



Gap design to enable functionalities into nested antiresonant nodeless fiber based systems

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Abstract: By modifying the interconnection design between standard single-mode fiber (SSMF) and nested antiresonant nodeless type hollow-core fiber (NANF), we create an air gap between SSMF and NANF. This air gap enables the insertion of optical elements, thus providing additional functions. We show low-loss coupling using various graded-index multimode fibers acting as mode-field adapters resulting in different air-gap distances. Finally, we test the gap functionality by inserting a thin glass sheet in the air gap, which forms a Fabry-Perot interferometer and works as a filter with an overall insertion loss of only 0.31 dB.

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1. Introduction

Hollow-core optical fiber (HCF) technology has advanced rapidly in the recent years and has become a promising alternative to the ubiquitous standard single-mode fibers (SSMFs). The latest low-loss HCF record of 0.174 dB/km was achieved using double nested antiresonant nodeless fiber (DNANF) [1], which is a significant improvement over nested antiresonant nodeless fiber (NANFs, 0.28 dB/km [2] in 2020 and 0.22 dB/km [3] in 2021). More importantly, this value is at parity with state-of-the-art Ge-doped SSMFs and it is only 0.03 dB away from the state-of-the-art attenuation in Ge-free silica-core optical fiber (~ 0.142 dB/km at 1550 nm) [4]. Encouraged by this impressive progress, the commercialization of the HCF technology has reached early-stage implementation. For example, transmission of 400 Gbit/s over >1000 km of cabled-NANFs in a recirculating loop was recently reported [5].

However, the lack of HCF-based components has been a long-standing challenge when it comes to all-fiber integration and HCF-based networks. In order to enable widespread applications of HCFs, HCF-based couplers, filters, wavelength multiplexers, isolators and other functional components are needed. Furthermore, the HCF-based components should maintain the HCF advantages, i.e. low signal latency [6], low nonlinearity [7], low thermal sensitivity [8] and high damage threshold [9].

To date, most of the research has focused on HCF-based couplers [10–12]. The first hollow-core air-gap antiresonant fiber coupler was demonstrated in 2017 [10], which utilised a dual hollow-core antiresonant fiber structure. Energy transfer was realized between the cores in a sinusoidal pattern along the fiber. The coupling strength can be adjusted by tuning the core diameter and air-gap width. Apart from HCF-based coupler, other HCF-based devices are also under exploration. An HCF-based filter was firstly introduced in 2018 [13], where an antiresonant fiber was heated with a CO₂ laser, which reshaped the fiber structure and resulted in a change in

the thickness of the capillary wall, leading to new transmission bands. Nevertheless, this method required delicate control of power and tension to ensure symmetrical heating without any twists or fiber stretching. This method also lacked the possibility of filter tuning.

An alternative approach to HCF-based components is exploiting directly the SSMF-HCF interconnection which is inevitable in the majority of fiber-optic systems. To provide such a component based on the SSMF-HCF interconnection, an interesting solution was presented in [14] where micro-lensed optics were used to expand, collimate and refocus the beam from SSMF to HCF, thus forming an air gap. The key advantage of this interconnection approach was the possibility to insert optical elements in the air gap and the flexibility of realizing various functions based on the requirements. Functional components such as an HCF-based isolator were demonstrated, with a total loss of 1.5 dB (including 0.53 dB insertion loss when there are no functional elements in the gap, and 0.97 dB additional loss introduced by the isolator).

