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# CO and $CO_2$ Laser Beam Guiding with Silver Halide Polycrystalline Fibers and Hollow Waveguides

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## ABSTRACT

Silver halide polycrystalline infrared (PIR) fibers and hollow waveguides (HWGs) have high transmission at mid-infrared wavelengths from 3 to 18 µm. Their applications include a flexible delivery of $CO_2$ and CO laser power. We investigated transmission of PIR fibers and HWGs at different bending radii using $CO_2$ laser radiation and studied the intensity distribution after the distal fiber. The PIR fibers show only a relatively weak decrease in transmission with increasing curvature 1/R or decreasing bending radius R. This is an advantage over hollow waveguides, where transmission decreases sharply with curvature. Disadvantages are high reflection losses at the PIR fiber end faces due to the high refractive index of 2.15 for wavelengths in the mid-infrared region. To reduce these losses, the surface of the fiber end faces must be treated with several special methods including microstructuring or coupling with an anti-reflective window. The measured near-field and far-field intensity distributions or beam profiles are highly inhomogeneous for both fiber types. For large core diameters of 0.9 or 1 mm, the beam profiles appear to be more homogeneous for the PIR fibers.

**Keywords:** infrared fibers, silver halide polycrystalline fibers, hollow core silica waveguides, infrared laser, beam guiding.

## 1. INTRODUCTION

The $CO_2$ (carbon dioxide) laser is a molecular gas laser that generates emission in the infrared region between 9 and 11 µm. Continuous-wave $CO_2$ lasers usually operates at 10.6 µm. Carbon dioxide lasers are widely used as industrial lasers for laser material processing, in particular for cutting, welding, soldering, etc. Moreover, $CO_2$ lasers are also used in laser surgery. Carbon-dioxide lasers have high output powers up to about 100 kW in cw mode and have high power conversion efficiency about 10-20%. $CO_2$ lasers are proven to be reliable over the past 50 years [1].

The laser design of CO (carbon monoxide) lasers is similar to $CO_2$ lasers, but with different excitation mechanism and emission wavelength around 5.5 µm. CO lasers have two advantages over the $CO_2$ laser in case of material processing. At first, many materials (e.g. metals, polymers, dielectrics, ceramics and composites) usually have the higher absorption at around 5 µm that leads to more efficient processing. At the same time, CO laser beams can be focused twice as tightly under the similar focusing conditions and thus have four times higher power densities compared to $CO_2$ lasers [1]. Relatively only recently CO lasers overcame challenges restricted them to only lab applications and now are available on the market with an acceptable reliability and lifetime required for industrial applications.

The industrial and medical applications of these lasers can be essentially extended by means of flexible fiber-optic cables that transmit the laser power to desired locations. There are plenty of infrared materials transparent in the spectral range from 2 to 18 µm, but only a few of them can be used for the manufacturing of uniform long-length IR fibers with acceptable optical and mechanical properties [2, 3]. For the mid-infrared spectral range various fibers are commercially available: chalcogenide, polycrystalline silver halide and hollow-core fibers. Here we discuss the silver halide polycrystalline fibers and hollow waveguides that are transparent in the broad wavelength ranges and are capable of transmitting the light from both CO and $CO_2$ lasers.

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### 1.1 Silver Halide Polycrystalline infrared (PIR) fibers

PIR-fibers are fabricated by hot extrusion from crystals of silver halide solid solution $AgCl_{1-x}Br_x$ (where $0 < x < 1$) and are transparent in a broad range 3 – 18 μm which includes so called "finger-print" region of the spectrum (3 – 16 μm). In contrast to the most IR materials AgCl:AgBr crystals are non-toxic and non-hygroscopic. Polycrystalline infrared (PIR) fibers are used for numerous applications like mid-IR spectroscopy, flexible IR pyrometry, flexible IR-imaging systems, modal wavefront filtering, power delivery for quantum cascade lasers, CO– and $CO_2$−lasers [2, 4-6]. These fibers have a polycrystalline nature: they are composed of small crystallites with grain sizes of several micrometers. PIR fibers have low attenuation losses, but high Fresnel losses about 25% from both fiber end faces due to the high refractive index about 2.15 in the mid-infrared region. Typical $CO_2$ laser transmission for PIR fiber with a 1 m length and 1 mm diameter is about 70%. Scheme of typical PIR cable is shown in Fig. 1.

