Learnings from the use of fiber optics in GRAVITY

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ABSTRACT

The use of optical fibers in astronomical instrumentation has been becoming more and more common. High transmission, polarization control, compact and easy routing are just a few of the advantages in this respect. But fibers also bring new challenges for the development of systems. During the assembly of the VLTI beam combiner GRAVITY different side effects of the fiber implementation had to be taken into account. In this work we summarize the corresponding phenomena ranging from the external factors influencing the fiber performance, like mechanical and temperature effects, to inelastic scattering within the fiber material.

Keywords: fibers, fiber technology, fiber optics, system development, scattering, GRAVITY, metrology, VLTI

1. INTRODUCTION

GRAVITY is a four-beam combiner at the ESO VLTI performing high-resolution imaging as well as narrow-angle astrometry. The main components of GRAVITY are the infrared wavefront sensors CIAO, the beam combiner instrument (BCI) and the laser metrology system. The beam combiner and metrology make use of fiber optics to guide astronomical as well as laser light through the instrument.

The implementation of fiber optics brings many advantages such as high transmission, polarization control, compact and easy routing as well as phase stability, only to name a few. Also, the market of telecommunication provides a lot of ready-made fibers and fiber components, which can be used for astronomical instrumentation. On the other hand, unwanted side effects can occur in the use of fiber optics, which we also witnessed during the assembly and testing of the GRAVITY instrument.

In addition, careful and clean handling of the flexible yet very fragile fibers is necessary to benefit from their functions mentioned above. This does not only imply the use of protection cables. Also the bending of protected fibers can heavily affect their transmission and polarization properties.

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Polarization-maintaining fibers support the guiding of light at a defined polarization state, but come with certain limits such as misalignments in connections or inside of fiber components. This effect does not only alter the polarization state but also phase measurements due to strong birefringence.

High power levels of injected light can lead to heat excess at sensitive points, to back reflections or even inelastic scattering. Heat generation by absorption of light needs to be considered especially for long-term operation and components with bad heat conduction. Back reflections occur at fiber connections, but can be minimized.

Specifically in the design of the GRAVITY metrology, non-common paths occur with respect to the science light, which require a high stability. External influence on fibers can cause variations of those paths as well as the previously mentioned high power levels do.

In particular, the biggest obstacle from fibers in the GRAVITY development was the inelastic scattering within fluoride-glass fibers triggered by the metrology laser. Its origin was two-fold, with Raman scattering via the excitation of phonons in the fiber material and fluorescence of rare earth elements as small contaminations in the fibers.[1] We followed various routes in parallel to mitigate these effects and in the end chose moving to small enough laser-power levels.

Here, we summarize key effects measured in the development of GRAVITY and the applied solutions. We also mention the tools specific to fiber handling, covering general fiber termination, cleaving and splicing. These processes are very useful for fixing damages in the fiber chain and most of all, splicing can help minimizing the number of fiber connections.

2. LEARNINGS

Building the GRAVITY beam combiner (BC)[2] involved various new developments ranging from near-infrared detectors,[3] K-band integrated optics[4] to a dedicated metrology system.[5]

The BC instrument uses fluoride-glass fibers to guide the astronomical light in the K-band around 2.2 µm. The single-mode fibers provide spatial filtering of wavefront distortions, introduced by turbulence in the atmosphere and the beam trains. The fiber path includes functions such as polarization control and differential delay lines by twisting and stretching the fibers.[2] This fiber control system was developed by the company Le Verre Fluoré and the French partners in the GRAVITY consortium LESIA and IPAG in Meudon and Grenoble, respectively. The fluoride fibers show low chromatic dispersion and birefringence. Their overall features ensure stability and repeatability for the GRAVITY measurements.

The metrology system is based on fused silica fibers, which are single-mode and polarization-maintaining for stable phase measurements. While the metrology laser operates slightly below the K-band at a wavelength of 1908 nm, the chosen fiber is a standard type in telecommunications industry for a nominal wavelength of 1550 nm, known as Fujikura SM15-PS-U25A or the equivalent Corning PM15-U25A. This choice ensured high throughput as well as single-mode propagation of the metrology light and opened up the use of a wide range of fiber components available on the market at that time. Nowadays, also the astronomical K-band is more and more covered by ready-made fiber optics.

