



**AFRL-AFOSR-UK-TR-2024-0002**

---

Quasi-phase Matched Optical Parametric Amplification in Gas Filled Hollow  
Fiber

**Wadsworth, William**  
**UNIVERSITY OF BATH**  
**CLAVERTON DOWN**  
**BATH, , BA2 7AY**  
**GBR**

---

**11/21/2023**  
**Final Technical Report**

**DISTRIBUTION A: Distribution approved for public release.**

Air Force Research Laboratory  
Air Force Office of Scientific Research  
European Office of Aerospace Research and Development  
Unit 4515 Box 14, APO AE 09421

## REPORT DOCUMENTATION PAGE

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

<b>1. REPORT DATE</b> 20231121		<b>2. REPORT TYPE</b> Final		<b>3. DATES COVERED</b>	
				<b>START DATE</b> 20200915	<b>END DATE</b> 20220914
<b>4. TITLE AND SUBTITLE</b> Quasi-phase Matched Optical Parametric Amplification in Gas Filled Hollow Fiber					
<b>5a. CONTRACT NUMBER</b>		<b>5b. GRANT NUMBER</b> FA8655-20-1-7046		<b>5c. PROGRAM ELEMENT NUMBER</b>	
<b>5d. PROJECT NUMBER</b>		<b>5e. TASK NUMBER</b>		<b>5f. WORK UNIT NUMBER</b>	
<b>6. AUTHOR(S)</b> William Wadsworth					
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> UNIVERSITY OF BATH CLAVERTON DOWN BATH BA2 7AY GBR				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> EOARD UNIT 4515 APO AE 09421-4515			<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> AFRL/AFOSR IOE		<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b> AFRL-AFOSR-UK-TR-2024-0002
<b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b> A Distribution Unlimited: PB Public Release					
<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b> This project was formed in order to investigate the properties of hollow-core optical fibres for optical parametric generation in gases. Phase matching for parametric generation is envisaged to be achieved using a fixed-pitch applied electric field modulation for quasi-phase matching (QPM). For this to be effective over a long length of fibre with many QPM periods the fibre propagation constants need to be very uniform along the fibre length. This requires micron-level stability of the core diameter, placing constraints on the longitudinal stability of the fabricated fibre, both in the size of the deviations and in the length scales over which any deviations occur. This project was to investigate fibre fabrication in the context of improved longitudinal stability and to evaluate the longitudinal uniformity of fibres that were fabricated. The project timing was particularly affected by UK and worldwide restrictions from the COVID-19 pandemic. We were not able to overlap the start of the project with the end of previous projects working on hollow optical fibres of this type. As well as a turnover of researchers, PhD and post-doctoral, there was a challenging recruitment environment for a researcher for this project. We have nevertheless made great progress in improving and understanding of the processes of optical fibre drawing to enable repeatable and uniform fabrication.					
<b>15. SUBJECT TERMS</b>					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>		<b>18. NUMBER OF PAGES</b>
<b>a. REPORT</b> U	<b>b. ABSTRACT</b> U	<b>c. THIS PAGE</b> U	SAR		7
<b>19a. NAME OF RESPONSIBLE PERSON</b> ANDREW GREENWOOD				<b>19b. PHONE NUMBER (Include area code)</b> 314 235 6037	

Standard Form 298 (Rev. 5/2020)  
Prescribed by ANSI Std. Z39.18

Grant N<sup>o</sup>: FA8655-20-1-7046

# Hollow Optical Fibers for Optical Parametric Generation

W.J.Wadsworth

15 SEP 2020 - 14 SEP 2021 (extended to 14 SEP 2022)

Final Report

## Introduction

This project was formed in order to investigate the properties of hollow-core optical fibres for optical parametric generation in gases. Phase matching for parametric generation is envisaged to be achieved using a fixed-pitch applied electric field modulation for quasi-phase matching (QPM). For this to be effective over a long length of fibre with many QPM periods the fibre propagation constants need to be very uniform along the fibre length. This requires micron-level stability of the core diameter, placing constraints on the longitudinal stability of the fabricated fibre, both in the size of the deviations and in the length scales over which any deviations occur. This project was to investigate fibre fabrication in the context of improved longitudinal stability and to evaluate the longitudinal uniformity of fibres that were fabricated.