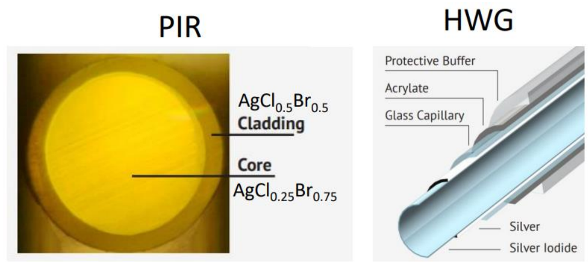


Figure 1. Silver Halide Polycrystalline infrared (PIR) fiber on the left and Hollow Waveguide (HWG) with air-core on the right.

There are several strategies how to overcome and reduce Fresnel losses in case of PIR fibers (Fig. 2). 1) One option is to use a cap with an anti-reflective window inside that pressed to the fiber. In this case we have 2 interfaces: fiber-window and window-air. Such a window must be made of material (for example, diamond) with the refractive index equal or closed to the refractive index of PIR fiber material to reduce the Fresnel losses at fiber-window interface. For window-air interface it is possible to use conventional techniques such as anti-reflective coatings or microstructures. 2) Other option is creating of anti-reflective or so-called "Moth-eye" microstructures to eliminate Fresnel losses. This can be done mechanically by imprinting by master plate with microstructure or simply cutting the fiber end face by profiled knife [7] or using pulsed femtosecond laser ablation [8]. Regarding a $CO_2$ laser transmission, using a cap with anti-reflective window at both fiber ends can give up to 29% relative transmission improvement; anti-reflective microstructures fabricated by imprinting or profiling on both fiber-end faces can achieve 24-30% improvement; In case of anti-reflective microstructures created by femtosecond laser ablation, it is expected to have 13-22% improvement when both fiber-end faces are treated. It is worth to mention that anti-reflective coatings can be also used for PIR fibers, but they have several drawbacks and limitations in this case [7].

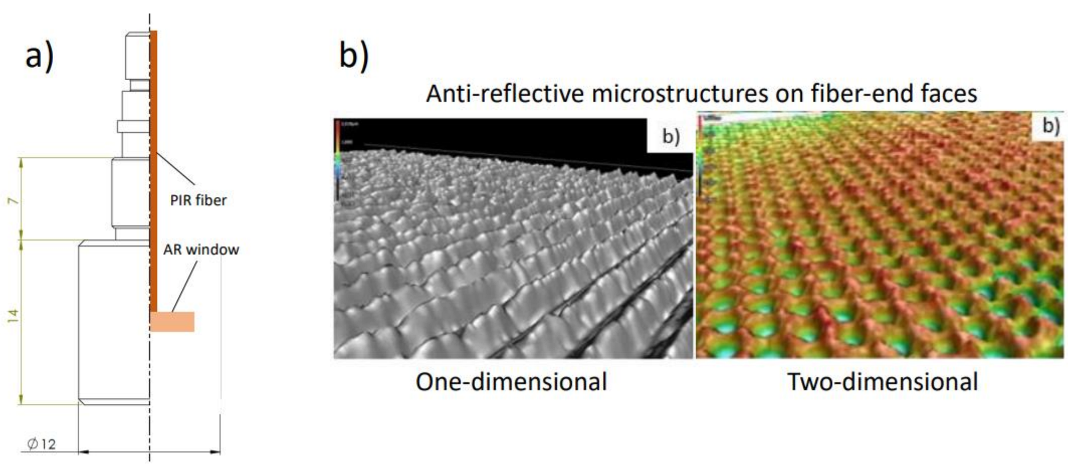


Figure 2. Strategies to reduce Fresnel reflection losses on PIR fiber-end faces. a) Cap with PIR fiber pressed to the anti-reflective (AR) window. b) Anti-reflective microstructures that can be fabricated on PIR fiber-end faces [7].

