"The Mid-IR Fibers and Devices Company"

FREQUENT ASKED QUESTIONS

Why chalcogenide glass fiber?

Chalcogenide glasses are made from mixture of the chalcogen elements: sulfur (S), selenium (Se), and tellurium (Te). The addition of other elements, such as arsenic, germanium, and antimony establish crosslinking between the chains of chalcogens to facilitate stable glass formation. It offers promising properties, such as transmission in the mid and far infrared, low phonon energies, high refractive index, and very large nonlinearities as compared to silica glasses.

Chalcogenide glasses are thermally stable, chemically durable, mechanically flexible, and easily fiberized. The spectral range of infrared transmission of chalcogenide glass fiber (1-12μm) is much broader than that of silica glass fiber (UV-2μm). Chalcogenide glass fibers have very high refractive index and very large nonlinearities (1,000 times that of silica fiber), allowing for the development of super continuum in the mid-infrared. Chalcogenide glass fibers are the ideal candidates for mid-infrared applications that require high-power laser delivery, chemical sensing, thermal imaging, and temperature monitoring.

Arsenic-containing chalcogenide glasses, such as arsenic sulfide (As_2S_3) and arsenic selenide (As_2Se_3), have excellent chemical and physical properties for active optical devices. The minimum optical loss in As_2S_3 and As_2Se_3 are 0.1dB/m between 2 and 10μm. Among any infrared optical material in use today (silica, fluoride, germanium, zinc selenide, and zinc sulfide), As_2S_3 glass has the lowest thermal change in refractive index. For this reason, lenses or windows made from As_2S_3 glass do not show optical distortion when subjected to the intense IR radiation from lasers such as YAG, ER/YAG or CO. The low thermal change in refractive index is thought to be the basis for the fact that 700 μm fibers made from As_2S_3 glass have been reported to transmit more than 100 W of laser energy from a CO laser emitting at 5.4 μm. In short, arsenic-containing chalcogenide, glasses are the most-used material for infrared optical fibers.

Comparison for As_2S_3 and As_2Se3 chalcogenide glass fibers, silica fiber and fluoride fiber

Composition	As_2S_3	As_2Se_3	SiO_2	Fluoride
Density (g/cm^3)	3.2	4.62	2.2	4.33
Coefficient of Thermal Expansion (10^{-6}/ºC)	24	21	0.55	17.2
Refractive Index (wavelength)	2.395 (3 μm)	2.8275 (3 μm)	1.455 (0.7 μm)	1.499 (0.589 μm)
ΔN/ΔT@10 μm (10^{-6} /ºC)	<1	~30	12	-15
Transmission Range (μm)	1-6	1-10	0.24-2	0.25-4
Optical Loss (dB/m) (Wavelength)	≈ 0.1-0.2 (3 μm)	0.5 (4.55 μm)	800 (3 μm)	0.05 (3 μm)
Glass Transition Temperature (ºC)	185	170	1120	265

Are chalcogenide glass fibers safe to use?

Chalcogenide glasses are very stable. According to the best of our knowledge, using chalcogenide fibers below 100°C is safe for handling, storage, and transportation. Above approximately 100 ºC, it is recommended to work under fume hood environment. Chalcogenide glass fibers have high stability to atmospheric moisture and do not crystallize. The Safety Data Sheet describes chalcogenide glass as nonhazardous and not absorbable through the skin. For medical applications, there is no data for chalcogenide glass fibers used in vivo. Related Material Safety Data Sheets for the chalcogenide glasses can be found at IRflex Corporation's website: www.irflex.com.

What about the chemical resistance of chalcogenide glass?

Chalcogenide glasses are insoluble in water, concentrated hydrochloric acid, non-oxidizing acids, alcohol, acetone, gasoline, and toluene. They are soluble in strong alkaline solutions, such as KOH.

Is chalcogenide glass like fluoride fiber?

Chalcogenide fiber transmits to longer wavelengths (up to 10μm) compared to Fluoride fiber (<5μm). Chalcogenide glass is insoluble in water, concentrated hydrochloric acid, non-oxidizing acids, alcohol, acetone, gasoline, and toluene, so it has higher chemical durability than that of ZBLAN glass (the most common fluoride glass). Fluoride fiber is hygroscopic so it needs to be protected from attack by moisture, especially in high-power laser applications.

