Drawing Optical Fibres from 3D Printers

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The temperature distribution within extrusion nozzles of three low cost desktop 3D printers are characterised using fibre Bragg gratings (FBGs) to assess their compatibility as micro-furnaces for topical fibre and taper production. These profiles show remarkably consistent distributions suitable for direct drawing of optical fibre. As proof of principle, coreless optical fibres (ϕ = 30 μm) made from fluorinated acrylonitrile butadiene styrene (ABS) and polyethylene terephthalate glycol (PETG) are drawn. Cut-back measurements demonstrate propagation transmission losses as low as α = 0.26 dB/cm, comparable with standard optical fibre losses with some room for improvement. This work points towards direct optical fibre manufacture of any material from 3D printers.

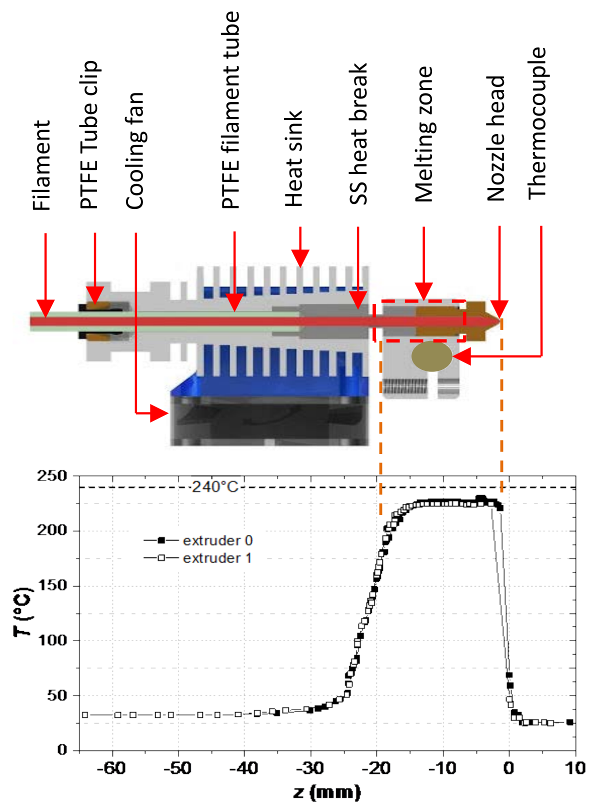

Fig. 1. Temperature, *T*, profile along the printing nozzles of the Redback 2 printer as a function of position as measured by fibre Bragg grating (FBG). The nozzles are very well matched but reach a peak temperature less than $\Delta T \sim 13\ ^0$C below that measured by the in-built thermocouple (240 ^{0}C).

3D printing has been successfully used to fabricate polymer preforms from which both structured and step-index optical fibres were drawn [1-3]. This work has heralded a new frontier on optical fibre fabrication, particularly as 3D printing improves to include silica glasses. Although the quality and confinement was limited by the printing resolution of a low-cost desk-top 3D printer, this work points to a major revolution in optical fibre manufacture, particularly as glass based printing comes online. In one of those works, we also suggested it was possible to eventually draw optical fibre [3]. In this paper, a careful study of the thermal properties of three commercial low-cost 3D printers are characterised with intent to demonstrate the potential to directly draw optical fibre from a 3D printer. The printers are then used to demonstrate drawing of coreless optical fibre 30 μm in diameter over meter lengths in transparent plastic. The results reported here ignite the possibility that it is indeed possible to draw fibres in the micron range and eventually sub-micron for taper production with sufficient precision using very low cost micro-draw “towers” within a desktop 3D printer. The possibility that one day every home could have a personal optical fibre manufacturing unit to build their own broadband network comes into being.

Table 1. Summary of the 3D printers characterised in this work.

