Versatile Optical Fiber Feedthroughs for Ultra-High Vacuum Applications

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Abstract

In this article we present an investigation of three different fiber optic vacuum feedthroughs. Using Swagelok-type tube fittings, metal tubings containing the optical fibers are sealed into a vacuum flange. This allows for easy replacement of the feedthrough without replacing the entire flange. Employing only epoxy resin for sealing the optical fiber into the feedthough we have measured a helium diffusion rate of $2.5 \cdot 10^{-10}$ mbar · l/s, whereas with a combination of a solderglass and epoxy resin seal we have obtained a diffusion rate below $1 \cdot 10^{-12}$ mbar · l/s. In a third approach, using small tolerance fiber optic ferrules in our feedthroughs, we have obtained helium diffusion rates of below $1 \cdot 10^{-12}$ mbar · l/s, making these feedthroughs well suited for ultra-high vacuum applications.

Delivering optical fibers into and out of ultra-high vacuum (UHV) systems is a common problem in many scientific experiments and other technical applications. Even though there are a variety of commercially available solutions, they are often bulky, expensive and limited to standard optical fibers. To overcome these limitations, several techniques have been developed. Some systems utilize compression fitting [1, 2, 3, 4]. However, tight tolerances for the fiber orifice are needed to enable a good seal. Moreover, the most common materials used in compression fittings are polytetrafluoroethylene (PTFE), which can result in unreliable seals, or metals, which can impart high pressure on the fiber and can lead to its cracking. Other systems are based on soldering metal coated fibers or potting of fibers using epoxy resin based adhesives [6, 7, 9, 8, 5], or combinations of compression fittings with other means of sealing [10, 11]. The use of metal coated fibers has the disadvantage that they are typically expensive, and that high temperatures are required for the brazing process.

In this article, we present three different types of UHV compatible feedthroughs for optical fibers which can be made reliably, are inexpensive and can be used for any type of optical fibers. We characterize the diffusion of helium through the different feedthroughs, showing that they are suitable for UHV applications.

Similarly to [10] our feedthrough designs are based on a Swagelok-type connector, which enables the replacement of the fiber feedthrough while providing an all-metal seal between the flange and the feedthrough tube. For the actual feedthrough we have designed three different types, as shown in Fig. 1. The simplest type (Fig. 1 (a)) is similar to [10] and is formed by a 3 mm outer diameter stainless steel tube (length of 40 mm, steel grade 316) with one end closed via cold forming. The closed end of the tube is then drilled open with a diameter marginally larger than the diameter of the fiber. The fiber, which has had its coating removed, is then inserted into the tube and sealed with epoxy resin (Epotec 353ND). To prevent air bubbles in the glue, three degassing step are conducted. First, after mixing the two part epoxy, it is degassed under vacuum in a small, shallow bowl until no bubbles are visible. After filling the resin into a syringe for injecting it into the feedthrough tube, the glue is degassed for a second time in the syringe with an open plunger. In this way all visible gas bubbles created by the transfer of the glue into the syringe are removed. Subsequent to the application of the glue into the feedthrough tube an additional degassing step ensures that there are no gas bubbles within the feedthourgh tube. The glue is then cured with an induction heater (Yosoo 1000W ZVS) for 5 min at about 120°C. This process forms a tight seal between the fiber and the tube.

To decrease diffusion of gases through the feedthrough, our second design includes an

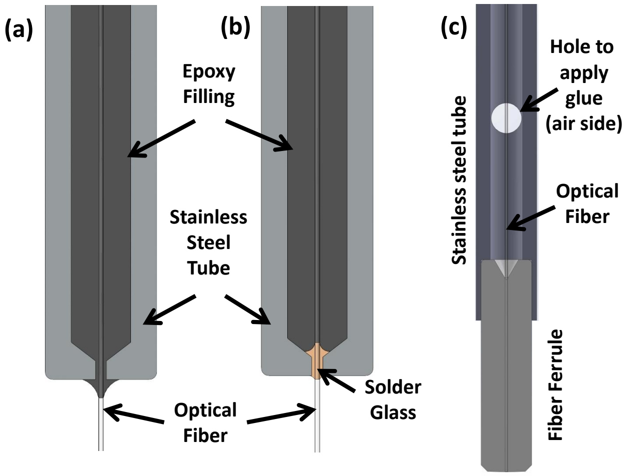

Figure 1: Types of feedthrough. (a) Epoxy sealed feedthrough. (b) Solder glass sealed feedthrough, reinforced with epoxy. (c) Vacuum side of feedthrough with epoxy sealed optical fiber ferrule.

additional diffusion barrier of solder glass (Fig. 1 (b)). The feedthrough is built by inserting the uncoated fiber into the small hole of the feedthrough tube and a solder glass preform (GSP-C-381-1054-254 from OZ Optics Ltd.) is slid over the fiber to the bottom of the tube. To form a seal between the fiber and the stainless steel tube, the solder glass is melted by heating the tube with an induction heater (Yosoo 1000W ZVS) to 400°C for about 1 min. This process readily forms a vacuum seal. However, to increase the mechanical stability of the uncoated fiber, the air-side bore is filled with degassed epoxy resin in the same way as descried above.

