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Flat fibre and femtosecond laser technology as a novel photonic integration platform for optofluidic based biosensing devices and lab-on-chip applications: Current results and future perspectives☆

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ABSTRACT

Flat optical fibre technology is a glass-based substrate technology that has emerged recently, it offers a flexible and potentially very long, distributed sensing medium, whilst also having increased lateral and vertical dimensions; this allows for the development of optical integrated circuits with the enhanced functionality promised by optical chips. In this work we report on recent developments to highlight the incorporation of integrated structures on the surface and in the bulk volume of flat fibres using femtosecond laser inscription. This fusion of two innovative technologies, and in particular the flexibility afforded by femtosecond laser inscription and micromachining, has led to the realisation of microfluidic channels, ring resonators, resonator disc, Mach-Zehnder and complex microfluidic designs in the surface of the optical chip, whereas Bragg grating waveguides have been recorded in the bulk volume of the optical chips. The flat-fibre platform offers a unique degree of freedom by allowing surface and sub-surface devices to be integrated onto a single optical chip with the potential for straightforward incorporation into integrated photonic circuits or opto-fluidic devices.

1. Introduction

There is significant interest in developing "facilitating technologies" for optics where the convenience of a flexible, optically-flat, glass waveguide offers a tantalising means to incorporate the advantages of densely packed planar chips, with the many advantages offered by optical fibres. A major challenge faced in opto-fluidics and integrated photonic circuits is the coupling of light to and from the substrate that incorporates any micro-optic circuitry; typically cylindrical optical fibres are attached to planar substrates, the ends of which must be cut and carefully polished to ensure low coupling losses, with all the alignment difficulties that this entails. Moreover, any fibre-to-planar-substrate joint is inherently weak. Hence a waveguiding glass substrate or flat optical fibre chip that is inherently compatible with optical fibres, or indeed that could replace the role of optical fibres, takes a significant step in overcoming this hurdle; this is the potential that is offered by flat optical fibres. The flat fibre can share all the advantages of the cylindrical glass optical fibres, such as immunity from electromagnetic interference, low waveguiding loss, the ability to withstand high ambient temperatures, and share the same basic manufacturing process and chemically inert silica host material. Flat fibres are manufactured using standard MCVD (modified chemical vapour deposition) followed in a later step by a preform collapsing technique and fibre drawing [1]. Drawing flat-fibre is achieved via a fibre drawing tower and was implemented in a very similar process as conventional optical fibre. However, in drawing the flat-fibre, the conventional process is altered whereby the upper end of the flat-fibre substrate is connected to a vacuum as illustrated in Fig. 1. This is to aid the collapsing process of the flat-fibre substrate, into a planar geometry, in the furnace chamber of the draw tower. Tractors act as a driving force to pull down the flat-fibre. Two important parameters in controlling the geometry of

