-lived, reliable fluid reservoir. In addition, a fluid can entrain dust particles which, over time, could migrate into and block the lightwave path.

Gels overcome each of these drawbacks. Optical gels are viscoelastic, so they accommodate the expansion and contraction of interconnect materials. In extreme environments, this viscoelasticity actually improves splice and connector reliability by protecting sensitive optics.

Compared to fluids, gels have an important stay-in-place characteristic. Not subject to flow, gels also immobilize dust particles so they will not eventually move into and block the lightwave path. As Bellcore research (Bellcore GR-2919, ref. 5, O4-102, para. 4.10) confirms, the reliability and cost advantages of index-matching materials in fiber optic interconnects are best realized with a "material with yield stress" — in short, an optical gel.

Two categories to choose from. Gels can be engineered in two forms: non-curing and curing. Non-curing gels are comprised of two major functional components: an optical fluid and an optical thickener, comprised of clear microscopic particles. While the consistency of non-curing gels can be reminiscent of petroleum jelly, their similarity to conventional grease ends there. Non-curing optical gels are manufactured via methods developed for synthetic precision greases used in spacecraft gyros and computer disk drive bearings. Consequently, they are both 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. Ultrafiltered to standards first developed for precision spacecraft lubricants, they contain no particles larger than 34 microns and have no more than 300 particles per cubic centimeter of any size above 1 micron.

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Non-curing gels are "non-Newtonian." They're not true fluids. While they have an apparent viscosity, which can be measured, their viscosity is shear-dependent, that is, as motion is introduced to the gel, its viscosity decreases. As the gel is forced through the dispensing needle of a syringe, for example, it is subjected to high shear, becomes more fluid-like, and can flow. This behavior allows the gel to be pumped into small assemblies. Toothpaste exhibits the same rheological property as it is squeezed from a tube. Once in the interconnect, when the shear rate is reduced to zero, the non-curing optical gel assumes the properties of an elastic solid and can stay in place indefinitely.

Non-curing gels offer several advantages. They are ready to use, they have no intrinsic limit to shelf life, and they do not cure or harden due to chemical reactions. While non-curing gels will shear-thin when dispensed, they still require higher dispensing pressures and flow at a significantly slower rate than curing gels in an uncured state.

Curing gels have two constituents: an optical fluid and "thickening agents." Mixing the components polymerizes the fluid molecules, hardening and immobilizing the gel. Depending on the formulation, the degree of hardness can be varied across a viscoelastic spectrum, from a Jello®-like consistency to a hard rubber-like elastomer. Once fully cured, these materials are as mechanically and chemically stable as the non-curing gels.

Gelled mechanical splices win on ease-of-assembly

Curing gels can be premolded and cured into shapes like washers, gaskets, or spacers. They can also be designed to cure in place in the optical device — through exposure to ambient atmosphere, exposure to elevated temperature, or by the physical mixing of separate gel components.

One advantage of curing gels is that they flow more easily than non-curing gels into very tight spaces. Prior to cure, their viscosity is similar to motor oil, or about three to four orders of magnitude less viscous than non-curing gels. A cured gel is also more elastic than a non-curing gel — a plus in re-matable connections where the spring-back of the gel allows the connection to re-seat more easily on successive cycles.

Several precautions must be observed with curing gels. These gels are chemically active until they have cured, which limits their shelf life in an uncured state to about six months. Until cured, storage temperatures should comply with the manufacturer's guidelines: in some cases room temperature storage is adequate, in other cases refrigeration of the product is recommended. Time and temperature curing guidelines, designed into the gel by the manufacturer, must be followed precisely. Additionally, the rate of cure can be affected by ambient temperature, the presence of reactive trace chemicals or incompatible plastics or elastomers, which could poison the cure rate, and the mixing ratio of the chemically reactive components.

GELS IN SPLICES AND CONNECTORS

For the purpose of this discussion, the world of optical interconnects can be roughly divided into two parts: splices and connectors. Splices are permanent; connectors are non-permanent and re-matable. Within each category, some optical interconnect applications are better suited to the use of gels.