The linear polarization is maintained by a PANDA design, consisting of two stress-applying rods built in the fiber cladding at both sides of the fiber core. The stress induces birefringence. Aligning the polarization to one of the two symmetry axes of the fiber maintains the polarization state. The axes are called fast and slow. The metrology propagation uses the slow axis in this respect. FC/APC connectors are used at the ends of the fiber cables. Their angled end faces minimize back-reflections. These properties are shown in Figure 1.

The use of fibers in GRAVITY provides an optical path, which is flexible and compact due to the variable curvature and small dimension of fibers. These mechanical properties together with high transmission levels deliver a high optical efficiency in the beam transport. However, the apparently easy routing of fibers also comes with certain limitations as discussed next.

2.1 Fiber handling

The handling of fibers and fiber optics should be executed very carefully as for most other optical components.

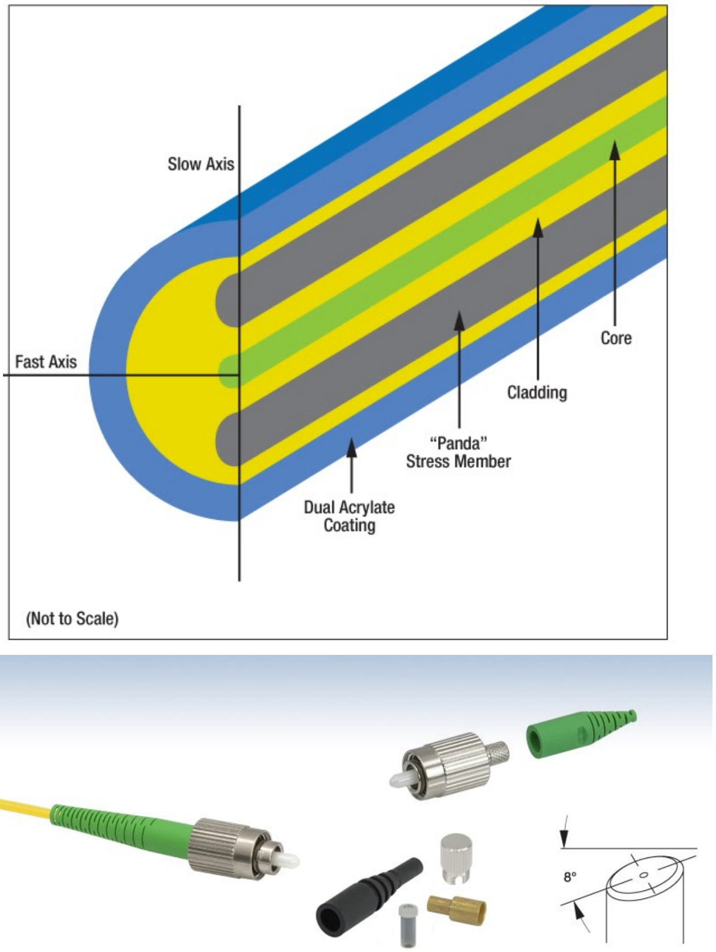

Figure 1. The top panel shows a polarization-maintaining fiber of PANDA type in its cross sections.[6] The bottom panel displays FC/APC connectors with different strain-relief boots and dust caps that are offered by Thorlabs.[6] The white ceramic ferrule of the connector comes with an angled end face to minimize back-reflections. The injected light propagates in the fiber core by reflection from the cladding. The coating serves as protection for the fragile fiber glass. Stress rods induce strong birefringence such that linearly polarization aligned to one of the two symmetry axes of the fiber is maintained. The connector orientation to this so called slow or fast axis is marked with a key on the metal housing surrounding the ferrule.

2.1.1 Protection jacket

Depending on the application, additional protection covering the fiber coating should be included. Standard fiber patch cords with connectors are protected by a tube or cable jacket. The thicker cables provide more protection, but also hide the actual fiber bending direction more. The material of the jacket might evaporate in vacuum systems.

Unexperienced users without briefing tend to treat fiber cables like electric cabling, which should be absolutely avoided. The fiber glass in the inside is much more fragile than electrical wires. For the metrology fibers outside the GRAVITY cryostat we chose a step-proof metal housing for maximum protection.