Model	Type	Source	Cost ($AU)	nozzle #	T_{max} (°C)
Delatsine Redback 2	Delta	3DBrink (Australia)	$3500	2	280
Dreamer	xyz	Flarshforge (China)	$1490	2	300
M200	xyz	Zortrax (Poland)	$2600	1	380

The three low-cost desktop printers chosen are summarised in Table 1. They span the budget printer to intermediate low cost printer. To compare between printers, the Redback (delta) [4] conditions were chosen to enable similar printing of transparent polymers to that of the Flashforger (*xyz*) [5], which required a printing temperature around $T = 230$ °C. These two are dual nozzle printers whereas the third printer, from Zortrax [6], is single nozzle xyz printer. All these printers have an in-built thermocouple (Type *K*) to measure and set temperature conditions for the printing processes so accuracy in this is extremely important. Ordinarily the manufacturer would use an infrared gun to estimate and calibrate the temperature. Whilst this might reasonably be accurate within a few degrees, it does not directly measure the temperature and its distribution inside and along the extrusion nozzles (internal $\phi = 0.4$ mm). Given the critical importance of both temperature and temperature distribution in the ability to control optical fibre drawing with high precision, we have characterised the internal temperature profile of the extruders. To do this, silica optical fibre Bragg gratings ($\lambda \sim 1547$ nm, $R \sim 35$ dB, FBG – $L = 2$ mm) were directly written using ArF 193 nm laser light through an optical phase mask into standard silica based telecom fibre (SMF28) and stabilised by annealing ($T = 300$ ^{0}C, $t = 15$ mins) to operate up to 300 ^{0}C [4].

The FBG is scanned from the entry of the nozzle tip through to the inside using each printers own translation stages. For the Redback 2, this involves moving the nozzle itself along the BFG grating propped up from the base (resolution ~ 2 mm/step,). Both the Flashforge and Zortrax are *xyz* stage based printers so the FBG is instead moved into the extruder nozzles (resolution ~ 2 mm/step) using these stages. All are controlled via the software of each printer. Of the three printers, the Redback 2 and Flashforge have dual extruders with similar measured extruder body lengths ,$L = (2.0 \pm 0.1)$ cm whilst the Zortrax, with a single extruder nozzle, is longer, $L = (2.6 \pm 0.1)$ cm. A reasonable expectation would be that the measured temperature profile will reflect this. Experimentally, the Bragg wavelength shift, $\Delta\lambda$, observed as a function of position, *z*, provides a direct measure of temperature within the hot zone of the extruder, analogous to a miniature optical fibre draw tower furnace. To characterise $\Delta\lambda$ in real-time and obtain the temperature, *T*, through the thermo-optic coefficient of the silica fibre, a Micron Optics Interrogator (SM-130) is used.

Figures 1, 2 and 3 summarise the measured data and align that with the schematic of each extruder for each printer. Of the three printers, the largest discrepancy between the measurements and the thermocouple is obtained with the Redback printer, the most expensive of the three printers and one designed around delta operation. To rule out differences arising with the method of scanning, consultation with the manufacturer, a local

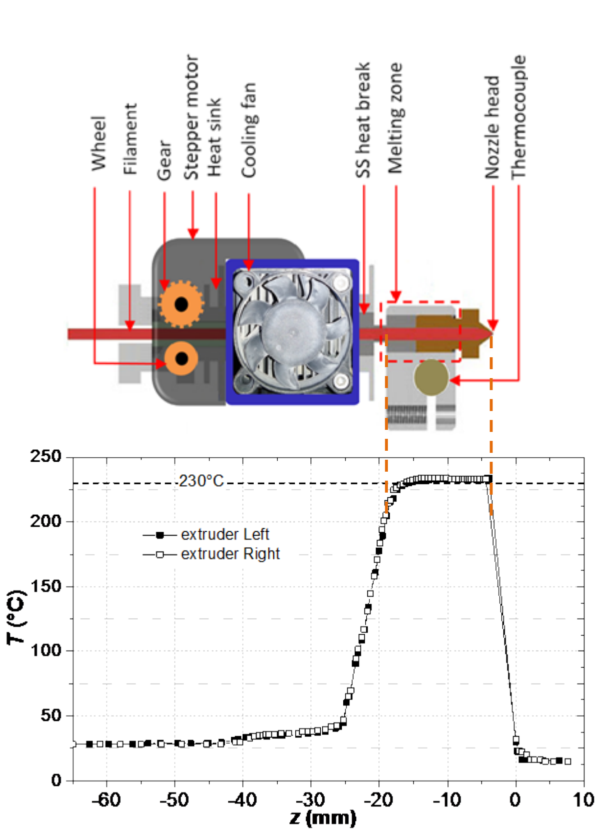

Fig. 2. Temperature, *T*, profile along the two printing nozzles of the Flashforge Dreamer printer as a function of position as measured by fibre Bragg grating (FBG). The nozzles are very well matched and reach a peak slightly higher, $\Delta T \sim (3 - 5)$ ^{0}C, above that measured by the in-built thermocouple (230 ^{0}C).