Do chalcogenide glass fibers have the same mechanical strength as silica glass fiber?

No. Chalcogenide glass fibers are softer glass fibers than silica glass (SiO_2) fibers used in telecommunications, which are essentially pure silicon dioxide, and possess 10 times the tensile strength. Therefore, special attention and different methods should be applied in handing chalcogenide glass fiber.

Are chalcogenide glass fibers polarization maintaining?

In fiber optics, polarization-maintaining optical fiber (PMF or PM fiber) is a single-mode optical fiber in which linearly polarized light, if properly launched into the fiber, maintains a linear polarization during propagation, exiting the fiber in a specific linear polarization state; there is little or no cross-coupling of optical power between the two polarization modes. Such fiber is used in special applications where preserving polarization is essential.

IRflex's chalcogenide glass fibers themselves are not polarization maintaining design. But it is possible to use the commercial available polarization controllers to adjust the fiber to polarization state. One of the examples is to use Thorlabs's FPC560-Fiber Polarization Controller with our singlemode fibers. In any case, we suggest trying with the large diameter paddles (>2").

Coating used on IRflex's commercial available fibers and its temperature range?

Coating is the protective layer applied directly to the glass during the fiber draw process. The standard silica fiber uses dual urethane acrylate coatings made up of 2 layers. The softer, inner layer cushions the fiber during bending and allows for ease of stripping, and the outer layer is a higher modulus for protection from abrasion.

In some applications, when exceptional adhesion to the fiber or smaller form factor is required, an outer single acrylate layer is used alone. We use standard telecom fiber coating. As our initial design requirement for the application, IRflex's chalcogenide glass fibers are coated with a single layer of acrylate. The temperature range for this acrylate is -40 to +85 ºC. For example: coating on our IRF-S-5, IRF-S-7, IRF-S-9, IRF-S-10, IRF-S-50/85 and IRF-S-100.

Some of our fibers are offered with other kinds of acrylate coating choices to enable premium fiber performance for client's special applications, where the operation temperature can withstand -20 º C to +130 ºC and the supplier also claims that the coating can withstand -40 º C to 200 º C for a brief period. For example: coating on our IRF-S-6.5, IRF-S-200, IRF-Se-100, IRF-Se-100(R&), IRF-Se-150 and IRF-Se-300.

What to use to remove coating?

The chalcogenide fibers supplied by IRflex are currently equipped with a standard single layer of acrylate coating. The fibers can be stripped chemically using a suitable solvent. The less aggressive and safer way is to soak the fiber end to be stripped, submerging only the length of fiber that will be stripped, in dichloromethane (CH_2Cl_2) (commonly known as methylene chloride) liquid to soften the acrylate jacket.

Prior to using dichloromethane, please follow manufacturers' guidelines for safe handling and storage of this solvent, read the Material Safety Data Sheet (MSDS) carefully. Avoid contact with skin and use only with adequate ventilation.

The dichloromethane causes the coating to swell after approximately 30 to 60 seconds in the solution. Once the coating swells and stretches out, using a razor blade gently score the swollen coating without touching the fiber. Gently pulling on the swollen coating propagates the cut and removes the coating from the fiber.

However, the coating cannot be removed by using mechanical strippers as for telecom silica fibers.

What to use to cleave chalcogenide glass fibers?

Fiber optic cleavers **with adjustable tension** produce the best cleaves on chalcogenide glass fibers. **Lower tensions are required** for chalcogenide glass fibers than what it typically used for silica fibers.

Laser induced damage threshold of chalcogenide glass fibers?

By definition, power density is power per unit area, which is usually expressed in terms of W/cm^2.

The amount of power our chalcogenide glass fibers can carry depends on the fiber's diameter and the laser induced damage threshold. The effective damage threshold can be affected by several factors: inclusions in the glass, cleave quality, surface cleanliness and wavelength of laser used. The theoretical laser induced damage threshold (LIDT) of the chalcogenide glass fibers have been calculated as $3GW/cm^2$ for a 10 nanoseconds pulse. In the case of continuous wave power, the fibers have been tested up to $11.8MW/cm^2$ without damage.