2.1.2 Mating

The connections between fiber patch cords are made with mating adapters. The type of mating adapter depends on the connector type. As mentioned previously, the metrology uses FC/APC connectors for minimizing back-reflections. The fluoride fibers in GRAVITY are equipped with E2000 connectors, which have built-in dust caps automatically opening or closing when the connectors are mated or unmated. Inspection and cleaning of the the connectors is of great importance before mating to prevent fiber damage by dust. In GRAVITY we only cleaned the particular fragile fluoride fibers when dust residuals were visible in the fiber video microscope. The metrology fibers were cleaned in a more regular fashion prior to almost every mating, as relatively high power levels are propagated there. This point is explained in more detail in the section about high power levels.

In addition to a suitable protection jacket and clean mating, fiber patch cords need to be routed properly to maintain their functions. In GRAVITY, a loose but fixed fiber routing ensured that no strain is put on the fibers, especially for rather stiff and heavy cables.

2.1.3 Routing

The high transmission and polarization alignment of light traveling through a fiber strongly depends on proper routing. Strain reduces the performance and therefore fiber cables and connectors include strain-relief components. Nevertheless, a minimum bend radius needs to be kept, as specified by the manufacturer.

In addition, the routing should agree with the intrinsic curvature of the fiber cables to prevent strain. When assembling the metrology fibers in the GRAVITY cryostat we found that wrong or too strong bending can particularly occur close to fiber connectors. Even if the theoretical radius is kept, the natural fiber curvature at the connector can deviate from the chosen routing. This can be omitted by increasing the bend radius. Also mechanical support structures can help keeping the routing in place, as well as fixing the fiber in its position at multiple locations does. The latter method prevents that strain from unwanted fiber displacements can easily off-load at a single location, e. g. at a connector. The strain-relief boots of connectors should not be bent at all.

In the case of permanent damage caused by strain, sometimes the damaged fiber part can be cut out and fusion-spliced with a dedicated device. During the development of GRAVITY, we could use this technique to repair fiber components that were damaged by unwanted mechanical impacts, by means of the Fujikura splicer FSM-100P displayed in Figure 2. This device is able to monitor the inner fiber geometry such that also PM fibers can be aligned and spliced. Splicing also helps to shorten excess fiber lengths and to avoid connections in order to optimize both the throughput and the polarization alignment.

2.1.4 Fiber termination

Splicing requires flat fiber end faces perpendicular to the fiber axis, which is realized by cleaving. The cleave breaks the fiber in a controlled fashion. Usually the fiber is scribed, for instance by a diamond knife, and then pulled. The tension results in the cleave. This can be done manually or with a cleaver device.

Typically, the fiber coating needs to be stripped for cleaving. The resulting bare fiber is very fragile and needs to be handled with great caution. The metrology system uses such bare fiber outputs glued to V-grooves to inject the laser light to the two beam combiners in GRAVITY by two 1x2 fiber splitters. These injection fibers have to be short and of equal lengths to minimize non-common path errors of the injection scheme. As a consequence, any induced damage cannot be repaired by cleaving, but requires exchanging the fiber splitter. We

Figure 2. Fusion splicer FSM-100P from the company Fujikura: in the middle the device is displayed with open lid. The surrounding three close-ups show the two displays with the result of a successful splice and the electrodes which perform the fusion splice. The fibers are placed in fiber holders next to the electrodes for this purpose. The left display shows the camera inspection of the splice in perpendicular x and y view. The right display summarizes the quality parameters of the splice with the angle of alignment and the corresponding extinction ratio.[1]

designed a dedicated tool to insert and fix these fibers safely during the metrology assembly, to lower the risk of fiber damage.

The metrology system also uses a bare fiber end at another location, namely glued to a lens in the GRAVITY instrument, to pick up the laser fringes for the first time after the metrology beams passed the beam combiner instrument. The lens-fiber assembly is displayed in Figure 3. A multi-mode fiber is used for this purpose. In order to minimize the damage risk when glueing the stripped and cleaved fiber to the lens, I developed a method to manually cleave the fiber without previous stripping. The critical step is to scribe deep enough through the coating with a pen-shaped diamond knife, but without inducing a crack to the actual glass fiber. Due to relaxed requirements on the fiber length I could repeat the procedure until the cleave was successful. For the inspection I used a regular fiber microscope for FC connectors. I inserted the cleaved fiber to a ceramic ferrule as used in fiber connectors to inspect the cleave in the microscope. Transmission tests of the glued fiber-lens assembly showed a thoughput of nearly 100%.

