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# INNOVATIVE kW RANGE OPTICAL FIBER BUNDLES

**GAME-CHANGING TECHNOLOGY** FOR MOST DEMANDING APPLICATIONS

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# THE WORLD'S LEADING OPTICAL FIBER PRODUCTION LAB.

For almost 20 years, we've been revolutionizing the world of optical fiber technology with our industry-leading products. Our commitment to persistent innovation and impeccable quality has earned us a reputation as the go-to supplier for global market leaders in healthcare, spectroscopy, science, and beyond.

# 4 different bundle end-treatment technologies

Synthetic silica large core multi-mode step index fiber bundling technology is a well-known solution to optomechanical engineers and original equipment manufacturers for several decades.

The latest fiber bundle end treatment technology dispels the myth that silica/silica, step index, multimode fiber bundles are lossy, while practical studies and usage proves low-loss, kW-range power handling capabilities.

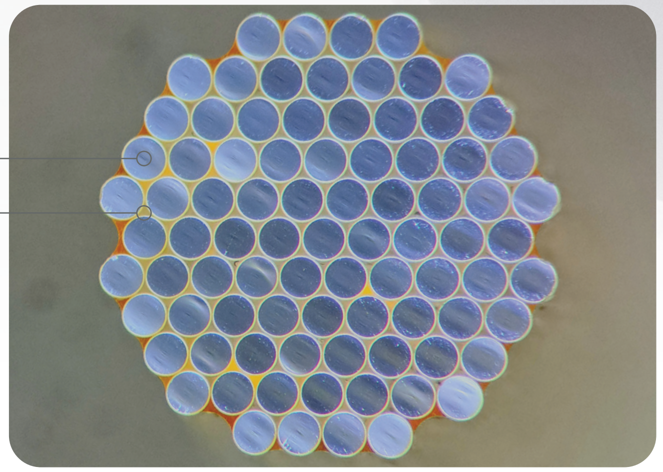
With recent achievements fiber bundling technology has become a powerful solution in combination with superior properties of fused synthetic silica material, like optical transparency in spectral range from 190nm to 2400nm, thermal and chemical stability.

## Lightguide advice and support our customer demands with four different fiber bundle end treatment technologies:

- Glued Bundle (GB)
- Clad Fused Bundle (CFB)
- Hexagon Fused bundle (HFB)
- Monolith Fused Bundle (MBF)

# 4 different bundle end-treatment technologies

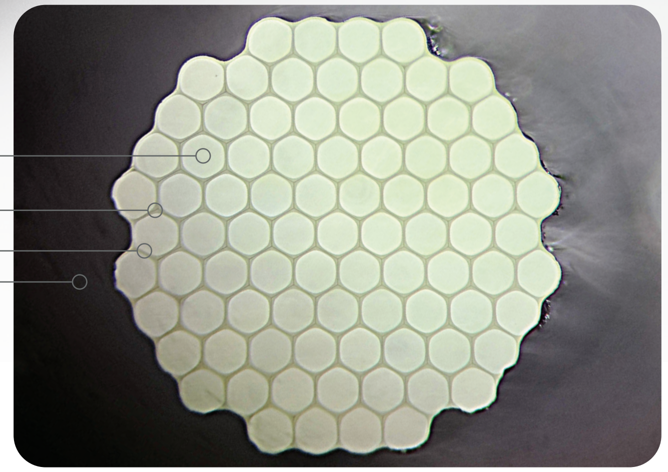
## Glued Bundle (GB)




Individual fiber consists from synthetic silica core and F-doped silica reflecting cladding **(a)** and lost areas in-between fibers are filled with epoxy **(b)**.

This is a simple technology where many fibers are glued together with epoxy glue. There are gaps between fibers caused by the circular shape of individual fibers and packing efficiency. The typical fill factor is around 0.85. Many companies can produce them in different degrees of quality. This is a cost-effective solution when maximum coupling is not required for the bundle outputs.

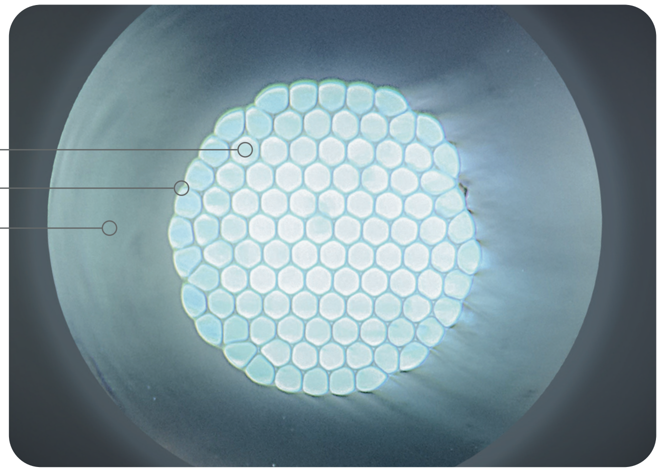
## Clad Fused Bundle (CFB)




During fusing process fibers change shape to hexagonal **(a)** and are packet together in honeycomb structure with no free spaces in-between fibers **(b)**, surrounding fibers are minimally defected **(c)** and fused end is surrounded by air or polymer **(d)**.