What is the minimum bend radius for optical fibers and cables?

Beside mechanical destruction, another reason why one should avoid excessive bending of optical fibers and cables is to minimize microbending and macrobending losses. If no minimum bend radius is specified, one is usually safe in assuming a minimum long-term low-stress radius not less than **15 times** the cable diameter or **200 times** bare fiber outer (cladding) diameter.

Can your singlemode fiber get singlemode below its cutoff?

In general, close to the cut-off (in the few-mode / multi-mode regime) single mode guidance is still achievable by carefully launching into the fiber; also shorter fiber lengths will do this better than longer lengths. To retain single mode guidance perturbations to the fiber while the light is being guided would be beneficial, such perturbations included: vibrations, bends, application of side force, etc. Of course below the cut-off the single mode guidance is not guaranteed but can be achieved in practice, for example, our IRF-S-9 fiber can have single mode output beam at 2um wavelength, even though its cut-off is at 3.56um.

Connectors used with IRflex's fiber?

Our standard fiber cables use Amphenol SMA905 and FC/UPC connectors. Customers can choose any combinations of connector and jacket.

For most applications, FC/UPC or FC/APC connectors will be sufficient. In terms of high power handling, FC type connectors can typically handle up to 5W of average optical powers before thermal induce degradation takes place. For higher optical power, we recommend using SMA type connectors. For average powers up to 50W, a standard SMA-905 connector is offered as the connector ferrule consists of solid stainless steel. The fiber at the tip of the connector is cantilever to increase power capabilities.

When considering connector type, please also take into account how much power our fiber can carry. The amount of power our chalcogenide glass fibers can carry depends on the fiber's diameter and damage threshold.

What is the difference between SMA Amphenol connector and SMA connector?

Amphenol is the manufacturer of the connector and they use stainless steel ferrules. Some SMA connectors from other manufacturers are not with stainless steel ferrules.

What kind of SMA connector would I need?

There are two different types of SMA connectors: 905 or 906. The 905 is actually a straight connector while the 906 is a SMA connector that has one end slightly smaller. If you use the right coupler you can actually join the two different SMA connectors together without any problems.

How to connect with a SMA connector?

You cannot be forceful at all when using a SMA connector. With little effort, you can actually damage it and be forced to put another one on and start all over again. Hooking up a SMA connector to any device is very straightforward. It is best to start by lightly hand tightening and make sure you are not stripping the threads. Once you have a solid connection then you can proceed to use a wrench to make a secure fit.

You also need to pay special attention to the entire connector as you are tightening your SMA connector to make sure you are not damaging your connection. This could severely shorten the life of your connector and give you horrible signal quality. So just be sure to pay special attention to installation and make sure that you have a very snug connection so that your signal quality does not suffer and your SMA connector will last longer.

What is the difference between a PC and a UPC polish?

A UPC (Ultra Physical Contact) is a higher quality polish then a PC (Physical Contact) polish. The UPC polish has less scratches and the higher quality as measured by the improved return loss. UPC connectors mate to PC connectors without any problem.

What causes insertion loss in a connector?

Insertion loss in connectors typically comes from misalignment of the fibers or bent fibers in the connectors. The misalignment comes from eccentricity of the core in the fiber, eccentricity of the hole in the ferrule and most of all the eccentricity of the fiber in the hole.

Can I use mating sleeves for chalcogenide glass fiber coupling?

NO. In the Telecom industry, FC/PC, FC/APC and SMA adaptors or ferrule mating sleeves are used to connect any silica fiber cable terminated with telecom industry-standard FC/PC, FC/APC, SMA connectors.