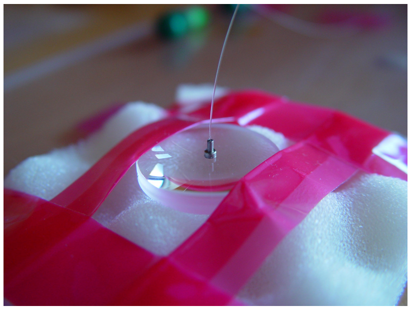

Figure 3. Metrology pick-up fiber glued to a lens.

The other fiber end is a connector, which is coupled to the metrology receiver by a fiber-to-diode coupler from OZ optics. Since the multi-mode propagation of the metrology fringes does not require polarization alignment, I could also easily prepare this end in the laboratory by cleaving the stripped fiber end and glueing it into a fiber connector. The final step in this fiber termination is to polish the connector in order to remove epoxy residuals and create a flat end face for proper throughput.

2.1.5 Environment

For GRAVITY we noticed that the time period needed to establish vacuum in the cryostat deviates from the expectations when assuming only air molecules to be present. A possible reason could be the evaporation of the fiber jackets.

Except for one, all of the fiber components of the metrology system showed similar throughput at cryostat temperatures of 240 K as at room temperature. The exception was a fused fiber splitter which showed no transmission in one of two outputs after a few days of operation at a few ~ 100 mW power. The examination of splitter showed that the fiber burned. We think that mechanical stress was induced by the deformation of the plastic housing at the low temperature. As the fiber was glued to the housing, the stress lead to the laser light leaking outside of the fiber core causing heat damage of the material. We solved this issue by installing a new fiber splitter but outside of the cryostat, before the metrology light enters the cooled environment.

2.2 High power levels

Optical fibers can transmit signals over long distances with few losses, also for high power levels. Guiding high powers in such confined waveguides also has the advantage of protecting the environment from unwanted reflections. Potential risks for GRAVITY were fiber damages by the heating of dust residuals or variations of optical path lengths corrupting the phase measurements of the metrology.

2.2.1 Fiber damage

The GRAVITY metrology injects > 1 W of laser power to the system. The laser has a fiber output. This and the further fiber chain allows for an eye-safe operation. The 30 meters from the laser to the GRAVITY cryostat are covered by fibers with step-proof metal housing, manufactured by FCC Fibre Cable Connect. The metal cable provides protection to the fragile fiber made from fused silica.

The laser rack is located in another room than the GRAVITY instrument. A 25 m-long fiber is used as connection. As another protection measure, we introduced two short fiber patch cords at both ends of the main fiber. This concept ensures that both the laser and the instrument can be disconnected from the long fiber without opening the connection directly at its ends. By this, neither the expensive laser nor the long fiber can witness any damage by the unwanted dissipation of the high power due to dust residuals. Instead dust can only enter in between the short fiber patch cords, which are easier and cheaper to exchange.

2.2.2 Non-common paths

The metrology light traces all the optical paths in GRAVITY and the VLTI up to the telescope pupils in order to track internal differential OPDs (dOPDs) between the two observed sources for astrometric measurements.[5] The metrology injection to the system shows paths, which are not seen by the astronomical light, so called non-common paths. These non-common paths need to be stabilized to a certain level such they do not perturb the actual dOPD measurements on the astronomical paths.

The dominating path fluctuations in the injection fibers were induced by differential temperature variations. On the one hand, this requires temperature control of the environment, which is provided in the GRAVITY cryostat. On the other hand, the main temperature fluctuations are induced by fluctuations of the high laser power.[7–11]

Another important element in minimizing errors from non-common paths are the exit splitters of the metrology. Two 1x2 splitters are used to feed each of the beam combiners in GRAVITY by two fiber outputs. This design feeds all four telescope inputs of the combiners with metrology light. The output fibers are kept short at similar length of order 5 cm, without fiber connectors cleaved to millimeter-accuracy. These fiber ends are mounted to V-grooves such that the injection can be controlled by xyz-actuators.

When positioning the fibers, the polarization direction can vary due to bending of the fibers. To minimize this effect, we do not use PM fibers as outputs but single-mode fibers. Tests comparing both solutions showed smaller changes in the output polarization of the single-mode fibers. They maintain the polarization as their beating length is longer than the used short fiber length. In contrast, the PM fibers are highly birefringent with the beating length being inverse proportional to the birefringence, making them much more sensitive to the stress from bending.[12]

2.3 Polarization-maintaining fibers

Polarization-maintaining (PM) fibers allow for guiding linearly polarized light. The metrology fibers are based on the PANDA design for this purpose. Such PM fibers contain two stress-rods on both sides of the fiber core, which introduce birefringence. In this scheme, the fiber has two orthogonal transmission axes, along which linear polarization is maintained.