### 1.2 Hollow Waveguides (HWGs)

Hollow waveguides provide an alternative way to IR-fibers for flexible delivery of mid IR-laser power and spectroscopy sensing, while their design is based on thin tubes with metal and dielectric layers deposited on internal wall surfaces. Scheme of typical HWG cable is shown in Fig. 1. HWGs are characterized by ability to transmit wavelengths above 2 µm and even beyond 20 µm, air core that makes them a good candidate for high-power laser delivery, relatively simple structure and low cost [2]. HWGs have high laser power thresholds, low insertion loss, no end reflection, ruggedness, and small beam divergence. Drawbacks include higher bending losses compared to PIR fibers, small numerical aperture and relatively short available lengths [6]. It's applications also include spectroscopic, for example gas spectroscopy, laser surgery and others. Losses depend on the optics at the input (see Fig.3), and the optimal optics for an efficient light coupling can be calculated theoretically [9, 10]. In case of high-power applications, the hollow waveguides can also be cooled internally by using a simple air cooling through the air-core. In addition, HWGs can transmit the visible light that is useful especially for laser surgery. In fact, it can be done through the air core or through the cladding.

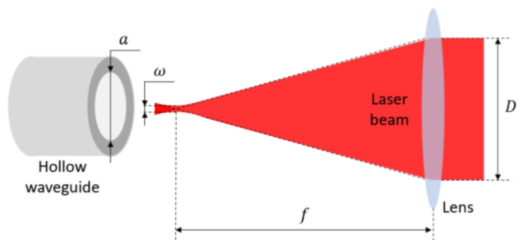


Figure 3. Coupling the light from laser into HWG with internal diameter *a*. Input conditions with the beam waist *ω* at focal point are defined by laser beam (gaussian) with diameter *D* and lens with a focal length of *f*. Corresponding f-number is calculated as *f/D*. Input numerical aperture is calculated as sin(*D/(2f)*).

## 2. EXPERIMENTAL METHODS

Silver Halide Polycrystalline fibers 1-2 m long with core/cladding diameters 400/500, 600/700 and 900/1000 µm and 1-2 m long hollow waveguides with internal diameters 500, 750, 1000 µm were fabricated at art photonics GmbH, Germany. $CO_2$ laser transmission were measured with $CO_2$-laser source (Diamond C-40 air-cooled laser GEM 40A Circular, Coherent Inc., USA) and necessary optical components to guide the laser beam and a power meter to measure transmitted power. Laser beam profiling was done with PYROCAM III (Spiricon, USA). Maximum $CO_2$ laser power was about 40 W. Transmission and beam profile measurements were done with laser power of about 1-3 W. Note that maximum recommended laser power depends on the diameter of waveguides according to their datasheets. Output numerical aperture were analyzed by measuring a beam divergence using a pinhole approach where the transmitted power is measured at regular intervals from the pinhole.

## 3. RESULTS AND DISCUSSION

For high power applications in order not to damage the fiber the near field distribution or intensity profile on the fiber end face must be analyzed. Resulted typical speckles are obtained with a $CO_2$ laser and presented in the Fig. 4 for PIR fibers and Fig. 5 for HWGs. For industrial and lab applications it is interesting to look at the far field intensity distribution of the output beams. The experimentally measured beam profiles for PIR fibers and HWGs are presented in Fig. 6 and Fig. 7. The measured beam profiles are highly inhomogeneous for both fiber types. For large core diameters of 900 or 1000 µm, the beam profiles appear to be more homogeneous for the PIR fibers. Note that in general beam divergence for HWGs (about 5.7° corresponding to numerical aperture of 0.05) are much smaller compared to the PIR fibers (about 35° corresponding to numerical aperture of 0.3).