The project timing was particularly affected by UK and worldwide restrictions from the COVID-19 pandemic. We were not able to overlap the start of the project with the end of previous projects working on hollow optical fibres of this type. As well as a turnover of researchers, PhD and post-doctoral, there was a challenging recruitment environment for a researcher for this project. We have nevertheless made great progress in improving and understanding of the processes of optical fibre drawing to enable repeatable and uniform fabrication.

## Methods, Assumptions and Procedures

Hollow core optical fibres rely on anti-resonant reflection from both thin glass elements in the cladding, and from the air gap between the thin glass elements and the thick jacket (Yu *et al.* 2012, Bird 2017, Song *et al.* 2019, Wang & Bird 2021). An example fibre to this type of design is shown in fig. 1. The important design decisions relate to the dimensions of the structure and the number and placing of the tubes around the core. The wall thickness of the tubes must be away from resonance at the design wavelength. It is usual to design this to be half-way between two resonances, the 'antiresonant' condition, however the thin film resonances are narrow and the regions between the resonances are wide. The important factor is then to avoid the resonances rather than to be precisely in the middle.

While very many fibre types have been designed and fabricated, showing the kind of properties needed for this application, it has always been challenging to fabricate long and uniform fibres with the very best properties. In fig. 1 the important features are thin tubes with precisely controlled wall thickness (to control the resonances). This naturally also requires that they are all the same. One of the leakage routes for light is through the gaps between the tubes which means that the best fibres have tubes that are close to touching. Surface tension is acting against these requirements during the fibre drawing process. As the glass is softened to draw the fibre, surface tension will act to collapse the tubes. Applying a differential pressure between the inside of the tubes and the hollow core during drawing provides an outward force to counteract this. However the pressure required to overcome surface tension changes with the diameter of the tubes. A tight curvature of the surface of a small tube gives a strong tendency to collapse and requires a high gas pressure to overcome it. A larger tube with less curvature only requires a small gas pressure to overcome the tendency to collapse, and will expand if a higher pressure is applied. This means that there are potential run-away effects when drawing this type of fibre: if the tubes are not identical the smaller ones will collapse faster and the larger ones may even inflate. Different inflation or collapse gives a trio of knock-on effects. Firstly the tubes