In this paper, we propose an approach of HCF-based component design without the need for any additional components (such as lenses) in the SSMF-HCF interconnection. We build upon our previous results in interconnecting SSMF (e.g., G.657 or G.652) and HCFs [15,16] and focus on the properties of the air gap between SSMF and HCF with the aim of achieving sufficient gap distance to insert functional optical components directly in the SSMF-HCF interconnection. We propose to significantly increase the air-gap distance by replacing the telecom-standard graded-index (GRIN) fibers acting as mode-field adapters with larger-core GRINs that are available commercially. Besides simulations that show the possibility of obtaining air gaps in excess of 2 mm, we also carried out a proof-of-principle experiment in which we increased the air-gap distance sufficiently to insert a 100 μm thick glass sheet. This glass sheet was uncoated in our experiment, consequently showing Fabry-Perot resonances in transmission. In the future, a thin-film filter could be deposited on its surface and the glass sheet could be tilted to tune its central wavelength. The overall insertion loss with the glass sheet inserted was only 0.31 dB, including 0.28 dB insertion loss when there are no functional elements in the gap and 0.03 dB additional loss introduced by the glass-sheet based Fabry-Perot filter.

2. Design principle and simulation

The SSMF-HCF interconnection we previously developed [15] used an OM2 fiber as a GRIN mode-field adapter (MFA), which was spliced to the SSMF. The GRIN fiber was polished to 0.25 pitch length (collimated beam output) as depicted in Fig. 1(a). This allowed almost perfect expansion of the SSMF mode-field to that of an HCF (6-tube NANF in [15]) resulting in the coupling loss of 0.16 dB. What we observed at that time was that the GRIN MFA and the HCF had a slightly reduced loss when we introduced a small (typically 20-60 μm) air gap in between the MFA and HCF. Here, we firstly experimentally investigate in detail how the loss changes with the gap for various MFA lengths. Further, we investigate the impact of the GRIN MFA parameters on the air-gap distance and design the air-gap size to be sufficiently large to enable the insertion of functional elements into it and thus to obtain added functionality at the SSMF-HCF interconnection.

For a GRIN-based MFA shorter than the 0.25 pitch, the output beam diverges. At 0.25 pitch length, the output beam is collimated (Fig. 1(a)), which is a scenario that was used previously for low-loss SSMF-HCF connection [15]. Once longer than the 0.25 pitch, the beam converges (focuses) first, reaching a beam waist in the air. This is advantageous when an increase in the air-gap size is desired (of interest to us) and low loss can be achieved when the beam waist size reaches that of the HCF fundamental mode. This situation is sketched in Fig. 1(b). We denote the distance from the end face of the MFA to the beam waist position (the air-gap size) as the beam waist distance.

Here, we analyze achievable beam waist distances using four types of GRIN fibers with different core sizes, numerical apertures, and refractive index profiles. These are standard OM2

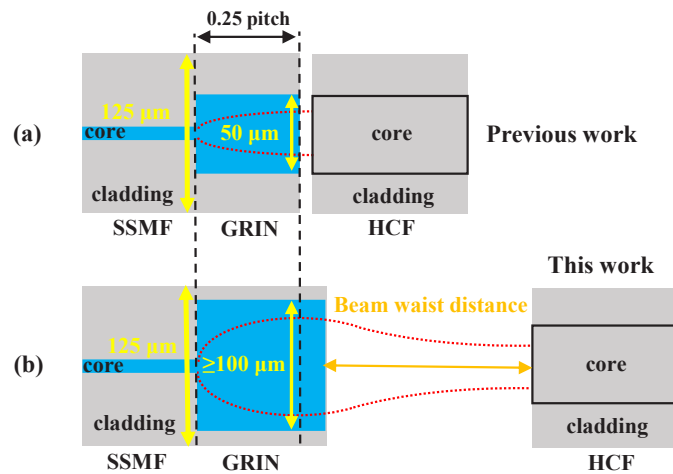


Fig. 1. Beam evolution (red dotted line) (a) when 0.25 pitch GRIN MFA provides ideal mode-field adaptation between the SSMF and the HCF. In [15], this was achieved using GRIN made of OM2 fiber (pictured here). (b) When GRIN provides a larger MFD than the HCF fundamental mode (GRIN100 from YOFC sketched here), it can be made >0.25 pitch long, resulting in output beam focusing, with GRIN length optimized to achieve HCF fundamental mode MFD at the focus and creating the desired air gap.