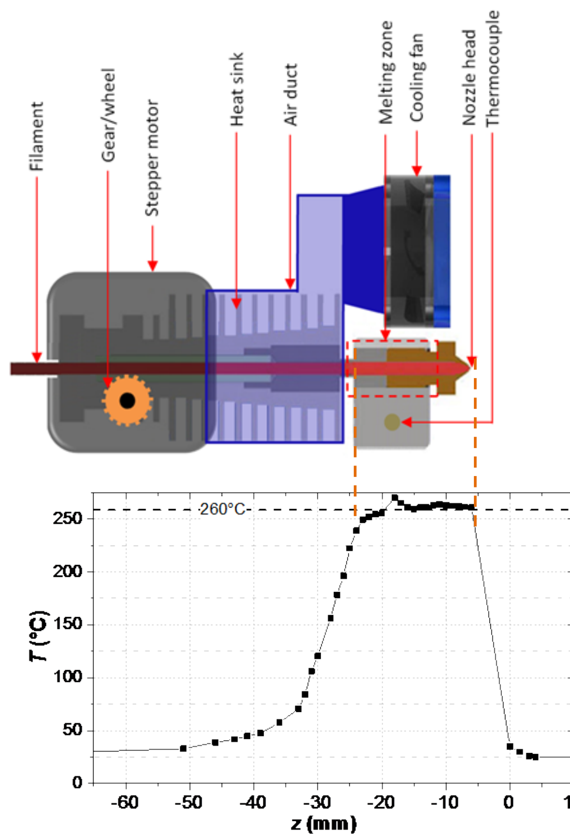

Fig. 3. Temperature, *T*, profile along the two printing nozzles of the Zortrax M200 printer as a function of position as measured by fibre Bragg grating (FBG). The nozzles are very well matched and reach a peak slightly higher, $\Delta T \sim 1$ ^{0}C, above that measured by the in-built thermocouple (260 ^{0}C).

start-up, verified the discrepancy is real and has since been rectified, demonstrating the practical value of the novel measurement process using FBGs. Overall, all three printers show very good distributions. Both the Redback and Flashforge show excellent agreement between dual nozzle heads. Despite being the lowest cost printer, the Flashforge has the smoothest distribution and the lowest temperature mismatch, although it does have a long secondary tail indicating thermal buildup as a result of fan overheating above the extruder head. The other printers are designed to avoid this problem with the Redback 2 probably being closest to an ideal top-hat profile. The Zortrax has an extended hot zone consistent with it longer body but it also shows a hot spot located where there is a junction between the metal extruder casing the material beyond this. This may suggest an air gap between the two materials, new information that is valuable to improving the engineering design of the printer.

The overall assessment of these printers is that they have excellent extrusion heating elements making them potentially ideal analogous micro-furnaces for drawing optical fibre directly, rather than only fabricate optical preforms and draw subsequently into fibre form on a specialized draw tower [1,2]. To test this potential, we used the Flashforge printer, since it provided the most reliable thermal distribution, as a micro-furnace for drawing optical fibre. Here, the filament plays the role of the optical preform and the materials (fluorinated acrylonitrile butadiene styrene ABS: at T_{print} = 230 °C ; and fluorinated polyethylene terephthalate glycol filament PETG: T_{print} = 230 °C) were drawn manually with a load estimated to be ~ 10 g and a draw velocity of ~2.5 m/sec. In these experiments the extruder micro-furnace is kept fixed and not scanned. These two optically transparent materials were previously used to fabricate step-index preforms using 3D printing and then drawing into optical fibre [2]. Their properties were summarised previously including their measured refractive indices (ABS: n_{SBP} = (1.542 ± 0.004); PETG: n = (1.522 ± 0.004), @ 633 nm). Their approximate thermo-optic coefficients were assumed similar to the unflourinated materials (ABS: $dn/dT \sim 7 \times 10^{-5}$ /K ; PETG: $dn/dT \sim 8 \times 10^{-5}$ /K, @ 633 nm [4]). These properties make them comparable plastics for thermal processing. In terms of optical transmission, the modified ABS was measured to have a deeper UV band edge than the modified PETG, although it also has a tail extending from this edge into the visible compared to the PETG making it a little lossier across the green region [2].

