Bend loss in multimode chalcogenide fiber at infrared wavelengths

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Abstract. The bending loss is a critical parameter for packaging, representing a limiting parameter in the mini-

mization of fiber-based devices. For applications in the mid-

infrared spectral band, chalcogenide glass optical fibers

are one of the few alternatives for high-power beam deliv-

ery. We present experimental results for the bending loss

of a sulfide-based multimode chalcogenide fiber for a

broad range of infrared wavelengths as well demonstrating

>5.8 W power handling for a 6.25-mm radius bend. © The

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1 Introduction

Optical fibers are most commonly used for routing of signals over long distances (meter to kilometer), meanwhile planar devices are the technology of choice for millimeter to cen-

timeter distances. However, for applications involving rout-

ing or combining of signals at centimeter to meter distances,

optical fibers can be used, but it is expected that routing will

involve centimeter to millimeter bending radii. These dimen-

sions are common for routing of signals inside handheld-size
devices as well as for routing signals between multiple de-

vices in laboratory-size environments.

For silica-based fibers, high-power beam-delivery over cen-

timeter to meter distances and the induced bend loss lim-

its have already been studied.1 Characterization of the losses

associated with bending for fibers that transmit high-power beams in the mid- or long-wave infrared ranges has been

much more limited. We focus on the mid-infrared range where there are multiple applications such as biomedical,
sensing, and defense. There are multiple material systems

that could provide infrared optical transmission over short distances such as metal coated hollow waveguides, hollow

core fibers, fluoride and chalcogenide fibers.2 However, investigations on the bending radii for many of these systems

reduce their attractiveness to short-distance routing. For example, the onset of significant bending losses for

~100-μm core fibers varies with bending diameters of

~100 mm in fluoride fibers,3 ~100 mm in metal-coated

hollow guides (with 530-μm bore, and higher for smaller

bores),4 and 300 mm for hollow core inhibited coupling

fibers.5

Chalcogenide fibers can withstand high-peak mid-infrared

laser power6 with over 1 GW/cm² (for nanosecond pulses) incident on the front face. To date, significant efforts have

been dedicated to this fiber system with research spanning

methods to improve coupling through reduction in reflection loss7 and modal matching and impact of nonlinear absorption

and optical scattering6 as well as design of complex single-

component microstructured fibers.8 However, there have

been no experiments to address the losses and reliability

of chalcogenide fibers when bending into tight turns, a prac-

tical condition of great relevance to packaging and design of

field-deployable systems. Here, we present the bending loss

for a multimode AsS3 chalcogenide fiber, which with its

known high-power handling in the mid-infrared indicates

that it is a viable alternative for broadband infrared routing

over short distances.

2 Setup

In the near infrared, there is a formal industry standard for
determining the bending loss of multimode fibers, IEC

60793-1-47. However, given the limited community inter-

ested in mid- and long-infrared wavelengths, no similar con-
sensus exists for determining the bending radius of fibers at

these wavelengths. We have decided to follow a similar

approach as the one used for short lengths of multimode

fibers in the near infrared. It involves measuring the loss
due to a one fourth turn around a mandrel of known diameter.

This 90-deg turn also most closely resembles the type of

bends expected when using fibers in packaging of small

core factor (handheld) devices.

The bending losses were measured for a 5-m long 0.257-

numerical aperture (measured at 1.98-μm wavelength) AsS3

fiber with 100-μm core and 170-μm cladding. The power

handling of multimode fiber is known to scale with the

fiber core diameter as the power is spread over a larger

area and larger number of modes. To simplify comparison

with bending losses of fibers manufactured from other mate-
rals, a core fiber of 100 μm was chosen, yielding between

~300 modes at 3 μm to 100 modes at 5 μm. The cladding

dimension was selected solely to simplify fiber fabrication

with the current experimental setup.

Figure 1 shows a schematic of the experimental setup

used in the experiment. A light source was coupled with

a very high numerical aperture parabolic mirror to ensure

equal filling of the modes. For the multimode fiber, a

Fourier transform infrared spectrometer (FTIR) was used
to excite as well as measure the fiber transmission. A clad-
ding stripper was used to remove any power leaked outside

the core due to the overfilling of modes at the input. The fiber

is bent around different metal mandrels and propagates for

~2 m before reaching the detector. Bending of the fiber will

cause some of the optical power to leak into the cladding,

so another cladding mode stripper was used prior to the output

reaching the liquid nitrogen cooled mercury cadmium tellu-

ride detector. Additionally, the setup shown in Fig. 1 was

modified to enable the measurement of a single-mode

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fiber by replacing the FTIR with a high-brightness laser source centered at 4.6 μm.

