

# Tailoring Light Coupling to Hollow-Core Fibres: Hyperbolic Micro-Lens based on Gradient-Index Section

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**Abstract** We present a hyperbolic micro-lens design for mode-field adaptation, enhancing butt-coupling efficiency of a 1310 nm laser diode beam into a hollow-core fibre (HCF). Our results show a 6.5 dB improvement with -3.3 dB transmission efficiency. ©2024 The Author(s)

## Introduction

HCF offers numerous advantages over conventional solid fibres<sup>[1]</sup>. Recently, Nested Anti-Resonant Nodeless Fibres (NANF) have garnered attention for their use in telecommunications due to their advantages in reducing latency, achieving attenuation record values even below those of Single Mode Fibre (SMF)<sup>[2]</sup>. Moreover, their low non-linearities make them suitable for high power pumping, reaching several kW<sup>[3]</sup> or even GW<sup>[4]</sup>, which could eventually enable the removal of amplifiers.

Among other characteristics, their large Mode Field Diameter (MFD), in the range of 20-30  $\mu\text{m}$ , represents an obstacle to adopt this kind of fibres due to the challenge of adapting very dissimilar MFDs. With the industry of optical communications primarily based on SMF (MFD around 9-10  $\mu\text{m}$ ), the research often relies on it to couple light onto HCF. Indeed, there is vast research about reducing Insertion Losses (IL) at the inter-connection between HCF and SMF<sup>[5]-[7]</sup>.

Today, there are not many works on coupling a laser diode (LD) to HCF<sup>[8],[9]</sup> and there is a lack of research on coupling of HCF to lasers with small MFD (1-3  $\mu\text{m}$ ) like Distributed Feedback Laser (DFB), even though these are typically used in high-speed optical communications in O or C band. The higher the MFDs misfit between the LD and the fibre, the higher the coupling loss, therefore the problem consists in tailoring the LD and fibre MFDs.

In this paper, we analyse the application of an hyperbolic micro-lens at the end of a Gradient Index Fibre (GIF) (also known as GRADHYP, Gradient index + HYPERbolic profile) to couple the laser beam onto a NANF, going from MFD around 3  $\mu\text{m}$  to 26  $\mu\text{m}$ . Furthermore, we fabricate such an optical solution and we show the transmission efficiency and tolerance of positioning compared to direct butt-coupling without mode-field adaptation.

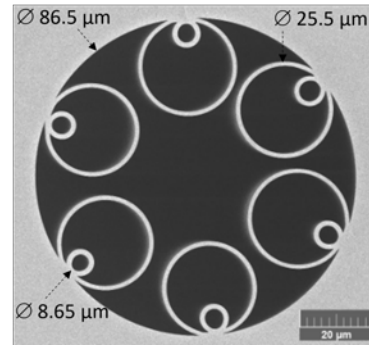


Fig. 1: Electronic microscope image of the NANF.

## Characterization and Analysis

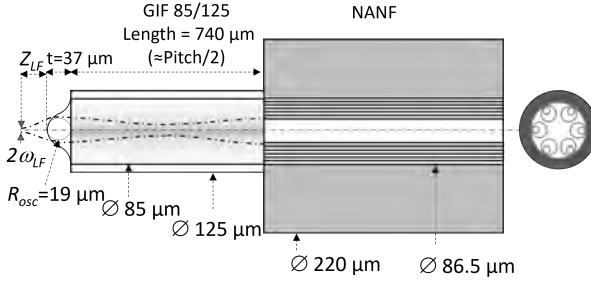
We can see in Fig. 1 the NANF used in this work. It was conceived to work within the O-band (1260 nm - 1330 nm) with their physical dimensions depicted in Table 1. On the other hand, the LD chip is an integrated Distributed Feedback Faser - External Absorption Modulator (DFB-EAM) emitting at a wavelength of 1310 nm with given divergence angles  $16^\circ$  and  $18^\circ$  at Full Width Half Maximum (FWHM), which corresponds to a MFD  $2\omega_{LD} = 3.4 \mu\text{m}$  and  $2\omega_{LD} = 3 \mu\text{m}$  in horizontal and vertical planes of the laser.