The last feedthrough design utilizes a ceramic optical fiber ferrule which enables the use of fiber connectors on both sides of the feedthrough (Fig. 1 (c) shows one side of the double-sided design). For this, a standard 3 mm diameter stainless steel tube is cut to a length of about 50 mm. A counter bore on both ends of the tube with a depth of 3 mm is machined to accommodate the fiber ferrules. The diameter of the counter bores is chosen to provide a press fitting with the ferrules (in our case 2.5 mm diameter FC ferrules). After pressing in the first ferrule and inserting the fiber, the assembly is sealed with an epoxy resin in the same way as described before. The air side of the feedthrough can then be finished by inserting the free end of the fiber into the second ferrule which is then pressed into the counter bore at the air side of the feedthough tube. In the last step, glue is applied to the inside of the tube through a small hole to fix the fiber into the air side ferrule (see Fig. 1(c)). Subsequently, both ends of the fiber feedthrough can be polished to provide low loss fiber-fiber connections. Note that the fiber can be left coming out of one or both ends of the feedthrough instead of cutting and polishing it at the ferrules' faces.

We measure the helium diffusion rate for the different types of feedthroughs. To do so, a Swagelok fitting is welded into a KF25 flange which in turn is attached directly to a calibrated leak detector (Oerlikon PhoeniXL 300). The feedthrough tubes are then inserted into the fitting and sealed with a locking nut. In a first step, we look for gaps in the seals and small cracks which can be detected by spraying helium around the feedthrough. For all feedthrough designs no immediate leaks were measurable (leak rate $< 10^{-12}\,\mathrm{mbar \cdot l/s}$). The helium diffusion rate through the feedthrough is then measured by connecting the air side of the feedthrough tube to a helium supply and continuously recorded for 4 hours after pressurizing the helium supply to a partial pressure of 2 bar. A schematic of the test setup is shown in Fig. 2.

The steady state helium diffusion rate is then determined by extrapolating the helium rate (similarly to [12]). Fig. 3 shows the diffusion rate of the feedthrough sealed with only epoxy resin. Apart from the onset after pressurizing the helium supply, the diffusion rate follows well the expected saturation behavior.

In order to rule out other means of diffusion of helium into the leak detector (e.g. leakage though the helium supply pipework), we replace the feedthrough tube with a solid stainless steel rod and repeat the measurement. As expected, this results in a leak rate which is below the leak detector's sensitivity.

To build our feedthroughs we used several types of fibers, including one multi-mode

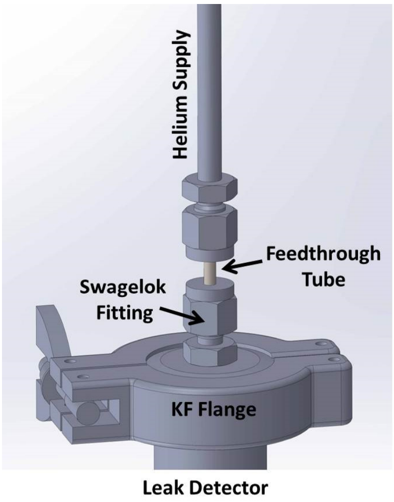

Figure 2: Setup to measure helium diffusion through the fiber feedthroughs. In order to measure the diffusion rate, the feedthrough is connected to a leak detector and, on the other side, a helium feed line.

fiber (FG200UEA), one single mode fiber SM850 and three polarization maintaining fibers (PM-S405-XP, PM630-HP and PM780-HP from Thorlabs). To test the optical properties of the fibers, the air side end of the fibers were connectorized and a free space laser beam was coupled into them. The transmitted power was then measured with a power meter (PM100D form Thorlabs) before and after the sealing of the feedthough. In addition to the fiber transmission, the polarization extinction ratio of the polarization maintaining fibers was measured with a polarimeter (PAX5710VIS-T / PAX5710IR1-T from Thorlabs) before and after the sealing process.