The utility of the surrounding silica tube became redundant for the latest CFB end treatment technology – fibers after fusing are hexagonally shaped and creates honeycomb packing. Elimination of the silica tube gives complete freedom of bundle end geometry as positive, negative angles and curvatures are possible now. Peculiarities of this technology determine that the fiber bundle pattern will not vary from bundle to bundle; surrounding fibers are not deformed too. Misaligned light will be dissipated in heath avoiding damage of assembly.

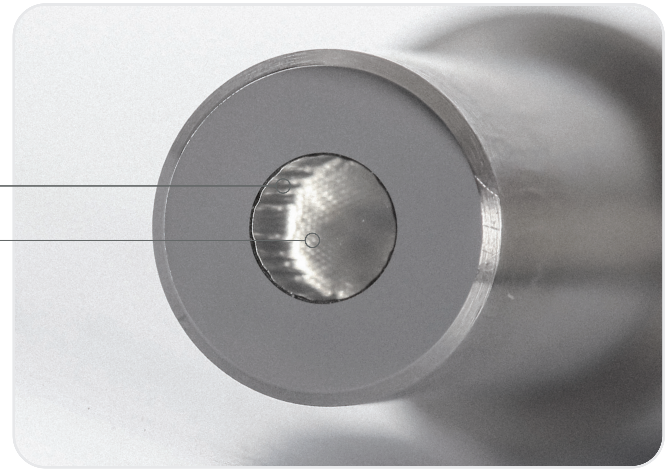
## Hexagon Fused bundle (HFB)




Fibers are pressed together with silica tube **(c)**. Fibers change shape to hexagonal and are packet together in honeycomb structure **(a)**, while surrounding fibers are defected and active end of bundle deviates from circular shape **(b)**.

This technology was developed around 30 years ago in order to increase the packing coefficient. Fibers are aligned together within a silica tube and fused together. During the fusing process fiber clads are melted together, shape of individual fibers transforms to hexagonal. Fibers create honeycomb-like packing after fusing with no ineffective gaps between fibers. The typical fill factor for all active area is around 0.93. Absence of glue at the bundle end allows to achieve better transmission and make bundles more applicable in harsh environments. Misaligned light coupled in surrounding silica tube will be absorbed and can cause permanent interruption of functionality.(b).

## Monolith Fused Bundle (MBF)



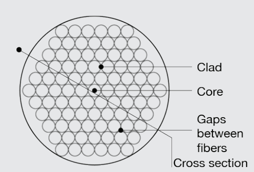
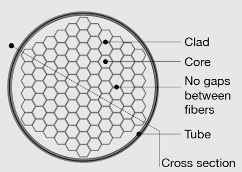
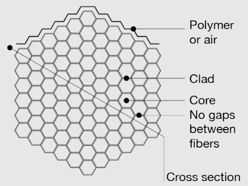
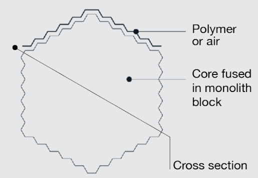
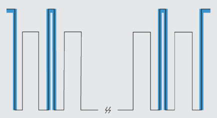
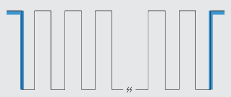
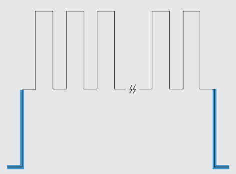
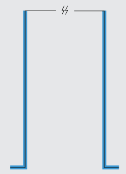

During fusing process silica fiber cores create monolith structure in length ~2cm **(a)**, while in a dept is possible to see silhouettes of individual fibers **(b)**.

Comparing CFB and MFB, there the main difference is that fiber clads are removed and the fiber cores are fused together making one monolith body. There are no individual fibers that can be recognized. This type of fused bundle has the same advantages as CFB, however, there is a difference. MFB gives homogenous near field beam profile. MFB is ideal for low power applications, where homogenization is on the agenda.

# Optical characteristics of fiber bundle end-treatment technologies

Lightguide has chosen to use a refractive index profile (RIP) approach to deliver optical principles in the different fiber bundles. Fibers in **HFB, CFB** and **MFB** are fused, eliminating the free spaces between individual fibers. The fibers change their outer shape and altogether create a honeycomb-like structure with no gaps between any fibers. It is possible to provide RIP for cross-sections of different fiber bundles.