Prior to analysing the mode adaptation we measured the actual MFD of both laser and NANF. We followed a near-field analysis<sup>[10]</sup> to measure the fibre MFD. This method analyses the image of the illuminated spot through a microscope objective at an infrared camera to later compare it with a reference, in this case a SMF fibre. With a 100 times magnification objective and 0.95 numerical aperture, this spot was measured in pixels to afterwards scale them to 1.3  $\mu\text{m}$  SMF MFD known value of  $9.2 \pm 0.4 \mu\text{m}$ . We measure for the NANF a MFD of  $2\omega_0 = 26.5 \pm 1 \mu\text{m}$ . For the light source we performed a far-field analysis and measured  $2\omega_0 = 2.85 \pm 0.5 \mu\text{m}$  which is in good agreement with the divergence angle given by the diode provider.

It was thus decided to use a GRADHYP to adapt such a large MFDs difference. Hyperbolic

**Tab. 1:** NANF physical dimensions

Hollow core diameter	$34 \pm 0.2 \mu\text{m}$
Outer microstructure diameter	$86.5 \pm 0.5 \mu\text{m}$
Outer capillary diameter	$25.5 \pm 0.4 \mu\text{m}$
Outer capillary thickness	$\approx 950 \text{ nm}$
Nested capillary diameter	$8.6 \pm 0.2 \mu\text{m}$
Nested capillary thickness	$\approx 925 \text{ nm}$
Outer cladding diameter	$220 \mu\text{m}$

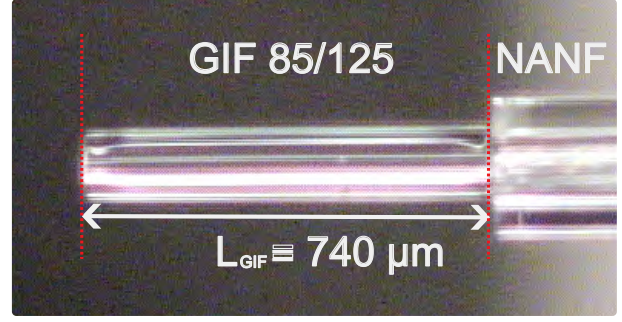


**Fig. 2:** Schematic of a GRADHYP coupled with a NANF

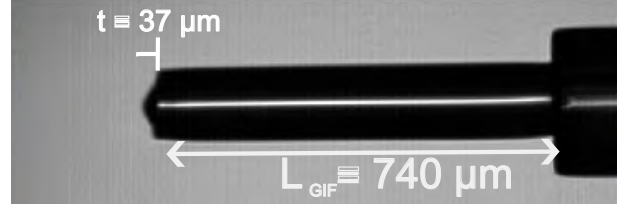
lenses have been extensively studied for coupling optical fibres and LDs<sup>[11],[12]</sup>. The principle of this lens is based on adding a droplet of fused silica at the end of a graded index section spliced to the fibre to be coupled with the laser (see Fig. 2). This profile makes GRADHYP a very interesting option thanks to their key characteristics:

1. Low-coupling loss.
2. Low back-reflections (<50 dB).
3. Compact size, suitable for mass production.
4. Spherical aberrations-free.

Adding this hyperbolic end with a given oscillating sphere radius  $R_{osc}$ , will modify the mode field radius from the initial  $\omega_0$  one to the final one  $\omega_{LF}$  and the beam will collimate at a determined working distance  $z_{LF}$  from the microlens output. The final mode field radius and working distance  $z_{LF}$  are calculated thanks to the ABCD ray matrix law<sup>[13]</sup> in the gaussian beam approximation propagation. To adapt the NANF MFD to the LD one (hence for  $\omega_{LF} = \omega_{LD} = 1.6 \mu\text{m}$ ), we calculated the following adaptation structure: an initial mode radius  $\omega_0$  equal to  $13 \mu\text{m}$  (half the NANF MFD) would need an hyperbolic end radius of  $R_{osc} = 18 \mu\text{m}$  to decrease down to  $1.6 \mu\text{m}$  leading to a working distance  $z_{LF} = 33 \mu\text{m}$ . We also added a GIF section in-between. It was designed for practical reasons due to the challenge of welding the micro-sphere next to the hollow micro-structure of the NANF, composed of air. Traversing the GIF, the MFD varies with a sinusoidal shape (the periodicity in length is also known as pitch) determined by the intrinsic characteristics of the fibre<sup>[14]</sup>. We calculated that with a GIF length of  $L_{GIF} = 740 \mu\text{m}$ , the propagation through the GIF section does not modify the MFD. Moreover, the GIF section