Splices are expected to provide a clear pathway for the lightwave, assuring less attenuation and reflection than re-matable connectors. Currently, the most popular is the fusion splice, where the opposing ends of fiber are carefully cleaved, polished, and literally welded together in a high temperature electric arc. When executed properly by trained technicians with properly serviced — and expensive — tools, a fusion splice is the ultimate zero-gap method for eliminating reflections, especially in a benign, inside-plant environment. However, fusion splices can suffer from embrittlement and eventual failure from rough handling, shock, vibration, or temperature cycling.

Another approach to the permanent mating of optical fibers is the mechanical splice, with or without an optical gel. Both can be assembled without expensive tools. A dry mechanical splice must still be designed to form a zero gap, a constraint which demands tight and costly engineering tolerances, not only on the parts but also on the cleaving, polishing, and splicing operations as well. A mechanical splice with an optical gel is often a better solution. When vibration, thermal expansion, or mechanical shock cause the fibers and structural parts of a connector to move, large stresses can be induced in the fibers. In a dry connector, if microscopic fiber motion is constrained under high stress, the fiber can fracture. Alternatively, if the design allows excessive motion, then the fiber-to-fiber air gap may become enlarged. An optical gel in the gap trumps this unhappy tradeoff. Since gels are viscoelastic, they can take up mechanical tolerance "stack-up" in other parts, and relieve stresses by expanding or contracting without delaminating at the fiber endfaces and breaking the lightpath. Gelled mechanical splices win on cost, complexity, ease of assembly, and, in severe environments, the mechanical pliability and sealant qualities of a gel help ensure reliable, long-life service.

Connectors, available in many standard formats, are the other half of the interconnect world. In fact, they are proliferating, and the hunt is now on for lower cost, reliable, easy-to-use connectors for "last mile" infrastructure (See "Fiber-optic Interconnect Sales Exceed $1.1 Billion in 1997," by K. Fleck,

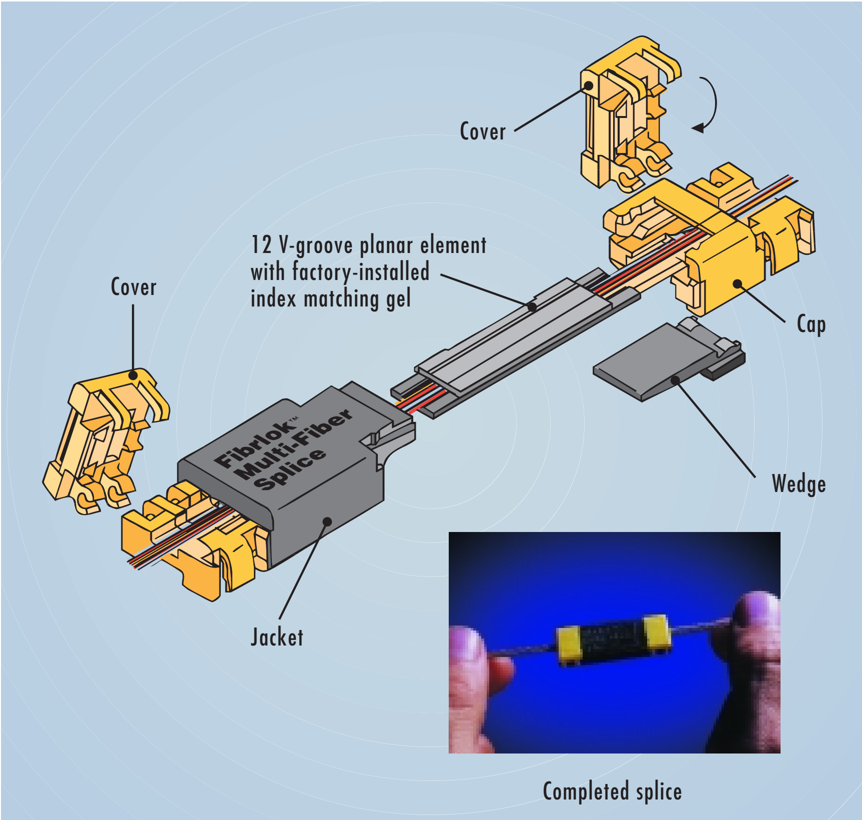

Figure 2 – Illustration of 3M's FibrlokTM Splice
After preparation, the fibers are inserted into the splice element. A tool is used to actuate the splice by moving a wedge component which forces the clamping and locating surfaces against the fibers and aligns the fibers precisely and permanently in place. The optical gel contained in the planar element completes the optical interconnection.