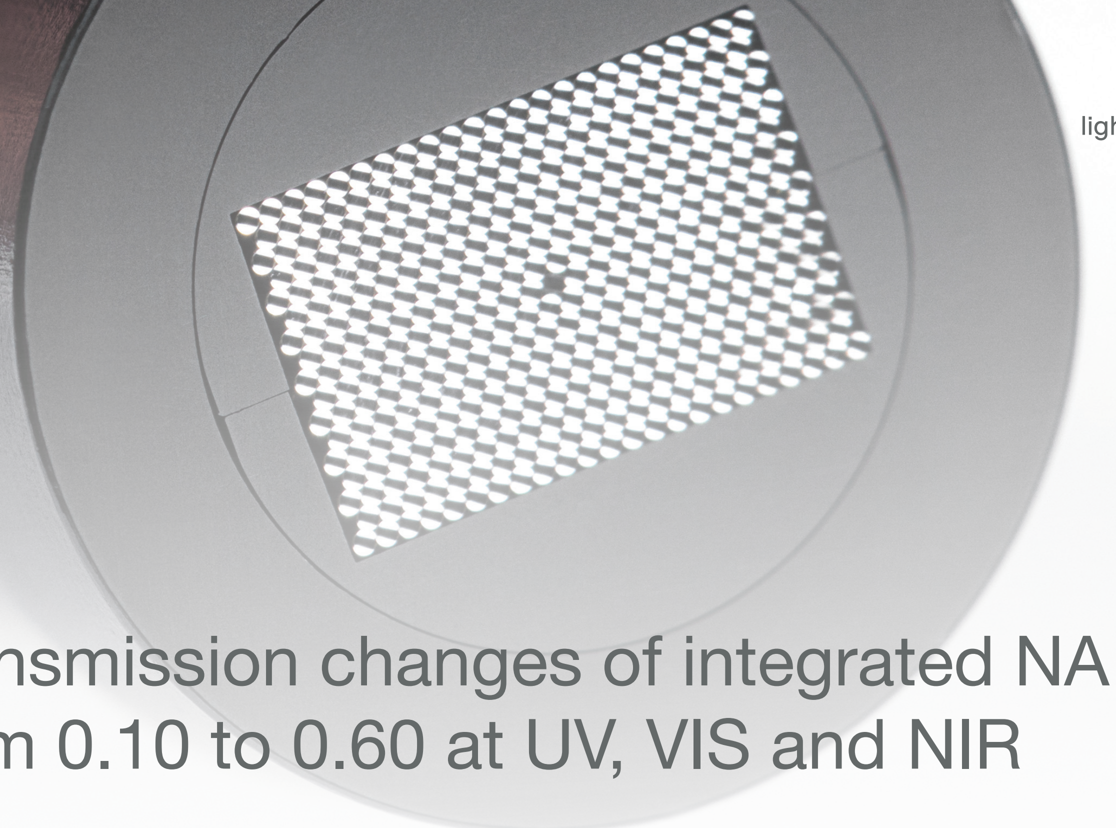
The upper row picture schematically explains the differences of different fused-end fiber bundle technologies. In contrast, the bottom row shows RIPs of corresponding fiber bundle cross-sections. The main difference between conventional HFB and the new fused end fiber bundle technologies CFB and MFB is the absence of the silica tube.

| Technology | Glued | **HFB** Hexagon Fused Bundle | **CFB** Clad Fused Bundle | **MFB** Monolith Fused Bundle |
|---|---|---|---|---|
| Schematic explanation |   |   |   |   |
| Refractive Index Profile (bundle cros-section) |  |  |  |  |

In the HFB design, the refractive index of the silica tube is higher than F-doped silica cladding of the individual fibers. In the CFB and MFB designs the fused fibers have a high refractive index cores and the outer layer of bundle is made of a low refractive index polymer or air.

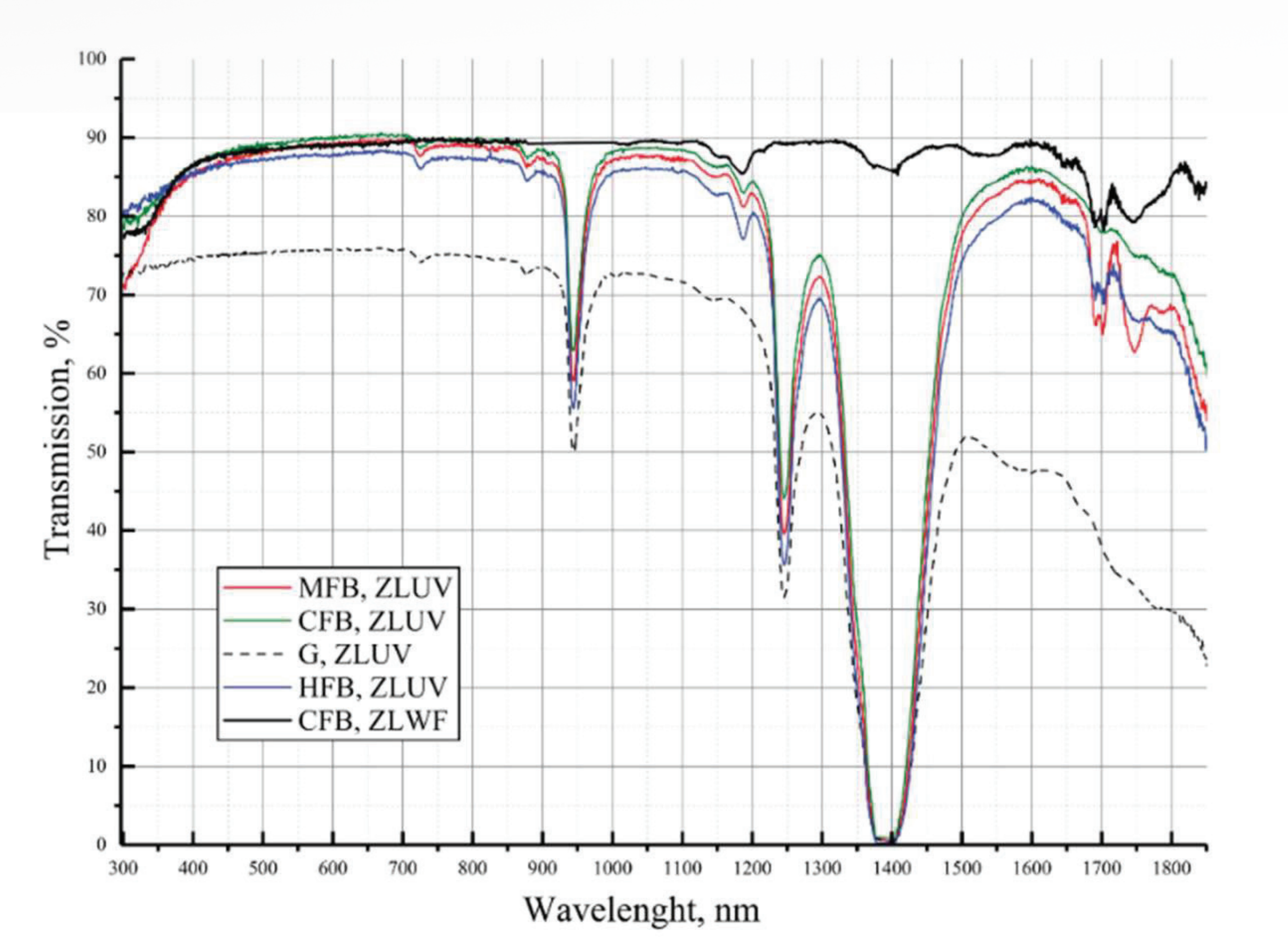
There were produced different fiber bundles for examination with intent to measure transmission in spectral range from 300nm to 1850nm and measure transmission of integrated NA using special setup* at UV, VIS and NIR.