GRIN fiber from OFS, GRIN100 from YOFC, and two GRIN fibers commercially available from Berkshire Photonics (GRIN200 and GRIN300). The specification of used GRIN fibers are provided in Table 1 and their measured refractive index profiles are presented in Fig. 2.

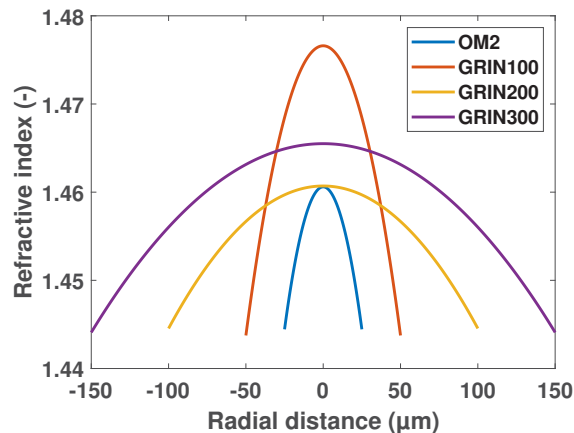


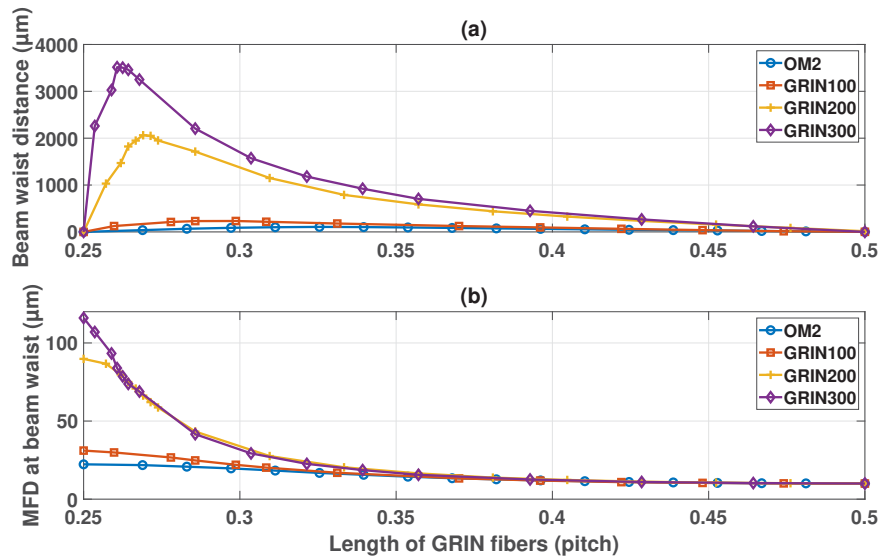
Fig. 2. Measured refractive index profiles of studied GRIN fibers (Table 1) at 1550 nm.

We performed simulations in Synopsys BeamPROP for our four GRIN MFAs. The simulation grid size was $1/3$ of the computation wavelength (i.e., $0.5 \mu\text{m}$). The mode-field first stabilized in the SSMF and subsequently propagated in a sinusoidal pattern in the GRIN segment. We swept GRIN lengths from 0.25 pitch to 0.5 pitch range, in order to estimate how the GRIN length impacts the beam waist distance and corresponding MFDs. The simulation results are presented in Fig. 3.

In Fig. 3(a) we see that the beam waist distance firstly increases with the increased GRIN length, reaching a maximum, and then gradually dropping down to zero when the GRIN length

Table 1. Specifications of GRIN fibers.

GRIN fiber type	GRIN OM2	GRIN100	GRIN200	GRIN300
Core diameter (μm)	50	100	200	300
Cladding diameter (μm)	125	125	220	330
Numerical aperture	0.20	0.29	0.22	0.25
Manufacturer	OFS	YOFC	Berk. Photonics	Berk. Photonics

**Fig. 3.** (a) Beam waist distance, and (b) corresponding MFD, in dependence on the GRIN length for MFAs based on OM2, GRIN100, GRIN200 and GRIN300.

equals 0.5 pitch. The MFD shows a different trend, Fig. 3(b), having maximum MFD at the 0.25 pitch length and then decreasing to $\sim 10 \mu\text{m}$ (MFD of the used SSMF) at 0.5 pitch.