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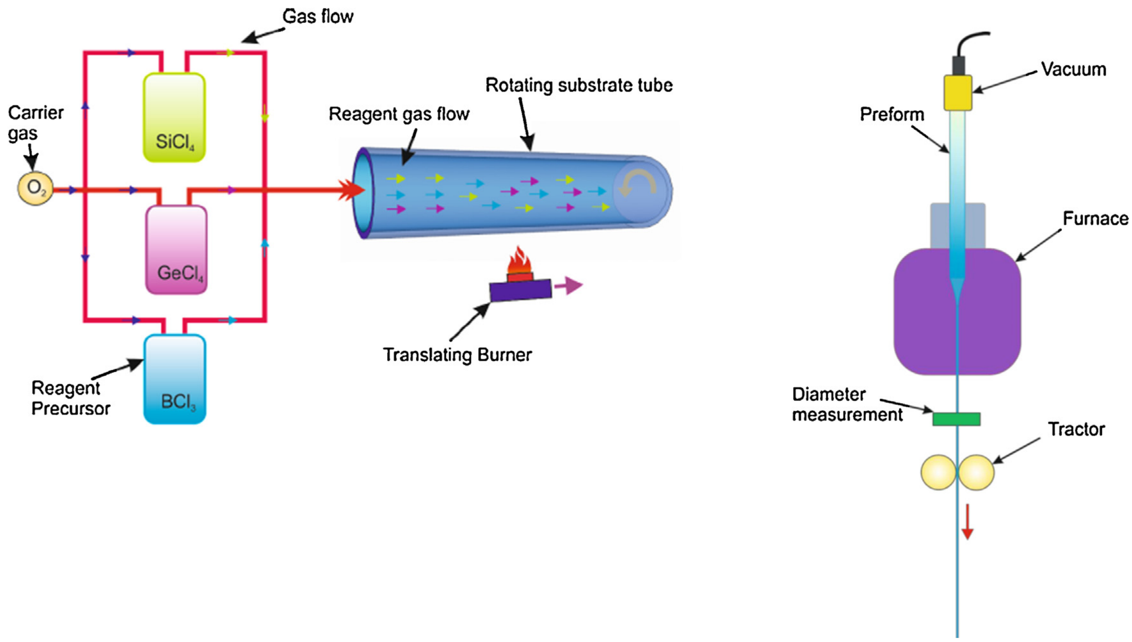


Fig. 1. Schematic illustration of the manufacturing process of flat fibres by the MCVD method. Illustrated the modified fibre drawing technique for flat fibre drawing. The applied vacuum to the upper end of the fibre induces the collapse of fibre perform leading to a modified flat fibre structure.

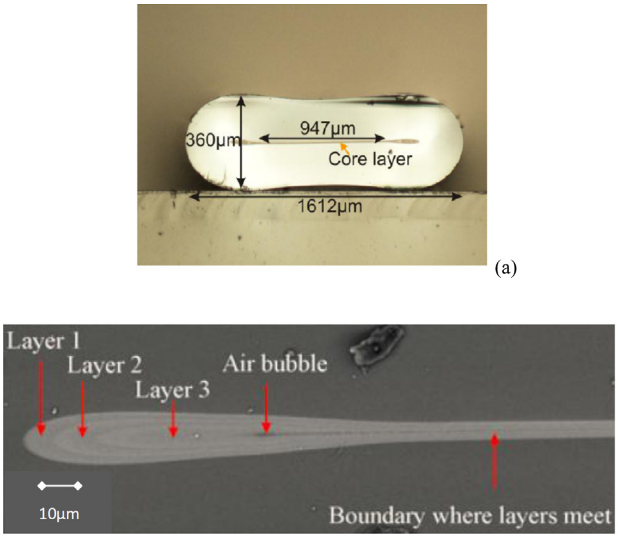
the flat-fibre are the vacuum pressure and the temperature of the furnace chamber. In this particular work, the vacuum pressure was set to 5 millibar and the furnace temperature was around 2100 °C. Once the right geometry is achieved, at certain value of pressure and temperature, the fibre is drawn into a long length of several metres. As a result of the final draw process, the fibre has a large, flat surface area allowing for direct surface or sub-surface material modification that is well-suited to femtosecond laser processing [2,3]. When considered with low manufacturing costs, these flexible optical "chips" can prove to be a key technology applied to disposable high-end sensing devices or fully distributed point sensors.