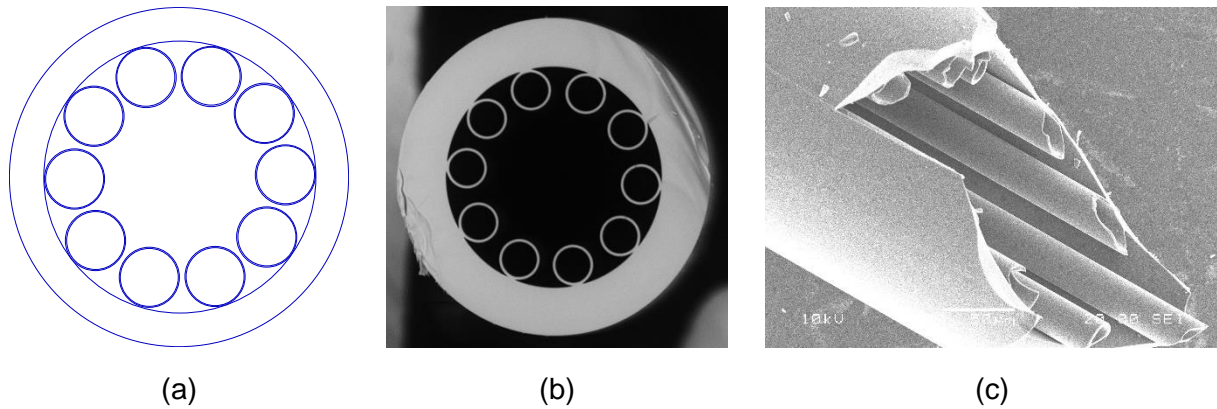


Fig. 1. Hollow optical fibres. (a) Basic design of the cross-section of a hollow optical fibre using antiresonant reflection for confining light. The number of tubes around the central core can vary, this example has 10. (b) SEM of the cross-section of a fibre fabricated to a similar design. Grey is silica glass, black is a void. The real fibre does not match the design in (a) by having relatively large gaps between the tubes which will allow light to leak out. (c) Side view of a similar fibre, broken at an angle to show the tubes running along the length of the fibre. In (b) and (c) the core diameter is approximately 100  $\mu\text{m}$ .

with different sizes will have different wall thicknesses because the same amount of glass is stretched around a shorter or longer circumference, which gives different resonance conditions and reduces the useful bandwidth away from the resonances of all of the tubes. Secondly if the tubes are different sizes then it will be likely that two adjacent tubes may expand so that they touch, these touching points are about twice the thickness which severely affects the resonances. Finally if the parameters can be adjusted to get the tubes reasonably large without any two touching, there will be large gaps between the smallest tubes, which allows light to leak out. These factors together mean that it is vital to control uniformity throughout the fibre drawing process and to seek drawing parameters where the process is less likely to run away.

## Results and Discussion

The majority of this project has been dedicated to methodical investigation of different drawing parameters. This has been done in the context of a wider programme of research on hollow optical fibres involving two PhD students and two post-doctoral researchers as well as three other members of academic staff. This project specifically funded one of the post-doctoral researchers for a part of their time, but by working together with different individuals investigating different aspects we have been able to systematically investigate much more than the sum of the parts and this report will summarise the overall progress. The first part of the wider development of understanding of fibre design, function, and fabrication was entirely outside this project, but in our collaborative research environment the team members were all closely involved in discussions and have benefitted from the outcome. Led by David Bird, a theoretical and fabrication effort has finally elucidated the clear and complete understanding of the physics of antiresonant hollow core optical fibre. This was published in 2023 (Murphy and Bird 2023) and shows that it is azimuthal variation of the refractive index in the region around the core that results in the very low leakage in antiresonant fibres. This is a significant step forward and provides an end to more than ten years of debate on the fundamental underlying physics of this technology. Significantly it shows that the ‘negative curvature’ of the wall around the core (curving inwards rather than outwards as in a simple tube) does not play a key role in

achieving low loss. It is instead simply a consequence of the types of physical structure that can be fabricated practically and exhibit the important azimuthal confinement mechanism. During this work a new fabrication procedure was also developed that is particularly useful for long and uniform fibres. The length of fibre that can be drawn in a single run relates to the amount of glass in the preform. Murphy *et al.* 2022 show that hollow optical fibre can be drawn directly from an initial stack (~25 mm diameter), without an intermediate preform stage (~2-10mm diameter). This increases the diameter of the glass source for a fibre draw by up to a factor of 10, and hence increases the length by up to a factor of 100. A much longer length, and so also potentially faster drawing speeds, will help fibre uniformity by allowing more stabilisation length before the fibre is collected, and by allowing less time for variations to occur when drawing a certain fibre length.