With respect to the beam waist distance, GRIN200 and GRIN300 can provide up to 2.0 mm and 3.5 mm, respectively. These are large enough to insert optical elements such as isolators or Faraday rotators [e.g., Magnet-free Faraday rotator with a thickness of $420 \mu\text{m}$ and corresponding optical length of $966 \mu\text{m}$ at 1550 nm or a GLB (G series, L-band) isolator with a thickness of $390 \mu\text{m}$ and corresponding optical length of $920 \mu\text{m}$ at 1550 nm] [17]. Indeed, the beam waist distance must be larger than the optical length of an inserted element. For GRIN100-based MFAs, the maximum beam waist distance is $\sim 230 \mu\text{m}$, which enables the insertion of thin elements such as thin glass sheet (e.g., microscopic glass sheets) acting as Fabry-Perot filters or as substrates for thin-film filters deposited on them.

To obtain low-loss coupling, we need the MFD at the beam waist point to be equal to the MFD of the fundamental mode of our HCF. Figure 4 shows what are the optimal beam waist distances for our 6-tube NANF with MFD of $26.3 \mu\text{m}$ at 1550 nm that we use in the follow-up experiments. For the OM2-based MFA, the maximum MFD (MFD at 0.25 pitch) is $22.3 \mu\text{m}$, which is smaller than that ($26.3 \mu\text{m}$) of the fundamental mode of our NANF, therefore, the optimum coupling should be obtained when OM2 length is 0.25 pitch and offering no air gap. For GRIN100-based MFA, the MFD at 0.25 pitch is $31.1 \mu\text{m}$, decreasing to the target $26.3 \mu\text{m}$ at GRIN length of ~ 0.28 pitch, offering an air-gap of $230 \mu\text{m}$. For GRIN200- and GRIN300-based MFAs, maximum achievable MFDs are $90 \mu\text{m}$ and $116 \mu\text{m}$, respectively, and the optimum coupling into our HCF

should be obtained at beam waist distances of 1.1 mm and 1.7 mm, respectively with GRIN lengths of ~ 0.31 pitch for both of them.

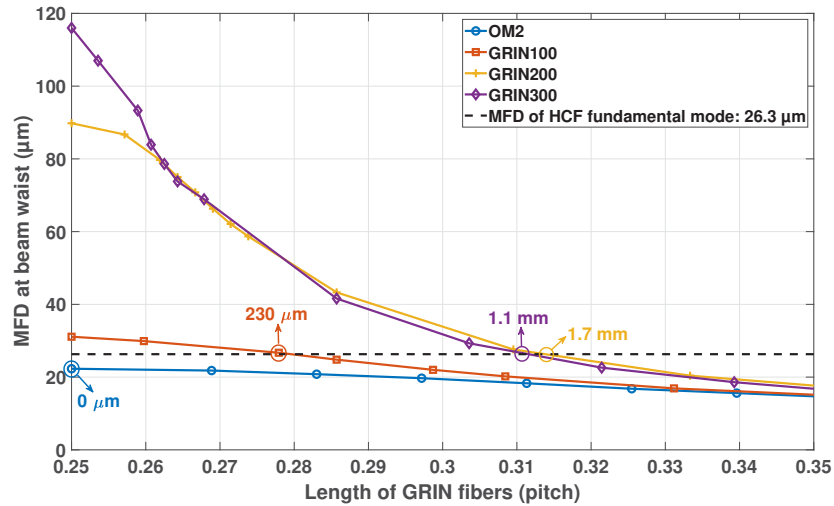


Fig. 4. MFD at beam waist in dependence of GRIN length and comparison of gaps provided by different types of GRIN-based MFAs under optimum coupling.

In this paper, we decided for proof-of-concept to verify our model on GRIN100-based MFA and compare it with the formerly used OM2-based MFA. GRIN100 has a cladding diameter identical to SSMF and offers a sufficient air gap for the proposed function demonstration.