Table 2. Summary of the two microfibres drawn.

	t_{draw} (s)	T_{draw} (°C)	L (m)	φ (µm)	α (dB/cm) @ 543 nm	α (dB/cm) @ 1550 nm
ABS	0.78±0.20	230	2.3±0.3	32 ± 2	0.33 ± 0.01	0.38 ± 0.01
PETG	1.04±0.20	230	2.4±0.4	33 ± 2	0.26 ± 0.01	0.26 ± 0.01

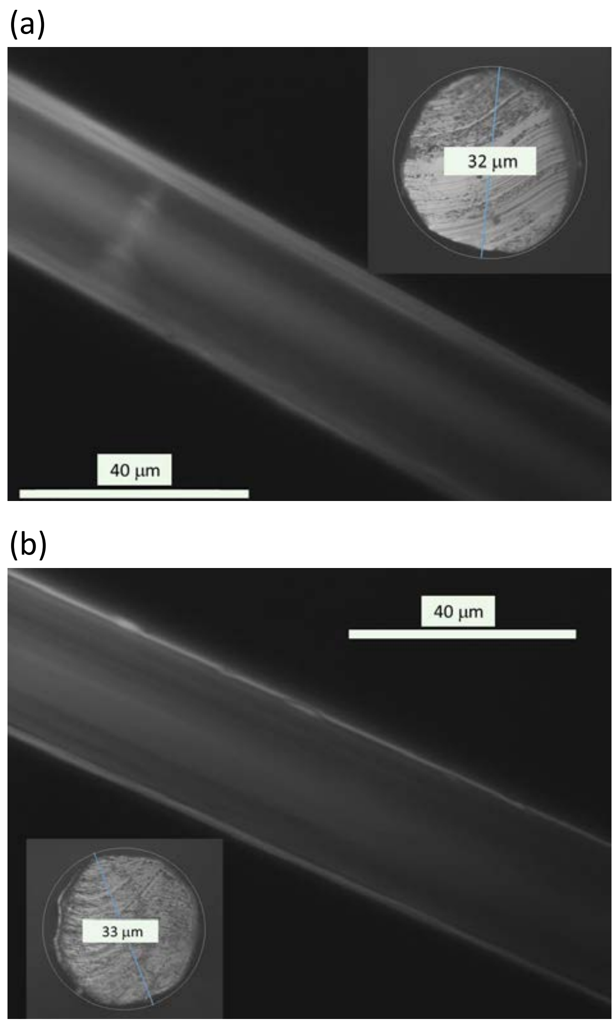

Fig. 4. Microscope images of the drawn fibres: (a) ABS and (b) PETG. Both are of similar dimension within the variables of the manual drawing process used. The inset images show the cross-section of each fibre.

The drawn optical microfibres are summarised in Table 2. They both have similar diameters $\phi \sim$ (32-33) μm and are over 2 m in length. However, manual drawing process restricted how small the fibre could be drawn so sub-micron tapers were not possible on the current setup. The thermal properties may also impact this. This also likely affected the circularity of the cross-section as show in the inset of those images. Automated control over the load and drawing tension will further reduce errors as well as enable sub-micron tapers to be drawn. Nevertheless, from a practical optical fibre perspective, these micro-furnaces are clearly sufficient to exceed standard optical fibre dimensions of ϕ = 125 μm and for producing micro tapers. Figure 4 shows optical micrographs of the two drawn micro fibres. Despite the manual drawing process, the uniformity is remarkable and can only be improved with automation.

By semi-automating the draw process using an 18V dc motor (50 rpm), it was possible to draw similar fibre over 100 m in length. Figure 5 shows an image of the spool of this fibre.

Fig. 5. Photograph of PETG microfiber drawn from the 3D printer.