| Abbreviation | Fiber glass Ø, µm | Core OH content | Fiber NA | Fiber count, psc | Fiber length, m | Notes |
|---|---|---|---|---|---|---|
| G, ZLUV | 200 | High | 0.22 | 199 | 1.12 | Bare (jacket removed) fibers, epoxied |
| HFB, ZLUV | 200 | High | 0.22/0.37 | 199 | 1.12 | Fibers fused in silica capillary tube |
| CFB, ZLUV | 200 | High | 0.22/0.37 | 199 | 1.12 | Innovative, silica/silica fibers |
| MFB, ZLUV | 200 | High | 0.22/0.37 | 199 | 1.12 | Innovative, silica/polymer fibers |
| CFB, ZLWF | 260 | Low | 0.22/0.37 | 85 | 1.00 | Innovative, silica/silica fibers |



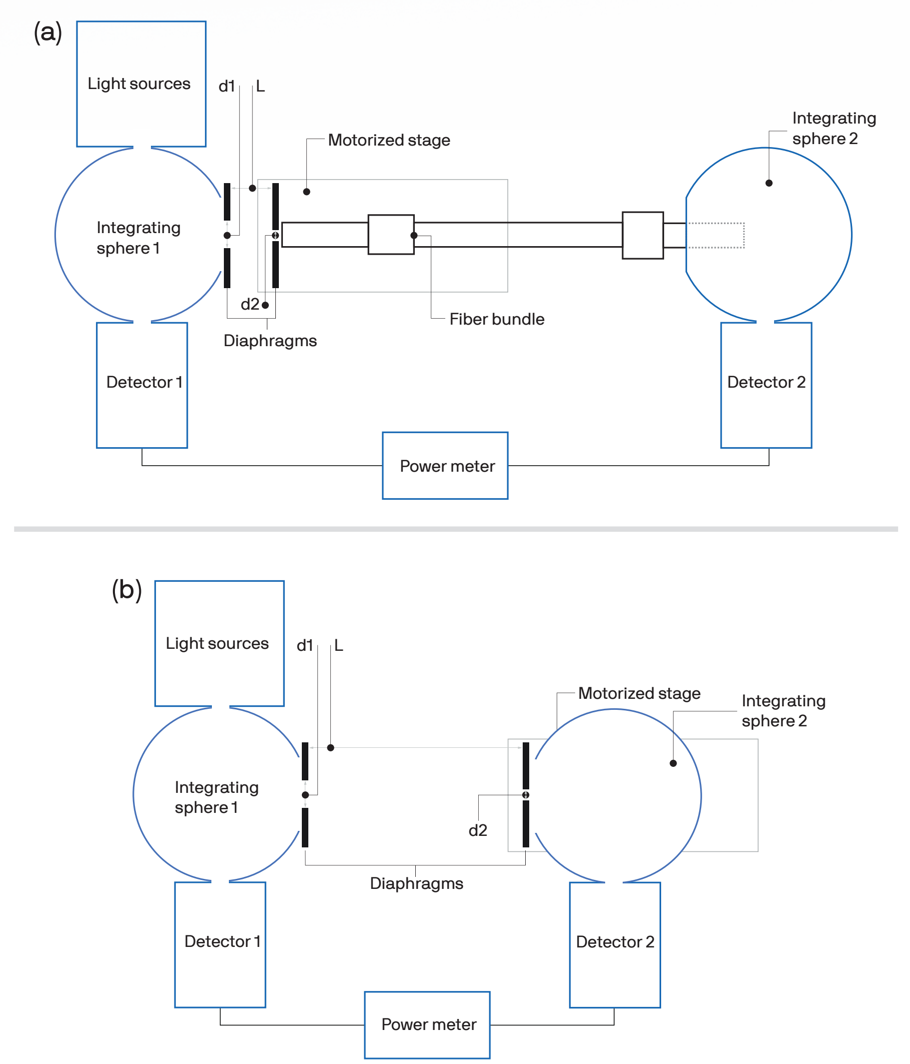
# Transmission of different bundle end-treatment technologies