3. Fabrication and measurement

To verify our simulation results, we have measured the coupling loss dependence on air-gap distance for both OM2- and GRIN100-based MFAs. We prepared a set of OM2-based MFAs with different OM2 lengths (0.25 pitch, 0.30 pitch, 0.31 pitch, 0.32 pitch and 0.37 pitch). For GRIN100-based MFAs, we also prepared a set of samples with GRIN100 lengths of 0.25 pitch, 0.28 pitch, 0.29 pitch, 0.31 pitch and 0.33 pitch. Both sets were prepared without anti-reflective coatings, as the goal was first to find the optimal gap distance.

The experimental setup is presented in Fig. 5. An Erbium-doped fiber amplifier (EDFA) was used as a broadband light source. The signal then passed through an optical bandpass filter (OBPF) narrowing the bandwidth to 1545-1555 nm. After that, the filtered signal was sent to the device under test (DUT), which consisted of an input GRIN-based MFA connected to the HCF, and HCF output was aligned to the output MFA with a fixed gap and it stayed untouched for the whole measurement. The used HCF was a 50 m-long 6-tube NANF [18] with MFD of 26.3 μm at 1550 nm, the microscope image of our NANF cross-section is presented in Fig. 5. Subsequently, the signal was split via a 3 dB coupler and detected by a power meter (PM, Thorlabs S154C) and an optical spectrum analyzer (OSA, Yokogawa AQ6370).

For precise insertion loss measurement, we first reference our setup by splicing the OBPF output pigtail to the input pigtail of the 3 dB coupler. Then we cut this splice and spliced in our DUT. The insertion loss per interconnection is then calculated as the measured insertion loss minus the HCF loss (0.04 dB) and divided by two. The samples were measured one by one. The air-gap distance was increased from 0 to 280 μm with a step of 20 μm . The results are shown in Fig. 6 for both OM2- and GRIN100-based MFAs. Note, that all the prepared samples are affected by Fresnel losses, which add 0.16 dB/interconnection. This can easily be remedied by an anti-reflective coating.

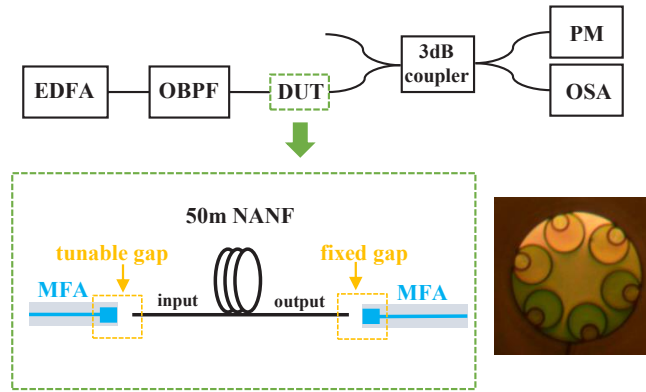


Fig. 5. Experimental setup (EDFA: erbium-doped fiber amplifier, OBPF: optical band-pass filter, DUT: device under test, PM: power meter, OSA: optical spectrum analyzer, MFA: mode-field adapter, NANF: Nested antiresonant nodeless fiber). Insets show DUT detail and microscope image of tested NANF.