With these developments made, we were free to investigate the factors affecting the uniformity of drawn fibres. The two main areas of development were controlling the rate of collapse, for the reasons discussed in the introduction, and controlling the positioning of tubes in the stack and the fibre to make sure that when the tubes are all the same size they are also at the same spacings. These issues were addressed across four projects; this project, EOARD grant number FA9550-17-2-7000, a UK research funded project on ultraviolet fibres for healthcare, and a project with the University of Colorado investigating fibres for the vacuum ultraviolet. For this project uniformity is the key parameter, along with attenuation. This places great emphasis on control of the tube sizes along the length of the fibre. As a surrogate for direct measurement of longitudinal uniformity, we have looked at the control of absolute diameter and uniformity of diameter between the tubes in the fibre cross section. In order to have uniformity along a length of fibre it is necessary to have a well-controlled process, which will also manifest in control over the sizes of different tubes. Tube position is of less importance in this application, except in so far as we want to be able to make the tubes very close together (fig. 1(a), compared to fig. 1(b)) which needs very even spacing.

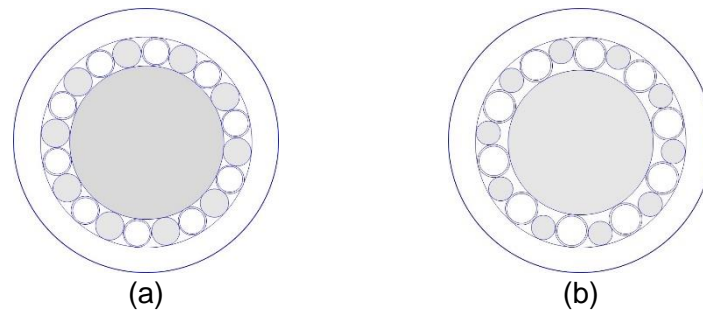


Fig. 2. Illustration of using different size tubes for stacking supports. a) tubes (open) and supports (grey) are all the same size. No freedom of design to adjust fit tolerances. b) tubes and supports are different sizes, providing an extra degree of freedom to adjust the fit tolerances.

In the usual fabrication process, as shown in fig. 1 of Murphy *et al.* 2022, the tubes in the stack are kept in position by separating them with identical size supports. This system however requires that the outer jacket tube and the central support tube have exactly the right ratio of sizes for  $2N$  tubes to fit snugly in the gap to make a fibre with  $N$  tubes. It does not have any free parameters to adjust for different jacket and support tubes that may be available, or to adjust for tightness of fit. The space in the azimuthal direction left because of the tolerance needed in

radial direction adds up. With 6 tubes (plus 6 spacers) and a tolerance of 20  $\mu\text{m}$ , the maximum gap around the ring of tubes is 240  $\mu\text{m}$ , a small but not necessarily unimportant percentage of the diameter of the stacked tubes, which may be 3.5 mm diameter. With more tubes the effect become very stark, for a fibre with 20 tubes that tolerance of 20  $\mu\text{m}$  on each tube accumulates to a potential gap can be 800  $\mu\text{m}$  which is half of the diameter of the smaller tubes needed to fit the 40 tubes and spacers around the stack. We have addressed this issue by designing stacks with the supports of different size from the tubes that we want. Figure 2 shows the difference between the two types of design. This releases a free parameter in the design of a stack and allows us to adjust for a range of jacket and central support tubes while maintaining a tight fit for excellent placement of the tubes in the final fibre. The benefit of this is clearly seen in fibres for other projects with many tubes designed for multimode guidance.

Surface tension is a critical issue for the uniformity of tubes in the cross-section and along a fibre. The main tool which we have at our disposal to fight against surface tension is viscosity. When the glass is at room temperature it is still in principle a fluid, but there is no flow. As we heat the glass, the viscosity decreases and the force of surface tension that is present all the time is able make the glass flow in the timescale of a fibre draw. The hotter the glass the faster the flow will be. We want to be able to draw the fibre to a smaller size, and we also want to inflate the tubes in the fibre until they are nearly touching. To do this we apply external forces – pulling the fibre onto a drum to make it longer and thinner and applying gas pressure in the tubes to make them expand. We can never reduce the surface tension force, but we can reduce its relative effect by increasing the external forces that we need to apply to make the draw that we want. In effect that means drawing with a relatively high viscosity/low temperature. There is a limit to how high the viscosity can be as we still need to draw the preform into a fibre by pulling on the small fibre itself. There will be a maximum force that is possible before the fibre breaks. We have investigated this process to find the best combination of parameters for drawing fibre with controlled tube sizes without breaking. The resulting improvements are shown in Figs 3 and 4. As part of the investigation we found some unexpected effects in the properties of the glass. During fibre drawing the silica glass does not exhibit Newtonian fluid flow, there is seen to be a velocity dependent viscosity. This is recorded in a submitted conference abstract (Mears *et al.* 2023). This discovery has a bearing on the modelling of fibre drawing processes, where glass is assumed to be Newtonian with a defined viscosity.