Lightwave, June 1998). While most connectors today are dry, i.e., do not use optical gels, development work is underway to bring the cost benefits of optical gels to connectors by designing connectors that are re-matable for some limited but adequate number of connect/disconnect cycles. A replaceable gel cartridge is one approach . A soft, "self-healing" curing gel is another. The distinction between a connector and a splice can be blurry; for example, there are mechanical splices on the market which use non-curing gels and allow up to 25 mate-remate cycles without performance degradation.

Gel connectors promise many of the advantages over dry connectors that gel splices have over dry mechanical or fusion splices, namely lower cost, ease-of-assembly, reliability, and ruggedness. While they may likely have fewer re-mate cycles than dry connectors, gel connectors may excel in reflection performance because they ensure intimate mechanical contact particularly after many re-mate cycles, when wear-out may alter critical dimensions and degrade the performance of a dry connector.

Today, the bar is being raised on reflection performance for connector and splice technology. As networks move toward Dense Wave Division Multiplexing (DWDM) to maximize use of fiber bandwidth, they are becoming more vulnerable to reflections from dry mechanical connector technology. Lower reflection is a performance advantage that optical gels can bring to connector and splice design for DWDM systems.

BRINGING THE GELS TO MARKET

3M, Lucent Technologies, and other manufacturers have seen the light about the advantages of optical gels in splices and connectors.

3M's splice of the pie. The FibrlokTM Optical Splicing System is a series of splice products designed for single mode and multimode fiber by 3M, Inc., of Austin, Texas (A multifiber version is shown in Figure 2). FibrlokTM splices incorporate a non-curing, index-matching optical gel with a refractive index compatible with fused silica.

3M's gel is also designed for exceptional thermo-oxidative stability, which ensures no yellowing, haziness, or decomposition. It is also designed for long-term stability under exposure to extreme environmental temperature and moisture conditions; zero oil bleed or migration; zero dry-out or evaporation; non-toxicity; and a refractive index temperature coefficient that is well-behaved over the service temperature range. A 3M Technical Report cites that insertion losses for these "gel splices" average < 0.1 dB. It also confirms exceptional thermal stability over the temperature range of -40°C (-40°F) to +80°C (+176°F).

Mechanically, 3M's use of an optical gel allows a less complex — and less expensive — splice design than would be required for an equivalent dry mechanical splice. Further, compared to fusion splices, Fibrlok splices offer significant savings during installation. The FibrlokTM installation tools are inexpensive and easy to use, allowing a better equipped workforce and reducing the training required for installers and contractors from days to hours, compared to dry mechanical splices or fusion splices.

FibrlokTM splice designs have been qualified for such environmentally severe locations as buried, underground, aerial, vault, and pedestal splice locations, as well as more benign inside-plant installations. A spectacular, though unintended, demonstration of the FibrlokTM System's ruggedness occurred during the 1993 floods in St. Louis, Missouri. A controlled environmental vault containing 144 fibers joined with FibrlokTM splices was flooded under 15 feet of contaminated water, silt, raw sewage, and jet engine fuel for more than 30 days. All 144 fibers delivered uninterrupted service throughout this period.

More recently, 3M has leveraged the ruggedness of these designs in another direction — re-matability. 3M's testing shows no degradation in performance after 25 mate/re-mate cycles, allowing this class of splice to compete directly with more expensive fiber optic connectors.

Gordon Wiegand, Senior Product Development Engineer at 3M, said, "The best thing about the FibrlokTM splice is how well it works and how easy it is to use. You don't have to worry if your fiber is cleaved to within hair-splitting tolerances, you get great optical performance under the most severe conditions — and it will last practically forever."