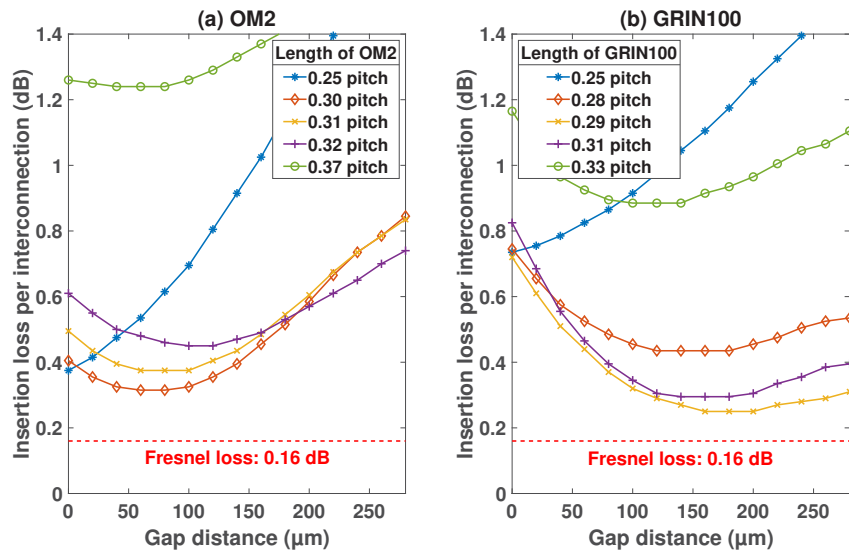


Fig. 6. Insertion loss for a single SSMF-HCF interconnection based on (a) OM2 MFAs and (b) GRIN100 MFAs.

From the results we can see that for GRIN MFA length of 0.25 pitch, the coupling loss increases with the air-gap distance, leading to no gap or a very small air-gap ($\leq 20 \mu\text{m}$) between GRIN MFA and HCF. For all GRIN MFA lengths longer than 0.25 pitch, the curves follow the same trend. The coupling loss firstly reduces when we enlarge the air gap, then it reaches a minimum, subsequently, the coupling loss increases again if we further enlarge the air gap. This coupling loss minimum is specific for each particular GRIN MFA and selected HCF, leading to a specific beam waist distance.

We can see in Fig. 6 that the maximum-obtainable air-gap distance of low-loss coupling is 60-80 μm and 160-200 μm in the case of OM2-based MFAs with OM2 length of 0.30 pitch and GRIN100-based MFAs with GRIN100 length of 0.29 pitch, respectively. For our NANF, the air-gap distances with low-loss coupling achieved for OM2-based MFAs and GRIN100-based MFAs are concluded in Fig. 7. This correlates well with the simulation results of OM2-based MFAs ($\sim 6 \mu\text{m}$ average offset). For GRIN100-based MFA, we see a constant offset ($\sim 35 \mu\text{m}$) between simulated values and experimental values. We believe this inaccuracy is caused by a slight imprecision in the refractive index profile of GRIN100 in the simulations, as the refractive index profile was measured at 589 nm (by Arden Photonics Ltd.), while our simulations and experiments were carried out at 1550 nm. The cladding refractive index was considered as pure silica and is well known both at 589 and 1550 nm (1.458 vs. 1.444). The maximum core refractive index, though, might have a different shift between 589 and 1550 nm. As we did not know exact doping, we used an approximation by the same shift as the cladding, then did a fitting with this shifted profile and used this fitted curve for the simulation model.

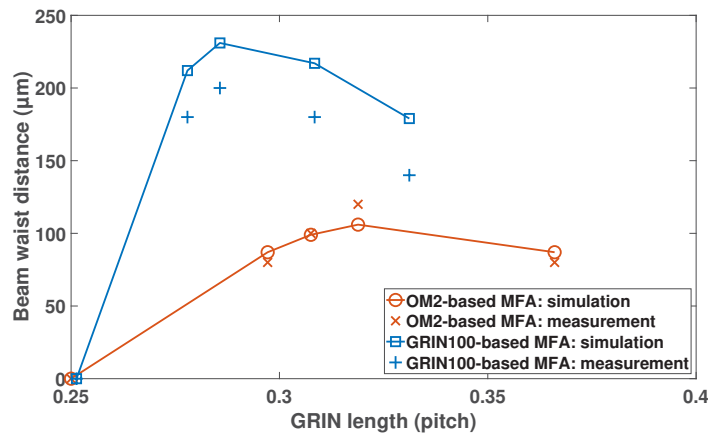


Fig. 7. Comparison of beam waist distances between simulation and measurement provided by OM2-based MFAs and GRIN100-based MFAs.