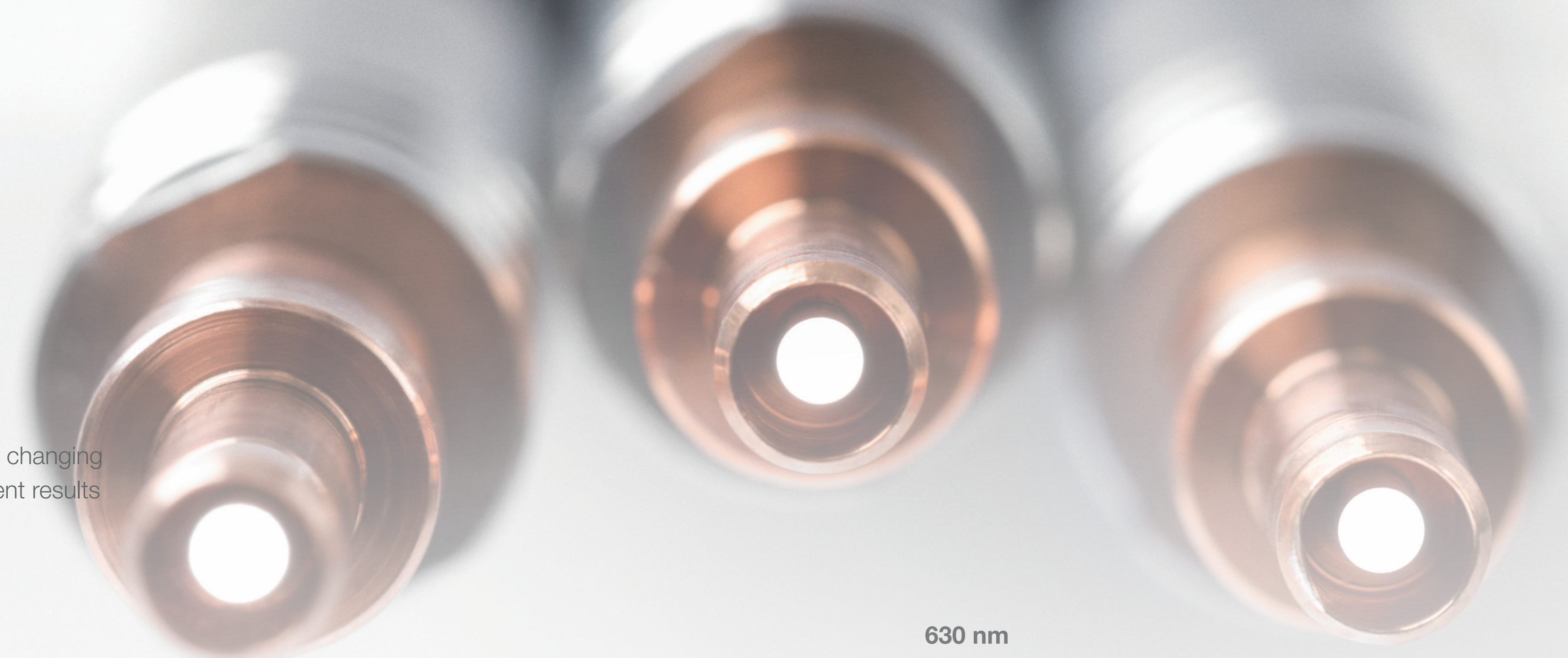
CFB shows a couple to a few percent advantage at NA values up to 0.22, which is a significant gain at high power applications, while superiority of the latest technology bundles from NA 0.22 to 0.37 is significant.




# Transmission changes of integrated NA from 0.10 to 0.60 at UV, VIS and NIR

For measurements of transmission at integrated numerical aperture (NA) following setup was built (a) and measurement setup of reference (b).