Femtosecond laser inscription and micromachining uses focused femtosecond laser pulses to modify materials, either on the surface of opaque materials, or within the bulk volume of optically transparent glassy or polymeric materials. The laser induced material modification can be used to produce intricate microstructures, with applications to medicine (stent production) and photonics (micro-devices, sensors). The extremely short temporal profiles of femtosecond laser pulses, when combined with tightly focusing optics, can produce sub-micron scale material changes when the optical intensity crosses a fundamental material threshold; the laser intensity typically reaches 10^{13} W/cm^2. These conditions promote intensity-dependent, non-linear absorption processes, such as multi-photon absorption and avalanche ionisation. Any subsequent structural changes to the material are essentially permanent. The non-linear absorption process is particularly important for transparent materials where the electronic band gaps are too large to bridge with a single photon process; the linear absorption of laser light does not occur and the material remains unchanged. With a tightly focused femtosecond laser beam the interaction can be activated and the non-linear effects dominate. Any structuring therefore only occurs around the laser focus, with strong spatial confinement. The induced structural changes can take many forms; index change and void creation are two common examples and can be used to form true 3D structures.

There are a number of issues and advantages that make favourable the use of flat fibres in combination with the flexibility of femtosecond laser writing capabilities:

(a) The flat fibre efficiently guides light over its length, behaving in a manner similar to a conventional fibre. The losses are not as low as cylindrical optical fibres and are typically and consistently in the region of 0.1 dB/cm. However this will improve in the future as the manufacturing method improves.
(b) Flat fire can be cleaved quite efficiently while planar silica-on-silicon samples need to be polished prior or following to laser inscription.
(c) It is often desirable for lab-on-chip, optofluidic and biosensing to "access" the guiding light so that the evanescent field can interact with an external fluid sample, typically for refractive index measurements. In the majority of cases the polishing of optical fibres to the core-cladding boundary is favoured and this is very time consuming and inefficient. In contrary the potential of connecting the waveguide core with the surface using a femtosecond laser waveguide offers an alternative method that is less time consuming. In this case the "connection" distance between the core and surface is short, perhaps only 50 μm, and waveguide losses will not be significant.
(d) Coupling light to a planar waveguide is time-consuming and not particularly stable over time; the flat fibre is a more "user friendly" option. And has the potential for fusion splicing with standard optical fibre as used in high power fibre applications.
(e) The alignment between the laser focal point and the material needs to be optimised only at the points of laser inscription/modification, whereas the planar sample must be perfectly aligned to the laser beam throughout the inscription process.
(f) Using femtosecond laser inscription the waveguides can now defined freely in the entire volume of the flat fibre not-restricted anymore to the core layer. Furthermore femtosecond inscripted waveguides could always arise or end at the planar core layer, by using suitable adiabatic S-bend transitions over the available length. This architecture could better facilitate the stable connection to an output single mode fibre SMF28.

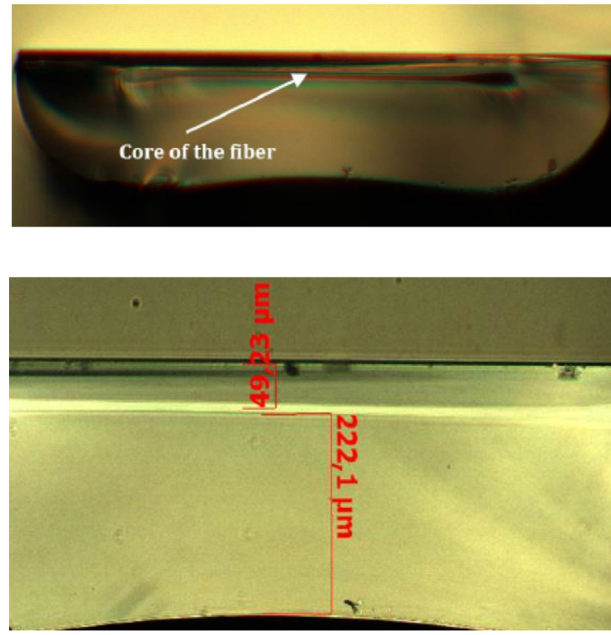
Here we present the realisation of novel integrated photonic structures, such as microfluidic channels, ring resonators and discs, Mach-Zehnder devices and Bragg grating based devices, and complex microfluidic devices, using a direct write approach through



(a)

(b)

Fig. 2. Images showing the flat fibre. (a) Cross section of a flat fibre, showing the "dumbbell-shaped" profile. (b) SEM image of the core layer of the flat fibre. The core layer is seen to comprise of three layers, reflecting the number of MCVD passes made during the deposition process.