The prerequisite for maintained polarization therefore is the alignment. The metrology light is linearly polarized with an amplitude ratio between the two polarization axes of $> 100 : 1$ at the laser output fiber. This extinction ratio of $ER > 20$ dB is typical for fiber connectors and can be as good as 30 dB. The fiber itself shows higher values of 50 dB.[13]

Since every connection between two fibers or fiber components introduces small misalignments, the number of mating points along the fiber chain should be minimized. Furthermore, special mating adapters for PM connections can be used for better stability. For the metrology system we used special adapters for PM applications from Thorlabs.

Fiber splices provide a better alignment, but of course can only be realized in a final system, which does not have to be disconnected at these points again. If polarization alignments are introduced and cannot be corrected by a fiber splice, one might consider introducing a fiber polarizer to correct the alignment for the further light propagation. The GRAVITY metrology performs phase-shifting interferometry by using phase modulators. These devices also are birefringent, such that the passing light witnesses different phase shifts in the two polarization axes. In order to feed one defined axis and to minimize the fraction of light guided in the other, we spliced fiber polarizers to the inputs and outputs of the phase shifters. The splicer alignment provides $ER > 55$ dB.

2.4 Backscattering

When integrating GRAVITY for the first time, the metrology laser triggered strong backscattering in the instrument fibers, which outshined the science detectors by several orders of magnitude. While the metrology wavelength was blocked by design using dedicated filters, two physical mechanisms were responsible for the unexpected backscattering at the longer detector wavelengths: Raman scattering and fluorescence. Both could be attributed to the fluoride-glass fibers in GRAVITY by a characterization in a dedicated laboratory setup,[1] shown in Figure 4. The figure also displays the measured spectrum for different fiber lengths.

The backscattering strength was found to be proportional to the fluoride-fiber length and to the laser power. Varying the fiber position, and therefore the coupling of the light to the fiber core, as well as the reducing the laser aperture decreased the backscattering flux. From these properties we concluded that the backscattering originates from the fiber cores and not from other parts, such as the fiber coating or the connector ferrule.

The mitigation of the backscattering required to upgrade the original dual-beam metrology to a new three-beam concept.[5] In the following, we summarize the responsible mechanisms as well as the mitigation strategies.

2.4.1 Raman scattering

Raman scattering produces an emission wavelength at a characteristic shift with respect to the absorption wavelength.[14–17] The underlying process is the interaction of photons with phonons in condensed matter, in quantum-mechanical description. In the classical wave approach, the electric field of the radiation couples to vibrational modes of molecules.

Due to polarizability of the molecules the electric field induces a oscillating dipole. One emission component has the wavelength of the incident photons, known as Rayleigh scattering. If the polarizability of the molecules changes with the oscillations, then also two inelastic Raman components appear.