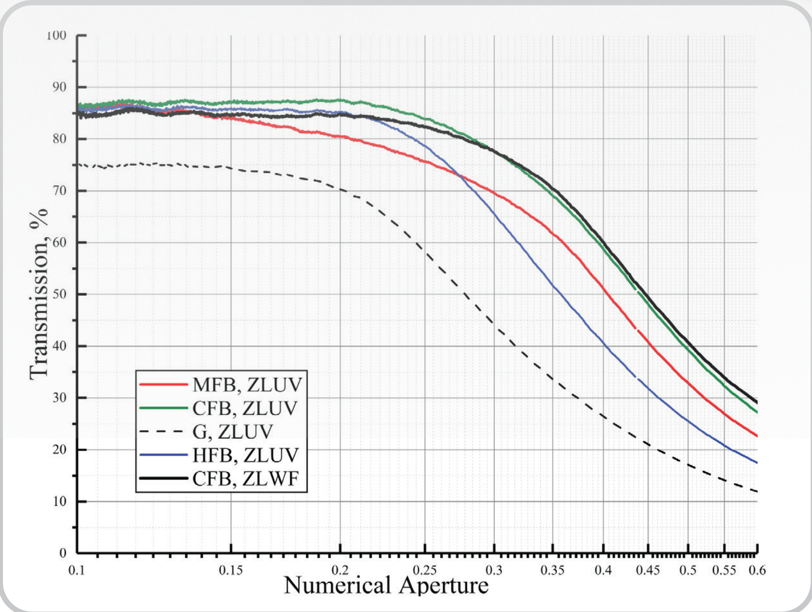




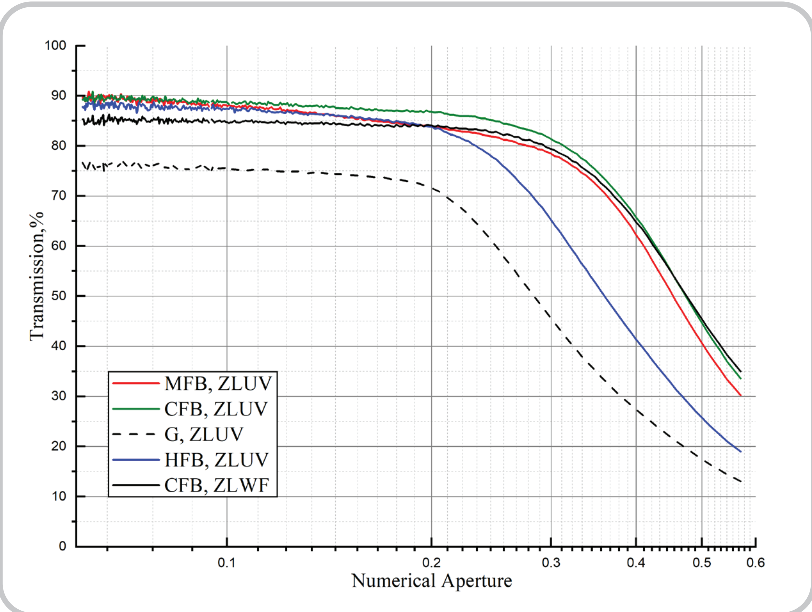
# Transmission data

Transmission data at 365nm, 532nm, 630nm and 1470nm changing NA of cone of incident light from 0.10 to 0.60 shows different results to be kept in mind during fiber bundle designing.