As shown in Fig. 8, transmission and output beam divergence of HWGs strongly depend on the input parameters, such as laser beam diameter and focal length of the lens, i.e., f-number. They also depend on bending and internal diameter. While theoretically, output numerical aperture matches with the input numerical aperture, in practice it can be higher.

During the bending additional losses take place, especially for the HWGs. Dependence of the transmission of $CO_2$ laser radiation on the curvature is presented in Fig. 9 where we can see that PIR fibers with reduced Fresnel losses can also achieve high transmission as HWGs and have more stable transmission under the bending. Bending losses for HWGs and PIR fibers are presented in Fig. 10.

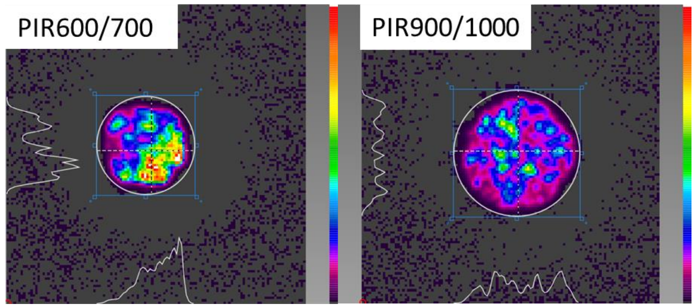


Figure 4. Experimentally measured $CO_2$ laser (10.6 µm) near-field intensity distribution at the output of the PIR fibers with different core/clad diameters (in µm). Numerical aperture at the input was 0.036.

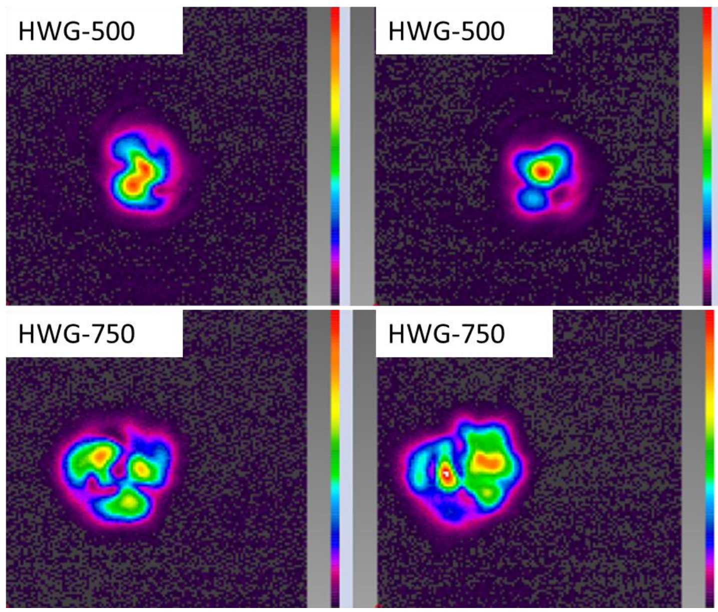


Figure 5. Experimentally measured $CO_2$ laser (10.6 µm) near-field intensity distribution at the output of the HWGs with different internal diameters (in µm). Numerical aperture at the input was 0.036.