**Fig. 3:** Fused NANF and GIF section before adding the micro-sphere



**Fig. 4:** Final hyperbolic profile at GIF section + NANF

insertion will allow to center the hyperbolic lens on the NANF core axis.

With this structure, the coupling efficiency  $\eta$  would be optimal. On the other hand, a direct butt coupling between this type of LD and the fundamental mode of the NANF would theoretically result in at least 12 dB IL coupling loss. The reader can refer to<sup>[15]</sup> for further explanation regarding coupling efficiency.

#### Fabrication

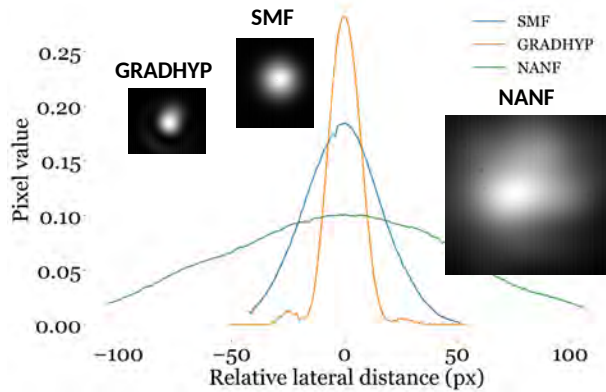
A total length of 1.3 m of NANF (therefore a negligible loss within the fibre) and a small length of GIF 85/125 was straight-cleaved and aligned in a fusion splicer to obtain the best coupling by measuring the transmitted power before splicing. The challenge of the process relies on splicing together the  $125 \mu\text{m}$  cladding diameter GIF without damaging the  $86.5 \mu\text{m}$  micro-structure NANF diameter. The parameters of the fusion-splicer were carefully chosen and a splicing between both sides with IL = 0.6 dB was achieved. The GIF fibre was then cleaved properly to obtain a  $740 \mu\text{m}$  long GIF section (see Fig. 3).

At the end of the GIF section, a GRADHYP with  $R_{osc} = 19 \mu\text{m}$  and full length  $L_{GHYP} = 777 \mu\text{m}$  was obtained including the thickness  $t = 37 \mu\text{m}$  of the hyperbolic section, as shown in Fig. 4. The difference in length before and after adding the hyperbolic droplet of silica on the GIF section is due to the intrinsic procedure of adding matter during the micro-lens fabrication.<sup>[16]</sup>

#### Results and Coupling Efficiency

We repeated the near-field MFD analysis on the GRADHYP (see Fig. 5), and we measured  $MFD_{GHYP} = 3.8 \pm 0.4 \mu\text{m}$ , which is close to the target value of  $3.2 \mu\text{m}$ .

For the coupling efficiency analysis, the LD output power  $P_{LD}$  was measured with a photodiode

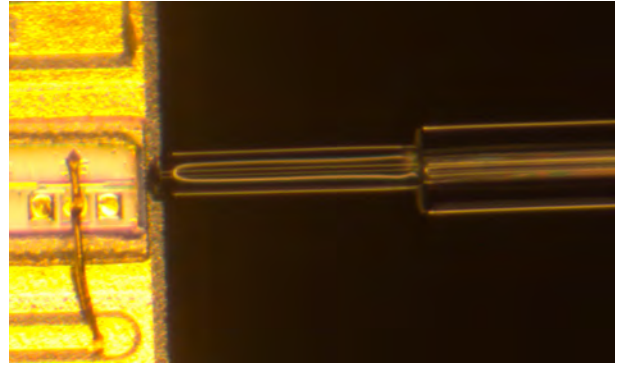


**Fig. 5:** Profile plot for MFD in three fibres. On top, images of three different spots illuminated at an infra-red camera.