### 365 nm

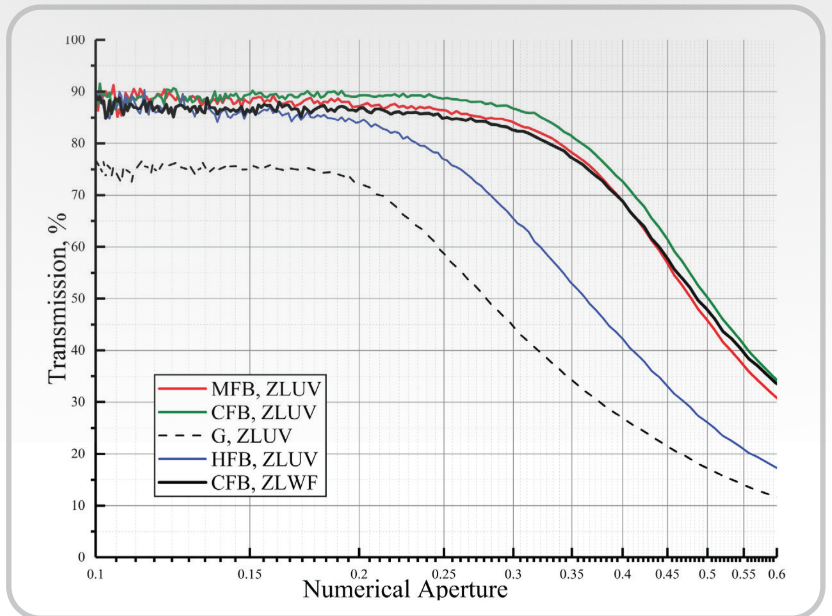



### 532 nm

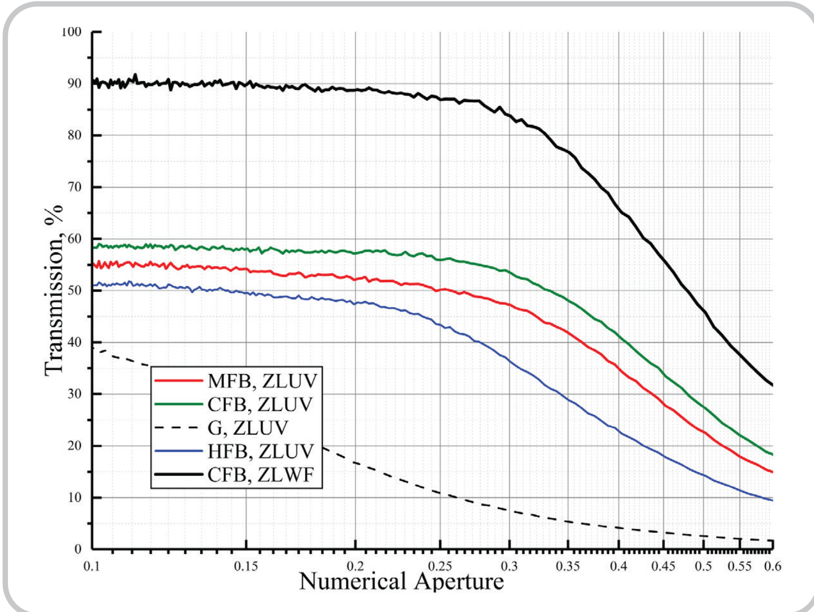


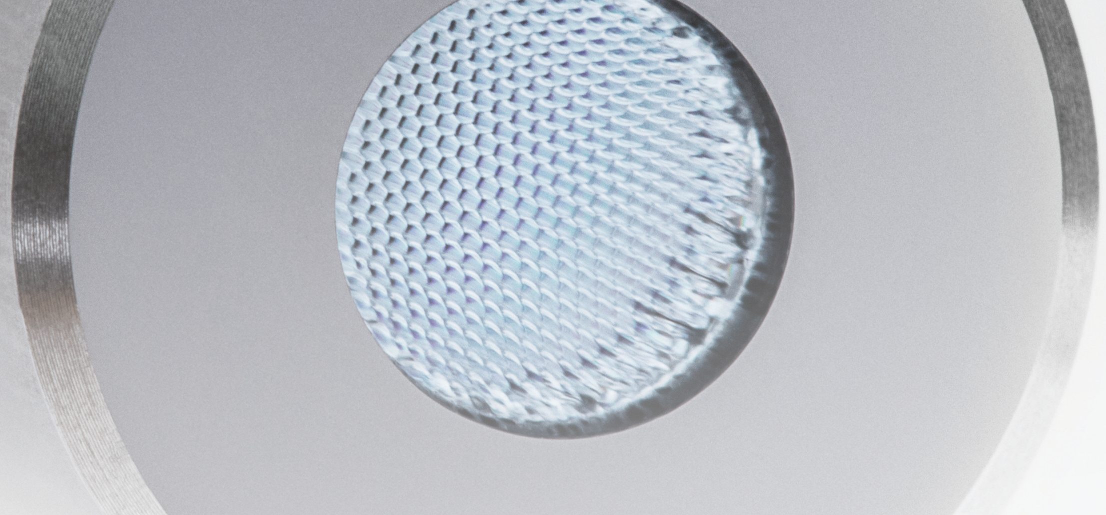



### 630 nm




### 1470 nm

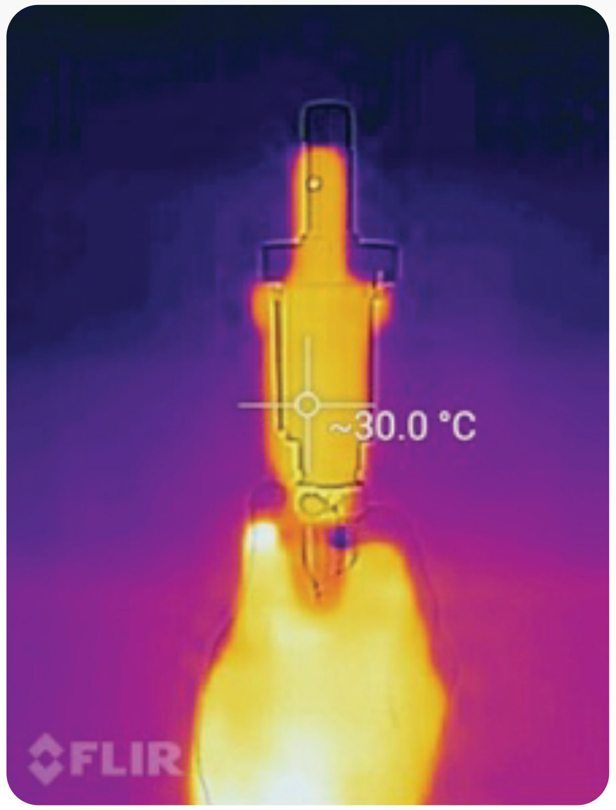




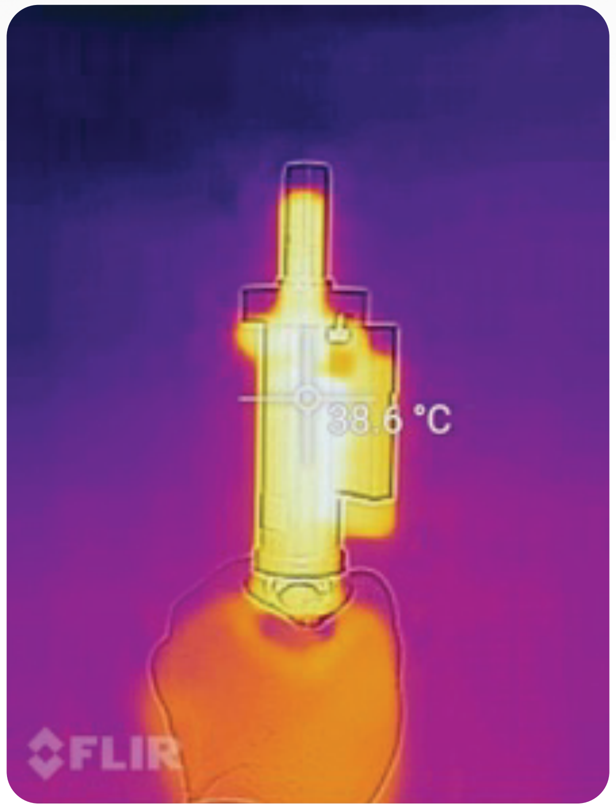
# CFB optical power threshold- kW range

Thermal images of the new generation fiber bundle input and output metal ferrules shows low temperatures of terminations after continuous operation.

Further studies of destructive testing are being continued to determine threshold values. Initial data confirms power handling capabilities of couple kW, CW, NIR.




CFB output after continuous operation at 700W, CW, VIS moment after disconnected from source, >2h operation, no forced cooling. Thermal image displays that temperature of metal ferrule is slightly higher than temperature of a human hand.

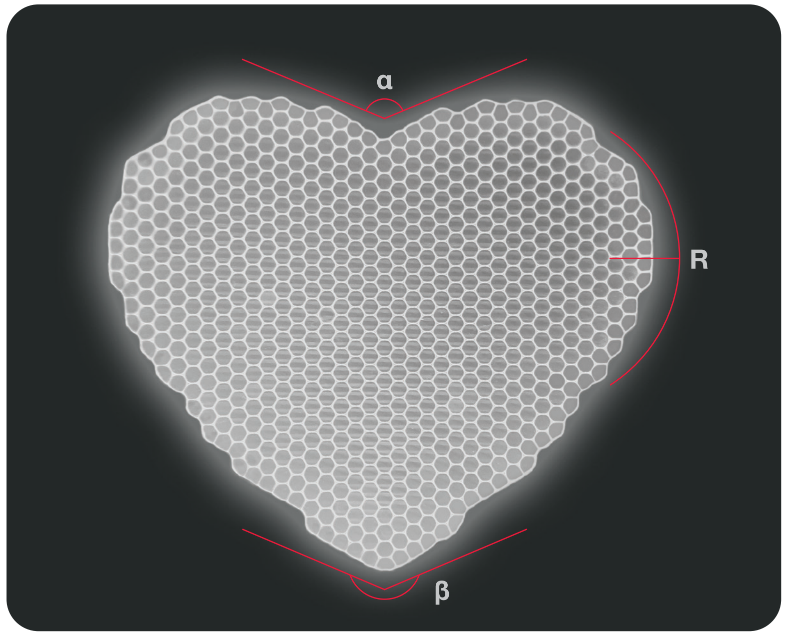



CFB 2.5mm input after continuous operation at 300W, CW, VIS moment after disconnected from source, >2h operation, no forced cooling. Thermal image displays that temperature of metal ferrule is below temperature of a human hand.

# Freedom of optical area shapes

In recent years Lightguide has made significant innovations in fused bundle technologies. It results in two new types of fused-end bundles (CFB and MFB) where the silica tube is removed, and any shape of optical area is possible. Compared to HFB, there are several significant benefits:

- Any shape is possible which leads to maximization of coupling with a light source.
- Smaller bundle diameter can be realized, which requires less space for the bundles.