4. Proof-of-concept demonstration of gap-enabled functionality

The above-achieved gap distance of 200 μm is already sufficient to insert thin functional optical elements, the schematic representation is shown in Fig. 8. For the proof-of-concept demonstration, we have chosen a thin glass sheet acting as a Fabry-Perot filter. The experimental setup is the same as shown in Fig. 5, excluding the OBPF, enabling characterization over a broader wavelength range of 1525-1565 nm. We inserted the glass sheet into the gap between the GRIN100-based MFA (0.29 pitch).

We conducted the experiments with two types of glass sheets: type #0 (Thorlabs, CG00C2) and type #1.5H (Thorlabs, CG15CH2), with thicknesses of $100 \pm 15 \mu\text{m}$ and $170 \pm 5 \mu\text{m}$, respectively. Both of the glass sheets are made from Schott D 263 M Glass, with refractive index of 1.5058 at

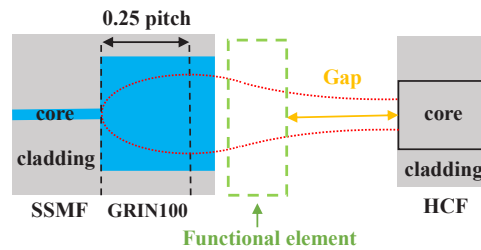


Fig. 8. Schematic representation of our interconnection method to provide additional functionality into HCF-based system.

1550 nm. Therefore, the optical thickness of glass sheet for type #0 and type #1.5H are 150 μm and 256 μm , respectively.

To reference the measurement, we first aligned the HCF with both input and output MFAs, then recorded the power and spectrum as a reference. In the next step, we inserted the glass sheet into the gap, aligned the MFA with HCF, then recorded the power and spectrum again. By comparing the power difference, we calculated the additional loss introduced by the glass sheet. Figure 9(a) and (b) illustrate the Fabry-Perot resonance spectrum resulting from the glass sheet type #0 and type #1.5H, respectively.

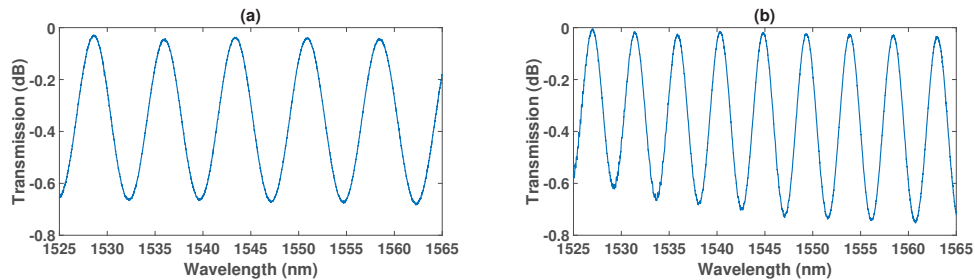


Fig. 9. Transmission spectrum of Fabry-Perot interferometer formed by the precision cover glass (a) #0 (physical thickness: 100 \pm 15 μm), (b) #1.5H (physical thickness: 170 \pm 5 μm).

The free spectral range (FSR) of a Fabry-Perot interference can be calculated as:

$$FSR = \frac{\lambda^2}{2nL} \quad (1)$$

where λ is the wavelength of light, n is the refractive index of the glass sheet and L represents the thickness of the glass sheet. Based on the spectra presented in Fig. 9, we calculated the average FSR, which was 7.25 \pm 0.15 nm and 4.56 \pm 0.07 nm, respectively. Therefore, the thicknesses ($L = \frac{\lambda^2}{2n \cdot FSR}$) of the glass sheets were 110 \pm 2 μm and 175 \pm 3 μm respectively, being in good agreement with the expected values of 100 \pm 15 μm and 170 \pm 15 μm , respectively.