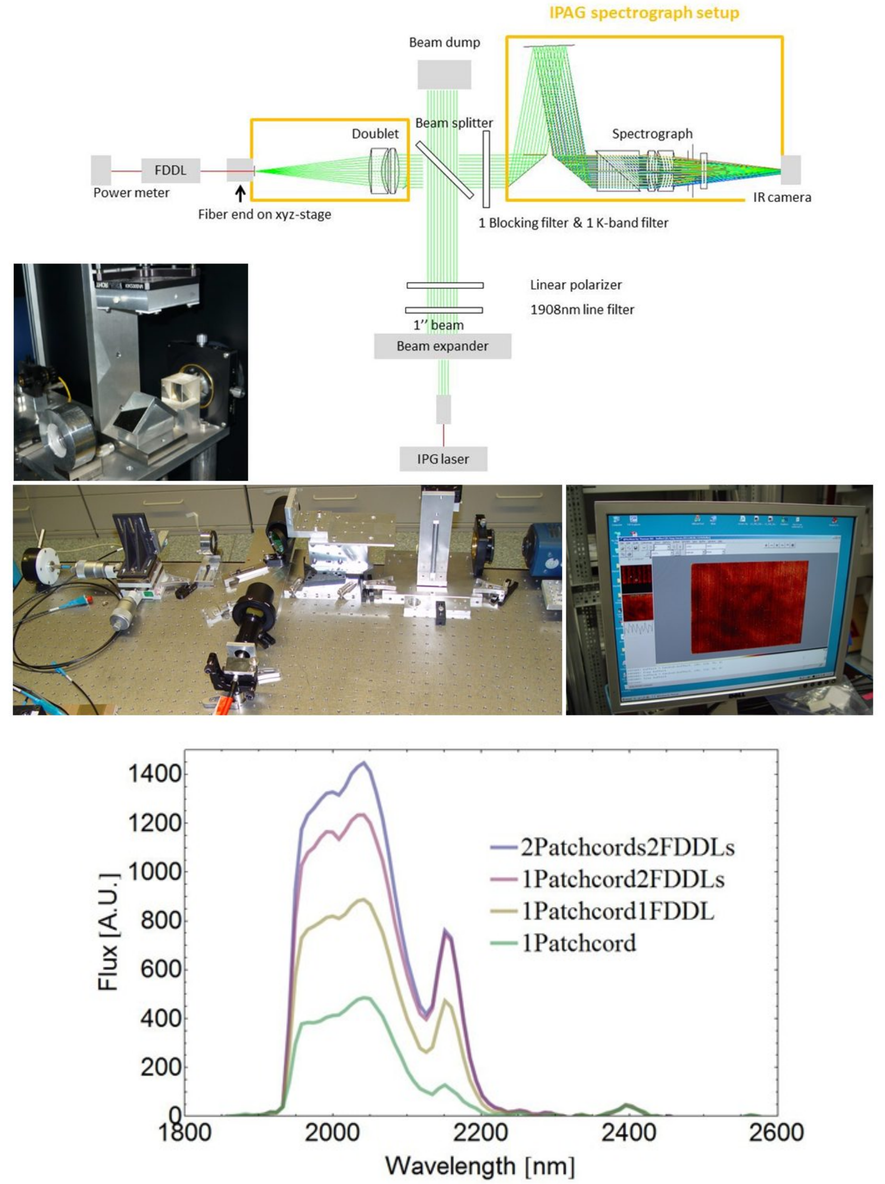

Figure 4. Top panel: laboratory setup for the analysis of the backscattering based on the GRAVITY configuration. The drawing demonstrates the laser injection on the bottom, the coupling to the fluoride fiber on the left and the spectral dispersion of the backscattering on the right. The photographs show the spectrograph, the entire setup and a detector image. Bottom panel: backscattering spectrum for different fiber lengths.[1]

Depending on whether the molecule is excited to a higher state or de-excited to a lower one by this process, the emitted radiation is at larger or smaller wavelengths than the incident light, at a shift characteristic to the material. This corresponds to the Stokes and anti-Stokes mode of Raman scattering as shown in Figure 5. Typically, the Stokes mode is stronger due to the higher population of lower states as described by the Maxwell-Boltzmann distribution in thermal equilibrium.

The metrology scattering in the fluoride-glass fibers produces a Stokes mode on the science detectors at a wavelength $\lambda_S \approx 2150$ nm.

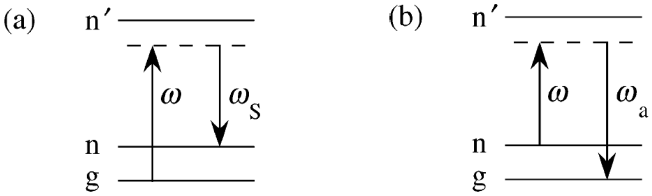

Figure 5. Energy transitions of Raman scattering from Boyd et al. (2008).[18] Panel (a) visualizes the Stokes mode by the excitation of the ground state g to a higher level n by radiation of frequency ω. The scattering leads to a reduced frequency ω_S via the virtual intermediate energy level n'. Panel (b) shows anti-Stokes process with increased frequency of ω_a compared to the incoming light.