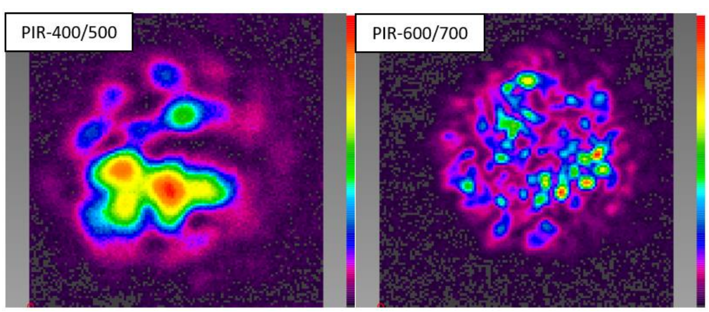


Figure 6. Experimentally measured $CO_2$ laser (10.6 µm) far-field intensity distribution at the output of the PIR fibers with different internal diameters (in µm). Numerical aperture at the input was 0.036.

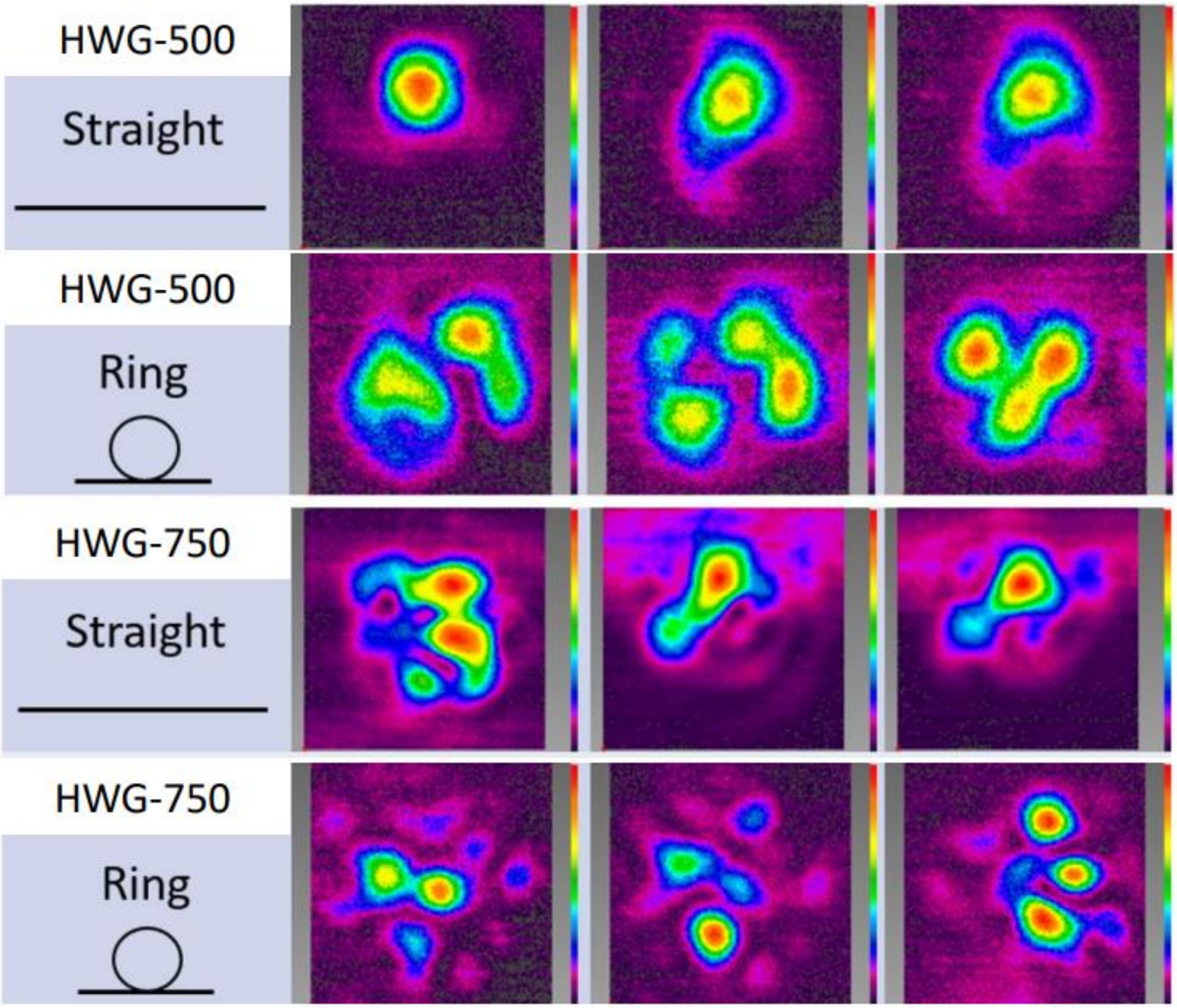


Figure 7. Experimentally measured $CO_2$ laser (10.6 µm) far-field intensity distribution at the output of the HWGs with different internal diameters (in µm). Numerical aperture at the input was 0.036. „Ring” refers to the cable with a single loop in the middle with 40 cm diameter. „Straight“ refers to the straight cable with only slight bending.