To characterise their propagation losses, cut-back measurements were made at two wavelengths: λ = 543 nm, from a green HeNe laser, and $\lambda \sim$ 1550 nm, from a broadband erbium-doped fibre amplifier (EDFA). Light is launched from a standard single mode silica optical fibre into the highly multimode plastic coreless micro-fibre. Results are shown in Figure 6. The measured losses for the ABS and PETG fibres at λ = 543nm are $\alpha_{ABS} \sim$ 0.33 and $\alpha_{PETG} \sim$ 0.26 dB/cm respectively and at λ = 1550 nm $\alpha \sim$ 0.38 dB/cm and 0.26 dB/cm respectively. These are ~ 2 – 3 times improvement over those reported for step-index fibre [2] where scattering at the core-cladding interface was substantial.

In conclusion, low cost desktop printers have been shown to have excellent micro-furnace extrusion heads suitable for drawing optical fibre

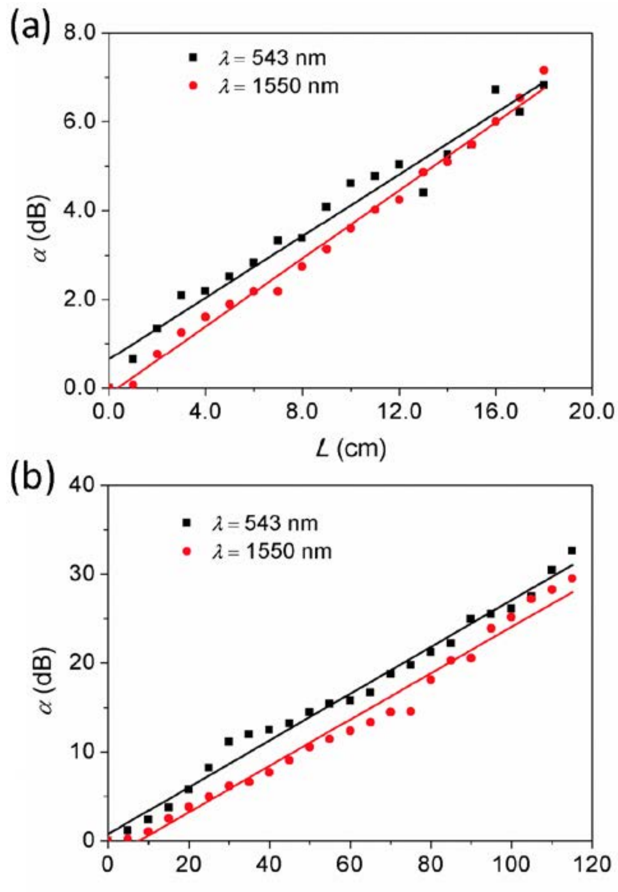

Fig. 6. Cut-back measurements at 543 nm from a green HeNe laser: (a) PETG and (b) ABS. The larger dc loss of PETG arises from differences in coupling; these do not translate into propagation losses.

directly. Their temperature profile was characterised using high temperature performing fibre Bragg gratings of short length scanned with the 3D printer's own scanning technology. They make an excellent characterization tool for plotting the internal thermal distribution within the micro-furnace – in principle it is possible to embed an array of high temperature gratings into the micro-furnace wall for permanent monitoring of the distribution over time. Given the relatively short lifetime of operation of current low-cost desktop printers, this could make an invaluable diagnostic tool to adjust their performance over time. The technology can also apply to much more expensive printers given the amount of time consuming and costly maintenance required to run customer outsourcing services. Micro fibres with diameters as small as $\varphi \sim 30$ μm were drawn manually and scope for sub-micron drawing using more automated and controlled drawing processes are assessed to be feasible. Although these fibres are coreless, this demonstrates the potential of direct optical fibre fabrication from 3D printers. The attention would now focus to designing customized preform filaments with optical cores or structure properties prior to drawing. Eventually it is conceivable with developments in new materials, including silicate glasses, that 3D printing can provide a cost competitive production process, both in terms of preforms and optical waveguides, to disrupt current methods involving lengthy and costly preform fabrication. Further, we believe the democratization of technology and technology education enabled by low-cost desktop 3D printers will also lead to transformative changes in society making advanced technology accessible to all.

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