The found shift in terms of a wavenumber of $\tilde{\nu}_i = \frac{1}{\lambda} - \frac{1}{\lambda_S} \approx 590\ \mathrm{cm}^{-1}$ is characteristic for fluoride glasses independent of incident wavelength λ, as literature shows. Figure 6 summarizes different studies performed at various laser wavelengths producing this shift in fluoride glass, independent of the detailed chemical compositions.[19–23]

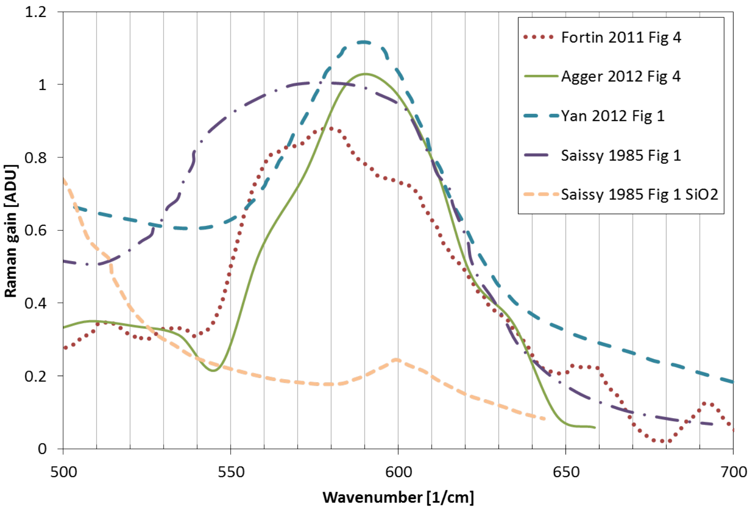

Figure 6. Raman spectra in fluoride-glass fibers from literature.[19–22] For comparison they are scaled to similar gains in arbitrary detector units (ADU). Different chemical compositions of fluoride-glass fibers show similar Raman shifts with wavenumbers of $\tilde{\nu}_i \approx 580\ \mathrm{cm}^{-1}$ or $\tilde{\nu}_i \approx 590\ \mathrm{cm}^{-1}$. The spectrum from Saissy et al. (1985)[22] corresponds to silica fibers as used by the metrology, which does not cause the observed Raman scattering.[1]

When building a system that guides relatively high laser powers by fibers, one should definitely prepare for Raman scattering that might occur. The Raman shifts for various fiber materials can be found in literature. In this manner, it is possible to check whether relevant instrument bands could be affected by Raman scattering.

Raman scattering of linearly polarized light leads to linearly polarized emission. Therefore, in principle a polarizer could be used to block the Raman radiation. For GRAVITY this was not an option, since the polarizer would also block a fraction of the astronomical light. In addition, the dominant backscattering mechanism in GRAVITY is fluorescence, which is not polarized.

2.4.2 Fluorescence

The fluorescence in the fluoride-glass fibers of GRAVITY originates from the rare-earth element Holmium. According to the manufacturer LVF, this is a contamination, which can occur when producing fluoride glasses.

The underlying process for fluorescence is the absorption of light by an atom and after some resonance time the emission, via electron excitation and de-excitation. Both the absorption and emission band can be broad, as the energy levels can split in manifolds of sublevels by the Stark effect. The Stark splitting is caused by local electric fields in the material.[24–26] If one sublevel is excited by radiation, quick thermalization between all sublevels by vibrational phonons leads to a Boltzmann distribution of populations on the sublevels, faster than the resonance time.[27] In addition, inhomogeneous distributions of the ions in the glass can induce differences in the local electric fields. As a consequence, different manifolds might occur, such that all the individual sublevels smear out to a continuous band. Other than for Raman scattering, this leads to a spectral shape of the fluorescence characteristic for the incident laser wavelength, as it corresponds to the de-excitation of a certain electron energy level in the material.

These absorption and emission bands can be found in literature, also for the Holmium ions Ho^{3+} in fluoride glass. The fluorescence measured in GRAVITY comes from the excitation of the ground state manifold $^5I_8$ to the first excited-state manifold $^5I_7$ of the valence electrons in Ho^{3+}, induced by the metrology laser. The strongest resemblance of the measured spectral shape is found in the work of Zhang et al. (2009),[28] shown in Figure 7.

This comparison also shows that also the rare-earth Thulium can be excited by the metrology laser. When testing shorter metrology wavelengths to mitigate the backscattering, we found that indeed also a Thulium contamination is present in the fluoride glass.

2.4.3 Mitigation

We followed different routes in parallel to find the best mitigation of the backscattering by factor 10^4 to 10^5, to reach a backscattering level on the science detector similar to its thermal background. The analyzed concepts were based on:

- **Fiber length**: reducing the length of the fluoride-glass fibers in GRAVITY to decrease the backscattering strength.
- **Fibers**: replacing the fluoride-glass fibers by new ones with a minimized contamination by Holmium and Thulium.
- **Wavelength**: changing the metrology wavelength to remove the Raman scattering from the K-band and to trigger less or no fluorescence.
- **Laser power**: reducing the laser power for less backscattering.