- Higher precision of the bundle can be realized, repeatability of fiber pattern is defined.
- Higher NA can be achieved due to the outer polymer cladding.
- CFB are suited better for high-power applications.




Inner angle **(α)**, outer angle **(β)** and curvature **(R)** structures are possible

New generation of fused-end bundles allows us to design and produce any active end shape possible to create from individual fibers with the condition, that each fiber is touched by another 3 fibers.

# Countless new applications

Innovative technology dispels the myth that silica/silica, step index, multimode fiber bundles are lossy. Comparable to singe fiber transmission rates allows utilize fiber bundles was not considered in a past.

CFB provides a number of gains, allowing to push the boundaries in fiber bundling technology:

- freedom of fiber bundle end shapes and dimensions
- wide angle of light acceptance cone, what is described by high numerical aperture (NA) values
- packing of fibers in honeycomb-like structures with fill factors close to 1
- high transmission
- utility of low refractive index surrounding medium
- good heat management of mis-coupled light
- design of larger NA light coupling systems gaining output power density
- active areas with dimensions up to 7mm
- maintains flexibility
- input-to-output beam shaping possibilities
- utility at kW range power delivery system
- etc.


**K. Alps, I.Brūvers** “Innovative fused end fiber bundle technology for high-brightness, irregular beam profiles”, Proc. SPIE 12403, High-Power Diode Laser Technology XXI, 124030N (14 March 2023)

# Notes