3 Results and Discussion

Figure 1 shows the infrared transmission of the multimode fiber for all the bend radii tested. The measurement shows a decrease in transmission normalized to transmission with a very large bend radius of 100 mm (set to 100%). The absolute wavelength-dependent loss of similar As₂S₃ fibers has been published elsewhere so we focus here on the increase in loss due to the bending of the fiber. Given the long length of fiber used (~5 m), regions of high absorption, such as that close to the absorption edge or to impurity bands, had low signal and resulted in noisy transmission values. For all bend diameters, a band at 3.5 μm is observed with increasing attenuation as the bend becomes tighter. A similar band at 3 μm is present for bends’ radii below 25 mm. These wavelength bands are associated with the two largest absorption bands in the polymer acrylate jacket indicating that the evanescent field at the edge of the cladding is being absorbed by the polymer. Removal of the polymer jacket eliminates the increased loss at the cost of decreased abrasion resistance.

The bending loss for two common wavelengths in the mid-infrared, 2 and 4.6 μm are displayed in Fig. 2. As expected for a multimode fiber, the bending loss is not very dependent on the wavelength used, with both colors displaying similar bend losses. It is interesting to note that even at 12.5-mm bending radius, the total increase in loss is <1 dB. For comparison, the bend loss at 4.6 μm for a fiber with 0.28 numerical aperture (measured at 1.98 μμ) with 8-μm core diameter and 128-μm cladding is presented in Fig. 1 (triangles). As expected for a single-mode fiber, the loss is negligible for large bends (as there are no higher order modes to be expelled from the core).

The solid line in Fig. 3 indicates a fit to Eq. (1) from Ref. 17. The model describes the power loss for a mode propagating at an angle θ to the axis of a step index fiber as

\[
\alpha = 2n_{core}k(\beta_l^2 - \theta^2)\exp\left[-\frac{2}{3}n_{core}kR\left(\beta_l^2 - \theta^2 - \frac{2a}{R}\right)^{3/2}\right],
\]

(1)

where \(n_{core}\) is the refractive index of the core, \(k = 2\pi/\lambda\) is the propagation constant, \(\lambda\) is the free-space wavelength of the light, \(\theta_c\) is the critical angle for propagation, \(a\) is the radius of the fiber, and \(R\) is the bending radius. To determine the accurate fit of the bending loss, we have followed a similar procedure as described in Ref. 17. The numerical aperture of the fiber is measured, providing the angular power distribution of the fiber. The measured numerical aperture of the multimode fiber was fitted to Supergaussian function

\[
P(\theta) = \exp[-(1/2b)|\theta|c]; \quad \text{with} \quad b = 10.95, \quad c = 4.95.
\]

The exponential loss induced by the bend according to Eq. (1) is calculated at each angle, and the transmitted power is determined with respect to the total input power.

The bending loss measurements at bending radii <5 mm were masked by the physical rigidity of the fiber. As can be seen in Fig. 3, when the mandrel dimensions became too small, the fiber failed to conform to the mandrel. The plot points for sub 5-mm radius in Fig. 3 indicate the
mandrel size is not the actual bend of the fiber, explaining the divergence between the theoretical loss and the measured loss for <5-mm bending radii. We observed that increasing the tension to ensure that the fiber would conform to the mandrel at these dimensions caused the fiber to break. This is consistent with the fiber bending strength expected from the fiber’s Young’s modulus. From the known fiber modulus, we can estimate the minimum radius at which the fiber will fail under tension to be somewhere between 2 and 3.5 mm.

The power handling of a tightly coiled fiber was also performed. These experiments were performed to simulate a realistic case scenario of high power handling of the fiber when coupled from a stand-alone laser. The laser emission of a 2-μm Thulium fiber laser was focused with a 40-mm focusing length CaF₂ lens, leading to a 70-μm focal diameter spot at the fiber input face. The laser was not modulated. Figure 3 shows the results at the smallest bend radius tested (6.25 mm). The maximum incident power on the front face of the fiber was 8.3 W, with ~5.8 W present immediately before the bend (calculated from the measured output power taking into account the end face reflection loss and transmission loss). A minimum bend radius of 6.25 mm was tested with no damage or transmission drop observed, even after 20 min of continuous monitoring.

4 Summary

We present results for the bending loss for a multimode As₂S₃ chalcogenide fiber over a wide range of infrared wavelengths and a single-mode fiber excited by a 4.6-μm laser. The increase in loss due to tight bends remains below 1 dB even for sub 10-mm bend radii. For packing applications, if the loss of 1 dB is tolerable, the main constrain will be the fiber’s critical mechanical limit, which occurs around 3.5-mm bending radius.

References