None of the feedthroughs showed any detectable leaks. However, there is a significant difference in helium diffusion rate for the different designs (see Table 1). Most noticeably, the diffusion through the feedthrough which is sealed only with epoxy shows the largest diffusion rate at $2.54(2) \cdot 10^{-10}$ mbar $\cdot$ l/s. This agrees well with our estimate of the diffusion rate of $1.3 \cdot 10^{-10}$ mbar $\cdot$ l/s, based on the literature values of the permeability of helium through epoxy resins [12] and the design geometry. The larger measured diffusion rate may be due to discrepancies between the machined

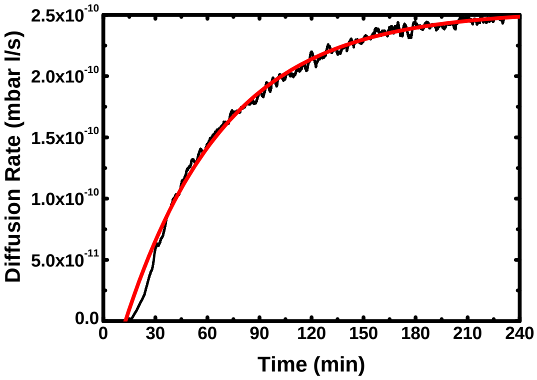

Figure 3: Helium diffusion rate of an epoxy-sealed feedthrough over 4 hours. The solid red line is a fit to the measured data (black).

metal tube and the design, as well as deviations of the helium permeability from the literature value potentially due to details of the curing process. The same measurement performed with an identical feedthrough resulted in the same diffusion rate.

Feedthrough Design	**Diffusion Rate (mbar · l/s)**
Epoxy sealed	$2.54(2) \cdot 10^{-10}$
Solder glass sealed	$< 10^{-12}$
Fiber optic ferrule	$< 10^{-12}$

Table 1: Summary of the measured diffusion rates.

For the case of the solder glass feedthrough the measured diffusion rate was $< 1 \cdot 10^{-12}$ mbar · l/s, significantly lower than that measured in the epoxy feedthrough. No helium permeability measurement has been published for the solder glass we used in our tests, so no estimation of the expected diffusion rate was possible.

A very low diffusion rate was also measured with the fiber ferruled feedthrough ($< 1 \cdot 10^{-12}$ mbar · l/s). Even though the sealing material is the same epoxy resin (Epotec 355ND), the cross section of the epoxy seal is significantly smaller

($6 \cdot 10^4\,\mu\mathrm{m}^2$ for the feedthrough in Fig. 1(b) vs only $200\,\mu\mathrm{m}^2$ for the ferrule in Fig. 1(c)), and the thickness of the seal is significantly larger (0.5 mm for the feedthrough in Fig. 1(b) compared to 9.5 mm for the ferrule in Fig. 1(c)). The estimated diffusion rate for the ferruled feedthrough is $0.9 \cdot 10^{-12}$ mbar $\cdot$ l/s, which agrees with the observed rate.

The optical properties of the fibers were tested before and after the sealing process, to ensure no deterioration happened. The optical power transmission was measured to remain unchanged within the uncertainty of the measuring device (±5%, Thorlabs S121C photodiode power sensor). The polarisation maintaining properties of the tested PM fibers was also found to remain equal within the measurement uncertainty (±0.5 dB, Thorlabs PAX5710VIS-T - TXP polarimeter).

While all feedthroughs preserve the optical properties of the fibers their diffusion rates and manufacturing complexities are different. The choice of sealing method depends on the application requirements. Using an epoxy seal without a ferrule (Fig. 1 (a)) gives the simplest feedthrough to manufacture, while offering acceptable diffusion rates for many UHV applications. This is a suitable method for when a simple solution is needed and a small diffusion rate can be tolerated. When the diffusion rate requirements are more stringent, however, the second (Fig. 1 (b)) or third (Fig. 1 (c)) methods are more suitable. The second method (Fig. 1 (b)) is the most complex of the three in manufacturing terms, as melting the solder glass beads requires higher temperatures than curing epoxy resin. The method is also more prone to errors if the heating parameters (heating time, temperature ramping speed, etc.) are not properly chosen. However, solder glass is less permeable to helium than epoxy resin, so this is likely to be the method that offers the best performance. The third method (Fig. 1 (c)) is only slightly more complex to assemble than the first one, but offers very low diffusion rates without the need for solder glass. However, this method relies on a tight fit between the optical fibre and the ceramic ferrule, so a matching combination is required. This is easy for most standard fibre diameters, as matching ferrules are commercially available off-the-shelf, but custom fibre diameters might require custom ferrules to match.

In conclusion, in this article we have presented three different types of fiber optics feedthrough based on the Swagelok connection systems. We have built and characterized the feedthroughs and have found the helium diffusion rate for two of the feedthrough designs to be below the sensitivity of the leak detector, which makes them well-suited for many applications in scientific experiments as well as technologies. Even the simplest fiber feedthrough design has a diffusion rate of $2.5 \cdot 10^{-10}$ mbar $\cdot$ l/s which makes it suitable for many ultra-high vacuum applications.

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