To analyze the glass sheet performance in detail, we measured the additional insertion loss dependence on gap distance (now with the glass sheet inserted). To ensure that the glass sheet is perpendicular to the beam propagation, we observed the interference spectrum and aligned it for maximum transmission contrast. In this measurement, the glass sheet was at a fixed distance (\sim 10 μm) from the MFA and we moved the HCF with a step of 20 μm . The results are shown in Fig. 10.

The additional loss and low-loss air-gap distance introduced by #0 and #1.5H glass were 0.04 dB, 120 μm and 0.03 dB, 80 μm , respectively. The total insertion loss of the SSMF-GRIN

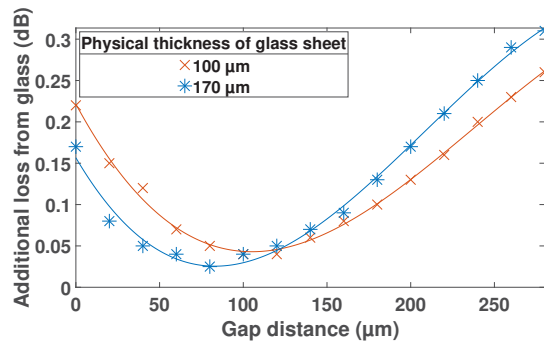


Fig. 10. Additional loss introduced by the glass sheet dependence on gap distance.

MFA-Glass sheet-HCF system is only 0.31 dB (which could be reduced to as little as 0.15 dB if anti-reflective coating is deposited on the GRIN end-facet, as demonstrated previously [15]).

For final packaging of such an HCF interconnection with a functional element in the air-gap, a modified approach based on gluing might be used, as we already demonstrated for fiber-array based HCF interconnection [19], or for glass capillary based HCF interconnection [20]. If needed, all components might be fixed on a supporting platform to improve the system stability and environmental resilience.

5. Conclusions

We have demonstrated that by designing the GRIN mode-field adapter, we can modify the beam waist distance (air-gap distance) in an SSMF-HCF interconnection, which enables the insertion of functional optical elements. Through our MFA design, we can create an air gap of predefined length as well as achieve low-loss coupling.

We measured and characterized the gap distances with OM2-based and GRIN100-based MFAs, respectively. With OM2-based MFA, we reached a gap distance of $\sim 80 \mu\text{m}$, which can be useful e.g., for gas sensing by allowing a gas inlet/outlet [20]. With GRIN100-based MFA, the optimal gap distance was doubled to around $200 \mu\text{m}$. Moreover, this gap can be extended to $300 \mu\text{m}$ at the sacrifice of only 0.06 dB higher insertion loss. The optimal gap distances matched with the simulation predictions of beam waist distances acquired by our MFA models. Furthermore, we also simulated GRIN200 and GRIN300, the gap can be expanded to 1.1 mm by GRIN200 and 1.7 mm by GRIN300, respectively with low-loss coupling to our HCF.

Finally, we demonstrated a Fabry-Perot filter by inserting glass sheets with thicknesses of $100 \mu\text{m}$ and $170 \mu\text{m}$ into the SSMF-HCF air gap. We have verified that our design not only provides low-loss interconnection between SSMF and HCF, but also creates a gap to introduce additional functionalities into an HCF-based system. Our design thus provides a versatile and efficient method to build low-loss HCF-based components without complicated adaption and structural alteration of the fiber.

In the future, it will be possible to insert thicker optical components by using GRIN200- and GRIN300-based MFAs, e.g. a Magnet-free Faraday rotator with an optical thickness of $966 \mu\text{m}$ at 1550 nm or a GLB (G series, L-band) isolator with an optical thickness of $920 \mu\text{m}$ at 1550 nm [17], which is generally used for in-line optical isolators with only a small increase of the component loss.

Funding. Grantová Agentura České Republiky (22-32180S); České Vysoké Učení Technické v Praze (SGS20/166/OHK3/3T/13); Engineering and Physical Sciences Research Council (EP/P030181/1); European Research Council (682724); Royal Academy of Engineering.

Acknowledgement. We would like to thank Arden Photonics for measuring the refractive index profiles of our GRIN fibers.

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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