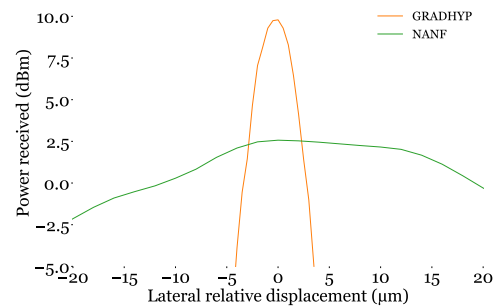
attached to an integrating sphere. The use of this optical device is crucial for this assessment to acquire all of the optical power exiting the cavity. To test the micro-lens, we chose the LD to work at 100 mA at 20°, obtaining  $P_{LD} = 13.6$  dBm. Next, a right-cleaved section of NANF was coupled to the laser, one side at approximately 40  $\mu\text{m}$  far from the laser cavity to avoid collision damage and the other side connected to the same integrating sphere. At this time the maximum power detected was 4.2 dBm, corresponding to 9.4 dB coupling loss compared with  $P_{LD}$ . The discrepancy between the theoretical coupling loss (12.2 dB) and the measured value (9.4 dB) can likely be attributed to the fact that the NANF is not perfectly single-mode. Given the short length of the fibre, some light may propagate through the micro-structures, potentially exciting at least the first higher-order mode. Finally, we placed the micro-lens in front of the laser (see Fig. 6) and we did the same measurement with the GRADHYP-NANF, aligning axes until obtaining the maximum output power  $P_{GHYP} = 10.3$  dBm, meaning only 3.3 dB coupling loss compared with the LD output power. At this point of maximum coupling, the experimental working distance was measured at  $z_{LF} = 35$   $\mu\text{m}$  which is significant to prevent damage collision. Comparing both solutions, we see here an improvement of 6 dB. To avoid higher-order modes or measuring coupled light from the cladding, it was repeated the measurement adding a 470 m extension NANF aligned at the end of the known 1.3 m NANF, finding a nearly exact difference value between and NANF and GRADHYP: 6.5 dB. We also did an analysis of position tolerance. As depicted in Fig. 7, the coupling is significantly improved, yet a lateral displacement becomes critical (adapting the small laser mode with the GRADHYP). This is expected, though, compared to a larger mode of the fibre in front of the LD, where the coupling is poor but the tolerance to lateral displacement is higher.

### Conclusion

Hollow Core fibres are experiencing a strong interest, as they have the potential to overtake



**Fig. 6:** Alignment of the laser chip and the micro-lens.



**Fig. 7:** Position tolerance of coupling

SMFs, while some challenges remain as the integration with common opto-electrical components. This paper has demonstrated a successful butt-coupling between a Distributed Feedback laser and an O-band NANF with mode-field adaptation using a GRADHYP micro-lens. We have highlighted the advantages of this method over direct butt-coupling, achieving a 6.5 dB improvement in coupling losses, demonstrating limited insertion losses to only 3.3 dB to an Hollow Core Fibre.

Additionally, this optical solution offers a flexible working distance, potentially enabling the integration of this component with the laser chip during manufacturing. However, there is potential for further improvement in the engineering process, such as the cleaving or fibre alignment stages as well as the fusion splicing steps. In some iterations of our development, we achieved losses as low as 0.05 dB after fusing the Graded-Index Fibre (GIF) section to the NANF, although the final average was 0.6 dB. This highlights the possibility for further industry optimisations towards achieving near-lossless transmission efficiency.

For future studies, implementing angled splices could reduce back-reflections at the silica-air interface. In any case, this type of component is particularly well-suited to these fibres, as the hyperbolic profile effectively mitigates most of the Return Loss (<50 dB).

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