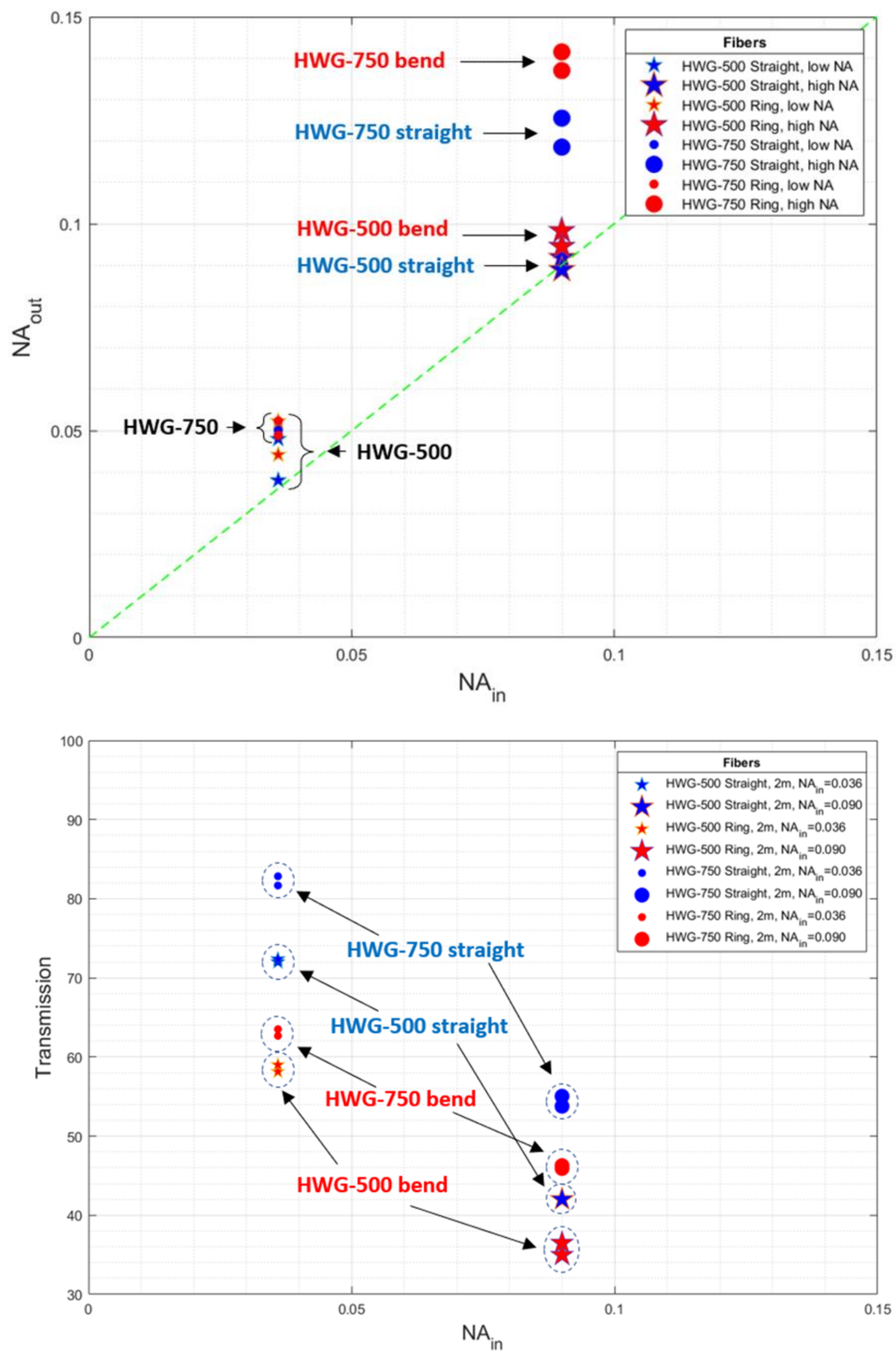


Figure 8. Output numerical aperture and transmission depending on numerical aperture at the input.

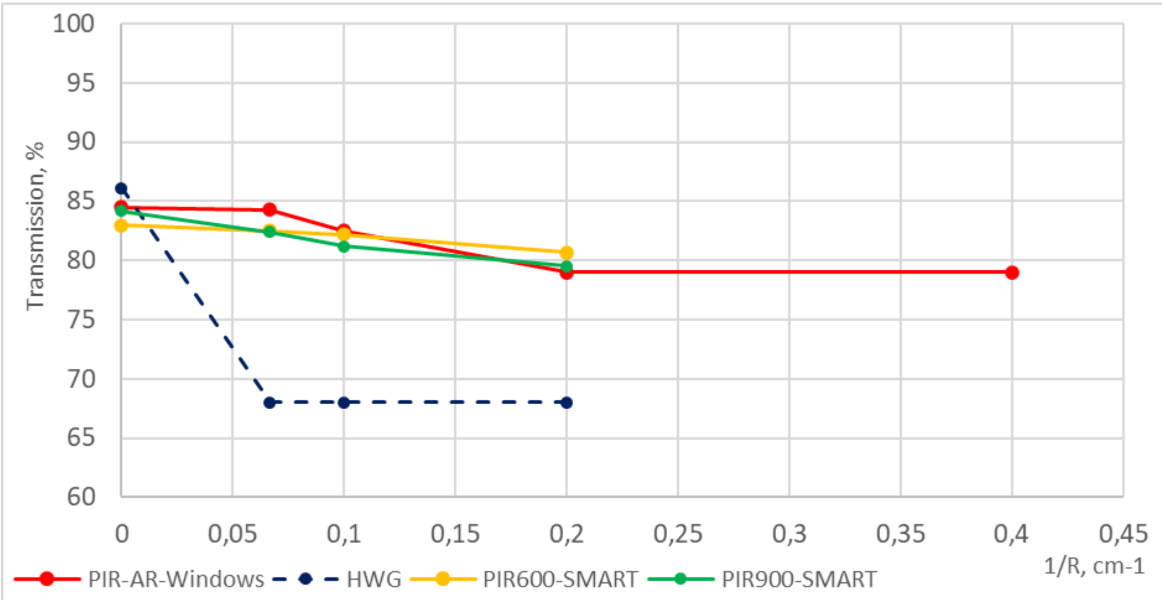


Figure 9. Dependence of the fiber transmission of the $CO_2$ laser radiation on the curvature 1/R in case of single loop. PIR-AR-Windows is a PIR fiber with the end face pressed to anti-reflective window inside a cap. SMART is a one-dimensional anti-reflective microstructure on the fiber end face fabricated by profiled knife.