Cleave, sleeve, and leave — from Lucent. An index-matching gel is also a key component in the CSL LightSplice manufactured by Lucent Technologies in Norcross, Georgia. Short for cleave, sleeve, and leave, CSL was originally designed for convenient field use for AT&T. It can accommodate all combinations of 250 µm coated fiber and 900 µm buffered single mode and multimode fiber (A single fiber version is shown in Figure 3).

Lucent specifies a non-curing index-matching gel for its CSL splice. The gel's index of refraction is tightly controlled at 1.46. Lucent engineers chose a gel viscosity of 800,000 cP to enhance the flow of the gel within the glass capillary tube at the moment that the two fibers are mated. Another key requirement of the Lucent gel is low volatility and low out-gassing. In any splice design, if the gel has excessive out-gassing, micro-bubbles may evolve during exposure to high temperature. If a bubble becomes trapped in the fiber interface, the index-matching condition is destroyed and dramatic increases in reflection and insertion loss can occur. Other CSL gel features include long term stability of the optical properties over temperature extremes and batch-to-batch repeatability of material properties. Lucent reports a low average return loss of < 50 dB, and an oper-

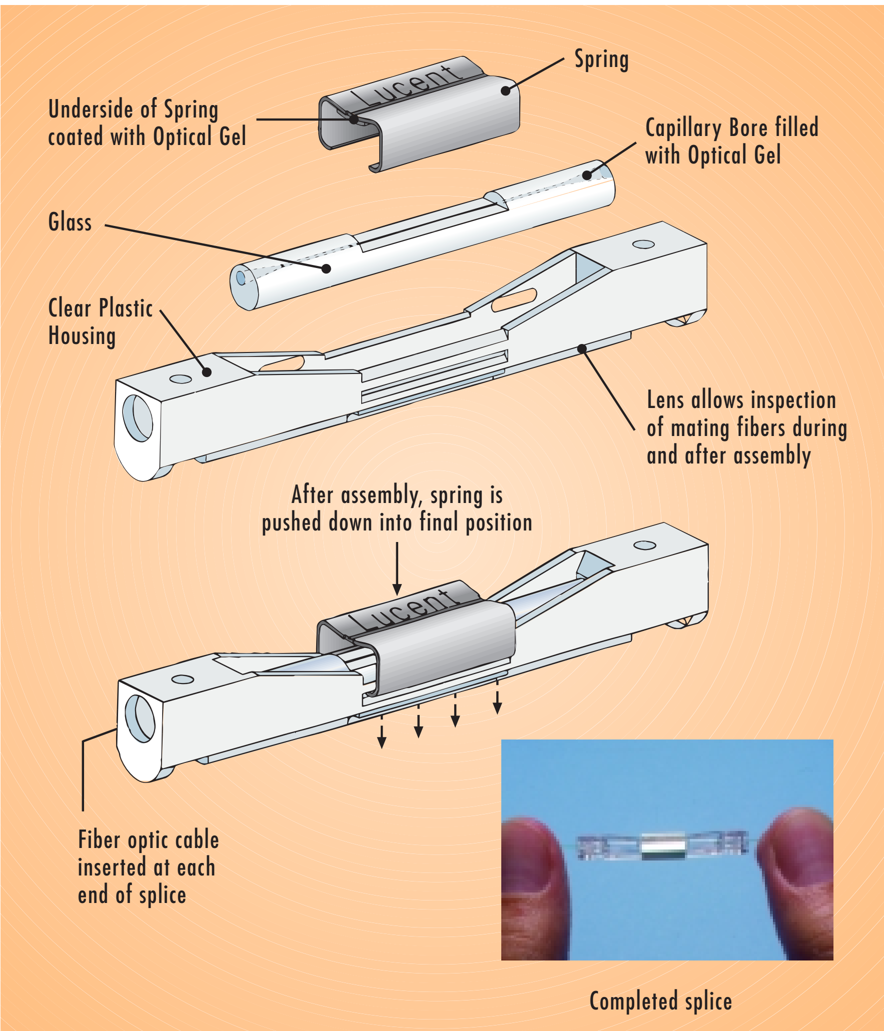

Figure 3 – Illustration of Lucent's CSL LightSplice
CSL has three parts: an injection molded clear plastic housing, a glass capillary rod which contains the index-matching gel, and a spring which provides mechanical clamping action. At the factory, the spring is preset in the open position. The stripped and cleaved fibers are inserted through the housing and into the funnel shaped ends of the capillary so that they meet in the center of the capillary. As they are pushed together, the ends of the mating fibers force the index-matching gel to fill the void between the cleaved fiber endfaces. Proper mating of the fibers can be confirmed by viewing the joint through a lens that is designed into the underside of the housing. The installer completes the splice by pushing the spring into the closed position, clamping the fibers in place.

ating temperature range of -40°C (-40°F) to +85°C (+185°F) for the CSL splice.

Lucent recommends the CSL splice for use in any environment: outside plant, premises distribution, private and local area networks, and original equipment manufacturer (OEM) applications. It can be installed in two minutes, with minimal installer training. In one set of training trials, inexperienced splicing crews were shown a six-minute training video. They were then asked to make several splices and were given two spools of fiber and an optical time delay reflectometer (OTDR) to measure splice losses. For the 120 individual splices made in this trial, splice insertion loss averaged only 0.18 dB, leading the splicing crews to consider the trial a tremendous success.

Fred Culvern, Business Manager for Fiber Optic Splicing and Closure Systems at Lucent, said, “The CSL LightSplice’s popularity comes from its reliability and cost effective ease-of-use. Optical gel technology helps make those features possible.”