In these tests, the most promising routes without major design changes for GRAVITY were decreasing the laser wavelength or power.

The culprit when going to lower wavelengths was that the Holmium fluorescence was gradually replaced by Thulium fluorescence and that the instrument fibers started to guide more than one mode. We found that a wavelength of 1750 nm would be an acceptable compromise between low backscattering and almost single-mode operation.

In the end, we implemented an upgraded three-beam concept of the metrology, based on reducing the laser power in the instrument by several orders of magnitude and amplifying the signal by a third high-power beam behind the fluoride glass fibers, as described in Lippa et al. (2016).[5] In this scheme, the remaining backscattering is still slightly larger than the thermal background, but only by a factors of few and only for a few pixels at the shortest wavelengths in the detector band. The power reduction also minimized the temperature-induced variations of optical path lengths in the non-common paths discussed above.

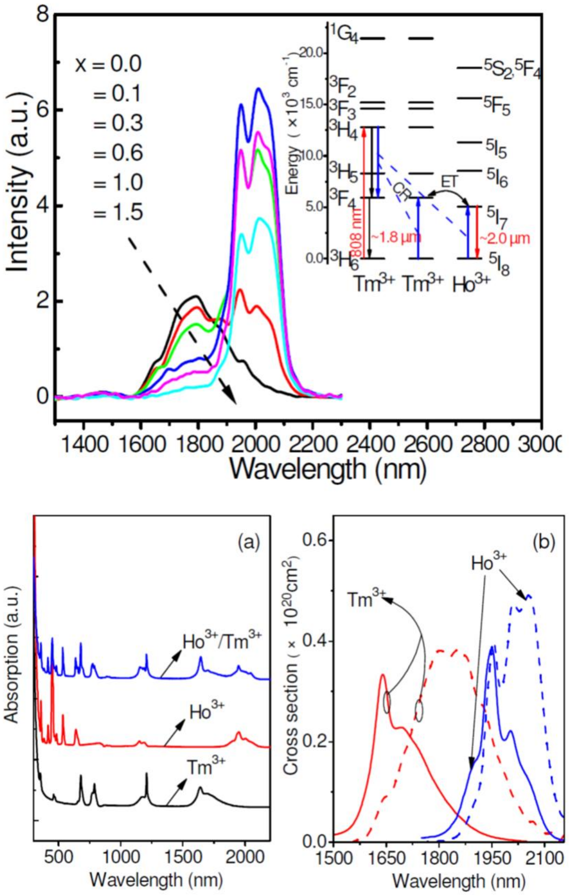

Figure 7. Absorption and emission spectra of Thulium and Holmium from Zhang et al. (2009).[28] Top panel: fluorescence intensities from fluoride glass doped with Thulium and Holmium with a ratio $1/x$. The energy-level diagram shows the transition in Holmium as observed in GRAVITY. Bottom panel: the absorption spectrum of 1/0.6 doping with Thulium and Holmium is plotted on the left. The right side shows their absorption and emission cross sections in solid and dashed lines.

3. CONCLUSION

In summary, fibers provide great advantages for the flexible guiding of light with high throughput and other features, such as polarization alignment, phase stability and spatial filtering of wavefront distortions. The successful development and operation of GRAVITY is strongly based on these fiber concepts. But also fibers and fiber optics come with certain limitations. With this paper, we highlight our learnings in this respect while building GRAVITY. Careful handling and routing of the fibers is the basis of integrating them to a system. Acquiring skills in fiber termination helps assembling own fiber solutions or fixing broken components. The influence of low temperatures and vacuum on fiber cables should be tested. Power fluctuations can induce temperature variations and by that variations in the optical path length. Polarization can be maintained in optical fibers. Misalignments can occur, but can be minimized. High-power levels can burn fibers when dust residuals are heated. In addition, strong backscattering can be induced not only at the laser wavelength but also at other wavelengths, by mechanisms such as Raman scattering and fluorescence. Particularly for the latter, the GRAVITY project also showed that even severe unexpected obstacles can be overcome successfully, such that the advantages of fibers and fiber optics prevail.

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