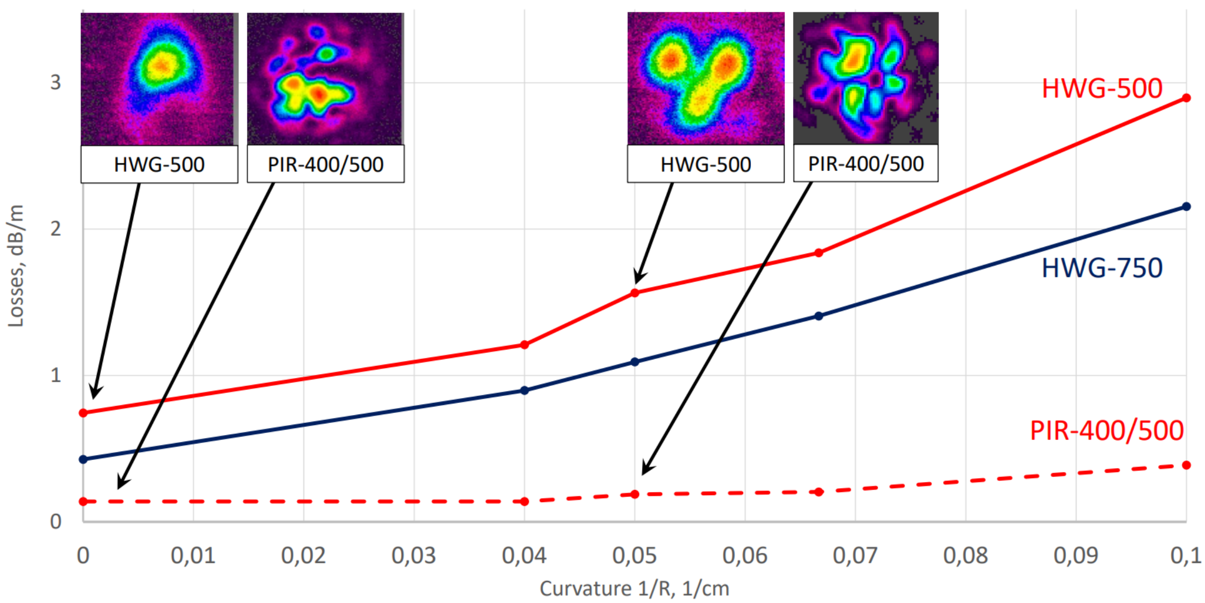


Figure 10. Losses in case of bending for HWGs and PIR fiber. Input numerical aperture 0.036. Corresponding beam profiles (far field) are presented.

## 4. CONCLUSIONS

PIR fiber and HWGs can transmit light in the broad wavelength range from 3 to 18 µm and are excellent candidates for CO and $CO_2$ laser power flexible delivery. PIR fibers have large numerical aperture, and their transmission is stable during the bending. Their performance can be increased by eliminating the Fresnel losses using different techniques so that the PIR fiber can have transmission similar to HWGs. HWGs don't suffer from Fresnel losses and have a much lower numerical aperture with low divergence and more clear intensity distribution of the output beam. However, HWGs are much more sensitive to the bending. Some of the discussed parameters of PIR fibers and HWGs are summarized in the Table 1.

Table 1. Some of characteristics of PIR fibers and HWGs that are important for a laser beam guiding.

| **Parameter** | **Silver Halide Polycrystalline fibers (PIR)** | **Hollow Waveguides (HWG)** |
|---|---|---|
| Fresnel reflection losses | ~25% for 10.6 µm ($CO_2$ laser) | None |
| Transmisison improvement strategies | - Cap with AR-window<br>- Anti-reflective microstructures | Choosing a proper optics for an optimal coupling |
| Numerical aperture | ~0.3 | ~0.05 (output numerical aperture, depends on the input conditions) |
| Attenuation at 10.6 µm | ~0.2-0.4 dB/m | ~0.3-0.7 dB/m |
| Additional bending losses at 10.6 µm for 360° single loop of 40 cm diameter | ~0.05 dB/m | ~0.5-1 dB/m |
| $CO_2$ laser transmission | Up to 90% with a special treatment | Up to 90% without any treatment |

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