DESIGNING YOUR OWN GEL

3M and Lucent have found that one secret to quality interconnect designs is to customize the optical gel. Gels can be engineered to have a range of characteristics. For example, the index of refraction can be specified to marry lightguide materials with higher value indices than those of fused silica; one such example is the joining of high quality plastic optical fiber (POF) in automotive and other short distance local area network (LAN) applications. In telecommunication electro-optics devices like transceivers, the gel index can be chosen to step the index between the mating fiber and the emitting laser source for optimum efficiency. A whole range of mechanical properties can also be built into a gel. Gels should also be specified for certain critical characteristics like low evaporation rate in order to ensure long and reliable service life. Table 1 provides a summary of properties most commonly specified for optical gels. ■

SPECIFYING YOUR OWN OPTICAL GEL

Gel Properties	Specification Guidlines
Index of Refraction	The ideal gel index is the index of the mating fibers. If the gel is used between two dissimilar materials, the ideal gel index is equal to the geometric mean of the indices of the two materials.
Apparent Viscosity (non-curing gels only)	Gel apparent viscosity is usually around 1,000,000 cP, the consistency of soft putty. Higher viscosity improves resistance to mechanical shock; lower viscosity allows more rapid flow during manufacture or assembly in the field.
Hardness (curing gels only)	Specify from “Jello-like” to “hard rubber”, for optimal strain relief or spring-back in the device.
Set Time (curing gels only)	Specify from minutes to hours. Set time is strongly dependent on ambient temperature during cure.
Temperature Service Range	Specify from below -65C (-85F) to +250C (+482F).
Evaporation Rate	Often overlooked as a critical specification, a low evaporation rate prevents micro-bubble formation and “dry-out” which might not become apparent in the field until months or years of service.
Thermo-oxidative Stability	Another oft-overlooked parameter, gel thermo-oxidative stability implies resistance to yellowing, hardening, or “going to soup” due to chemical changes over time. Stability is dependent on maximum service temperature and presence of moisture, corrosive gases, etc.
Cleanliness	Specify maximum microscopic particle count < 300 particles/cc for particles 1 to 34 microns in size with no particles > 34 microns in size. Clarity Specify minimum optical absorption, measured in % absorption per micron path length. This ensures negligible lightwave signal loss through the gel.
Material Compatibility	Ensure that base fluids and thickeners in the gel are compatible with plastics, elastomers, coatings, and adhesives specified in the design.

All of these properties can be specified for custom-designed optical gels to optimize both optical and mechanical performance and to ensure ruggedness and long-service life. Some properties can be traded off against others.