The geometry tolerances on Telecom silica fibers (outside diameter, core/clad concentricity, ellipticity) and the connectors (ferrule hole diameter and concentricity) are so tight that the use of connector mating sleeves and adaptors precisely aligns the cores of each terminated fiber to produces good coupling and minimize back reflections by bring them into physical contact. But chalcogenide fibers' geometry has lower tolerances (fiber diameter ±1 micron, core/clad concentricity ±3 micron, ellipticity X-Y >1 micron) and the stainless steel ferrule for the chalcogenide fiber are custom-drilled with hole diameter up to 5 micron larger than the fiber diameter. The cumulative geometry variations on the chalcogenide fiber and the ferrule hole cause misalignment in the cores of the fibers when connector mating sleeves and adaptor are used. The core misalignment induces coupling loss that can become higher especially in the case of single mode fibers. Besides, chalcogenide glass fiber is about 5 times softer than silica glass fiber, so any physical contact will scratch the polishing end and damage the connector end face

We do not recommend using these adaptors/mating sleeves with our chalcogenide glass fiber cables.

Regarding the proper way to couple into our fiber, we recommend the use of ***free space coupling*** with an appropriate lens to match the fiber's mode field diameter. The lens used depends on certain factors such as the wavelength of interest, the beam diameter at the lens and the fiber's mode field diameter and numerical aperture.

What is the refractive index of IRflex's fibers?

The refractive index (or index of refraction), *n,* of an optical medium is defined as the ratio of the speed of light in vacuum, *c* = 300,000 km/s, and the velocity of light in the medium, v.

$$n = \frac{c}{v}$$

For example, the refractive index of chalcogenide AsS glass is 2.4 at 2 micron wavelength, meaning that light travels 2.4 times faster in vacuum than in the chalcogenide AsS glass.

Our fiber is composed of two concentric layers, called the core and the cladding as illustrated in the Figure 1

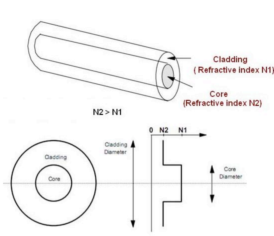


Fig (1)

The core and cladding have different refractive indices. The refractive index of the core, n_1, is always greater than the index of the cladding, n_2. The core transmits an optical signal while the cladding guides the light within the core. Since light is guided through the fiber it is sometimes called an optical wave guide

Knowing the core refractive index of the fiber as well as its numeral aperture (NA), one can easily calculate the refractive index of the cladding by using the following equation:

$$NA = \sqrt{n_1^2 - n_2^2}$$

For example: our IRF-S-9 has core refractive index of 2.4 and NA of 0.288, so the cladding refractive index is:

$$n_2 = \sqrt{n_1^2 - NA^2} = \sqrt{2.4^2 - 0.288^2} = \sqrt{5.76 - 0.0829} = 2.38$$

So, the difference of refractive index of core and cladding of our IRF-S-9 is 2.4 - 2.38 = 0.02

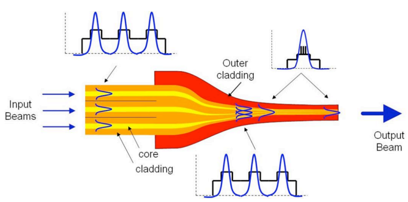
Another example of our IRF-Se-12, which has core refractive index of 2.7 and NA of 0.47, so the cladding refractive index is:

$$n_2 = \sqrt{n_1^2 - NA^2} = \sqrt{2.7^2 - 0.47^2} = \sqrt{7.29 - 0.2209} = 2.66$$

So, the difference of refractive index of core and cladding of our IRF-Se-12 is 2.7 – 2.66 = 0.04

What is the Fused Fiber Combiner?

Fiber optic combiners are used to combine two or more fibers into one common aperture. The signals from several sources are combined into one fused fiber, thereby combining their output powers and wavelengths. IRflex's proprietary manufacturing techniques of chalcogenide glass Mid-IR fibers make it possible to extend the power combining capacity from 1.5 to 6.5μm wavelength range. MWIR-FC-3 and MWIR-FC-7 models are commercially available.



What is the anti-reflection (AR) coating and why choose an anti-reflection coating on the connectors of IRflex's mid-IR fused fiber combiner?

Anti-reflection (AR) coating is a type of coating applied to optic designed to minimize reflections within an optical system and maximize throughout.