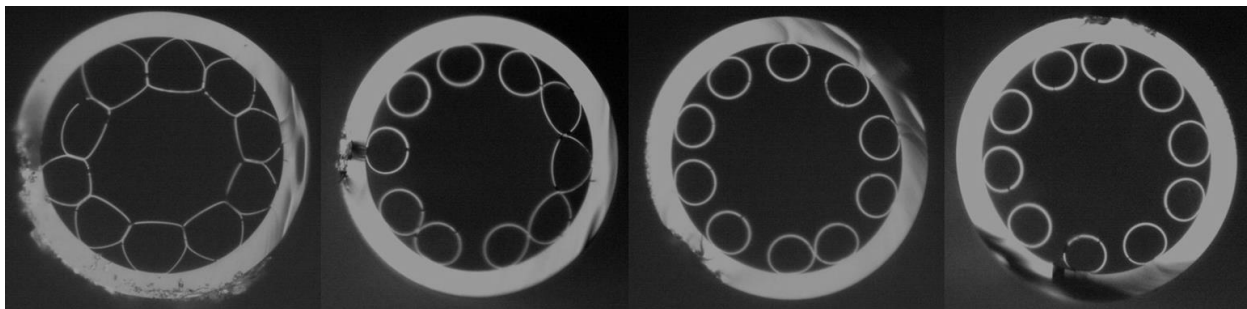


Fig. 3. Evolution of hollow optical fibre internal structure as draw parameters (pressure and/or temperature) are changed, approaching the best fibre attainable from this preform (on the right). Two tubes have been able to move closer together than the others which means that the gaps between the other tubes are relatively large. The tubes are also not uniformly round. This shows a need for new drawing practices.