As light passes through an uncoated glass substrate, for example, with chalcogenide glass, approximately 17% will be reflected at each interface due to chalcogenide glass's high refractive index (n=2.4), this results in a total transmission of 69% of the incident light. To meet optimum transmission requirements, the fiber end faces may need to have AR coatings to increase the throughput of the system and reduce hazards caused by reflections traveling backwards through the system (ghost images). AR coating is also very durable, with resistance to both physical and environmental damage.

When specifying an AR coating to suit your specific application, you must first be fully aware of the full spectral range of your system. While an AR coating can significantly improve the performance of an optical system, using the coating at wavelengths outside the design wavelength range could potentially decrease the performance of the system.

IRflex offers Anti-reflection coating, broadband or at a specific wavelength, to any flat input and output fiber connector of our MWIR Fused Fiber Combiner as an option.

What is fiber bundle imager?

Current infrared cameras are commercially available for thermal imaging systems in the range of 2-14 μm. These cameras are made of a high-resolution uncooled focal plane array (FPA) that is a two-dimensional array of infrared detectors used to create a thermal image. Ferroelectric detectors and microbolometers are two uncooled technologies used today. A typical infrared camera has a high resolution (320 x 240 pixels). These cameras have pixel size of 50 μm squared, a length of 5.5 in., a width of 4.5 in. and a height of 4.5 in., and weight of 3 lb. The camera includes a lens to create an image on the FPA. Some critical military applications require high spatial resolution IR fiber bundle for imaging in areas inaccessible to the cameras because of size and/or harsh environments. This is the case where IR imaging in the range of 1-12 μm is needed for spatial analysis of combustion processes in turbines combustors and afterburners. Coherent fiber bundles are commonly used in the visible and near infrared (0.4 to 1 μm) to remotely transfer images to cameras. Unfortunately, there exists no coherent Fiber bundle imager (FBI) for IR imaging in the range of 1-12 μm.

IRflex is committed to develop innovative processes to produce low-cost coherent infrared imaging fiber bundles that are of minimum bend radius and attenuation over the spectral range of 1 to 12 μm. Recent developments in IR optical fibers and the current state-of-the-art fabrication processes of coherent fiber bundle offer the potential to develop a technology for the IR FBI. The benefits of the IR fiber optic bundle are illustrated in Figure C-1. A scene or object is imaged through a lens and transmitted through the flexible fiber optic bundle to a camera. The novel FBI will enable IR imaging in areas where space is limited and/or in harsh environments.

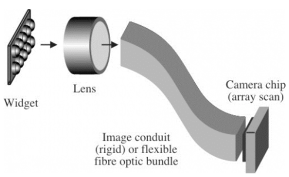


Figure: Coherent fiber bundle to transmit an image of a remote camera.

Are IRflex's products subject to U.S.'s Export Administration Regulations?

Our commercial available products are not ITAR controlled. They are classified as EAR99 for export.

EAR99 is a classification for an item. It indicates that a particular item is subject to the Export Administration Regulations (EAR), but not specifically described by an Export Control Classification Number (ECCN) on the Commerce Control List (CCL). While the classification describes the item, the authorization for shipment of that item may change, depending on the circumstances of the transaction.

NLR stands for the "No License Required" designation. NLR may be used for either EAR99 items, or items on the CCL that do not require a license for the destination. However, exports of an EAR99 items to an embargoed country, an end-user of concern or in support of a prohibited end-use may require an export license.

IRCM

Infrared countermeasures (IRCM): a device designed to prevent a heat or plume-seeking missile from reaching its target. It generally consists of a flare, laser or other bright illumination source and optics combination that, when placed on an aircraft, confuses a missile's target acquisition system.

CO_2 laser

The carbon dioxide laser (CO_2 laser) was one of the earliest gas lasers to be developed (invented by Kumar Patel of Bell Labs in 1964). The CO_2 laser produces a beam of infrared light with the principal wavelength bands centering around 9.4 and 10.6 μm.

QCL

Quantum cascade lasers (QCLs) are semiconductor lasers that emit in the mid to far infrared portion of the electromagnetic spectrum.

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