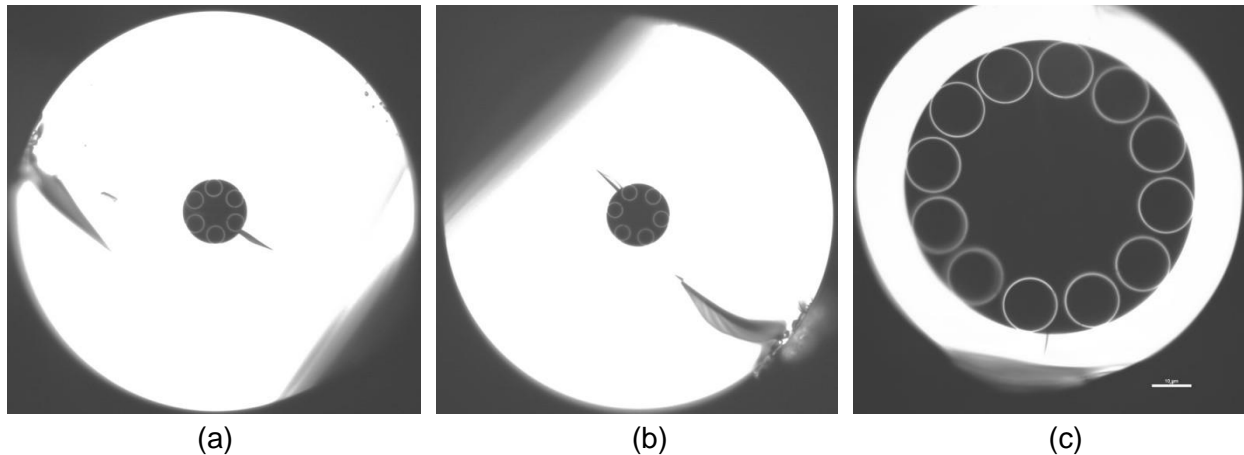


Fig. 4. Fibres made using the new developments. a), b) small fibres drawn for the UV to demonstrate control of the structure where the effects of surface tension are most extreme. Core diameter 10  $\mu\text{m}$ , design guided wavelength  $\sim 300\text{ nm}$ . The small difference between the fibres is a deliberate change in draw parameters showing the level of control now available. c) 12-tube fibre drawn for the near infrared, showing very uniform size and spacing of the tubes, which allows the gaps between tubes to be very small without any of the tubes touching each other.

Figure 4 shows the examples of the control available and the quality of fibres that can now be produced. The fibres in fig. 4(a),(b) are drawn to small sizes where the effect of surface tension is particularly severe. The current state of the art in this spectral region (Yu *et al.* 2018) shows clear differences in the diameter of different tubes, and rather large gaps between the tubes. Here the tubes are not only of even size and spacing, but we have sufficient control of the tube diameter to make small adjustments as between fig. 4(a),(b) giving small gaps between the tubes without any tubes touching. The fibre in fig. 4(c) shows size and position control for a fibre with more tubes where positioning is more difficult. The tubes are uniformly sized and uniformly spaced, allowing the gaps between the tubes to be reduced considerably compared to fig. 1(b) or fig. 3. Control of surface tension has also allowed the fibre to be made with thinner tubes, giving the guidance band between the first resonance and the zeroth resonance. In principle this band ranges up to infinite wavelength (zero frequency), in practice it is limited by confinement in the small core at increasing wavelength. We have demonstrated guidance in a single band from 400 – 1400 nm in this type of fibre.

## Conclusions

A large amount of progress has been made in the aim of the project to understand better the drawing processes to be able to draw more uniform hollow optical fibres. We see much better predictability and reproducibility in the drawn fibres, and we are able to draw fibres with much more challenging parameters. We expect that these improvements also lead to improvements in longitudinal uniformity which is required for parametric generation.

## References

Bird, D.M. "Attenuation of model hollow-core, anti-resonant fibres," Opt. Express 25, 23215 (2017)

Mears, R., Harrington, K., Stone J. and Birks, T.A., "Non-Newtonian flow in optical fibre drawing," submitted to OFC 2024

Murphy, L.R. and Bird D.M., "Azimuthal confinement: the missing ingredient in understanding confinement loss in antiresonant, hollow-core fibers," Optica **10**, 854-870 (2023)

Murphy, L.R., Yerolatsitis, S., Birks, T.A. and Stone, J.M., "Stack, seal, evacuate, draw: a method for drawing hollow-core fiber stacks under positive and negative pressure," Opt. Express **30**, 37303-37313 (2022)

Song, P., Phoong, K. Y. and Bird, D. "Quantitative analysis of anti-resonance in single-ring, hollow-core fibres" Opt. Express. **27**, 27745-27760 (2019)

Wang, W. and Bird, D. "Confinement loss of anti-resonant capillaries with curved boundaries" Opt. Express. **29**, 25314–25326 (2021)

Yu, F., Wadsworth, W.J. and Knight, J.C. "Low loss silica hollow core fibers for 3-4  $\mu\text{m}$  spectral region," Opt. Express **20**, 11153–11158 (2012)

Yu, F., Cann, M., Brunton, A., Wadsworth, W. and Knight, J. "Single-mode solarization-free hollow-core fiber for ultraviolet pulse delivery," Opt. Express **26**, 10879-10887 (2018)