(a)

(b)

Fig. 3. (a) Cross section of the polished flat fibre with (b) a remaining over-cladding of ~50 μm from the fibre core.

femtosecond laser inscription and micromachining in this new flat-fibre platform.

The availability of such diverse photonic structures in a single platform could allow the development of functional microfluidic/optofluidic based biosensing systems supported by the presence of those ultra-sensitive resonant structures acting as detection/response interrogators, over a relatively long length available by the flat fibre. The inscribed structures are subsequently filled with active polymers and other materials that could be employed for various applications. Furthermore, direct write femtosecond-laser inscribed Bragg gratings have been written in the Ge-doped core of the flat-fibre. The morphology of the fabricated structures has been characterised using optical microscopy and 3D optical profilometry. Both of these characterisation methods give useful information regarding the uniformity and quality of the micro-optic circuits.

2. Flat fibre

The flat fibre production process is adapted from the conventional MCVD fibre fabrication method, whereby hollow silica preforms with deposited core layers are combined and subsequently collapsed into a rectangular geometry, Fig. 1. This is achieved through the application of a vacuum during the fibre drawing process and results in extended lengths of mechanically flexible flat glass [4]. Fig. 2(a) shows the flat fibre in cross section, whereas Fig. 2(b) shows an SEM image of the core layer of the flat fibre. One observes the presence of an "air inclusion" at the edge of the core that results from the collapse of the cylindrical geometry to the rectangular shape. We also note that the core layer is silica doped with germanium and boron, in order for the fibre to exhibit photosensitivity [5,6], but this is actually unnecessary for the inscription undertaken in this work. Due to the flat fibres' drawing-based manufacturing process the platform has the potential to achieve very low loss, much lower than the traditional silica-on-silicon planar waveguide technology. There has been initial characterisation of basic waveguide properties based on UV inscribed Bragg grating measurement techniques [1]. The exhibited to date channel waveguide loss is 0.12 ± 0.024 dB/cm. Furthermore it was also measured the waveguide birefringence and was measured to be less than 4×10^{-4}. Lengths of fabricated flat fibre can be several metres and there is not a restricting factor for longer fibre production.

Although many flat fibres have been realised with a variety of dopants for active and passive fibres, the fibres used in this work had a core doped with germanium (5.4 mol% Ge) and boron (13.3 mol% B), a core thickness of 7.5 μm and an effective index at 1550 nm of 1.4505. The core size ensured single mode operation at 1550 nm and that there was good mode matching with standard single mode optical fibres. Furthermore, our flat fibres were utilised having two different sample sets; the first fibre set had a thickness of ~390 μm whereas the second fibre set was polished to ~50 μm distance from the core. In order to improve mode matching with single mode fibre, such as SMF-28, and particularly at the C-band wavelength of 1550 nm, the core was restricted to 8 μm in height. However, because of the flat-fibre format the core width was several hundred microns wide. The overall width of the flat fibre, including the cladding layer, was ~1.1 mm. The cross section of the polished fibre is shown in Fig. 3(a) and (b). The lengths of all the samples (polished and unpolished) were cleaved to be ~1–2 cm long, although we note that the fibres could have had far longer lengths.

Using a commercial mode solver (Rsoft BPM), we calculated the fundamental flat-fibre guiding mode with an effective as having an effective index of $n_{eff} = 1.45068$. Fig. 4 shows the end facet of the fibre before (Fig. 4(a)) after (Fig. 4(b)) coupling light to the fibre core at 633 nm.

3. Femtosecond laser inscription process in flat fibres

The femtosecond laser direct writing technique is an alternative route to fabricate channel waveguides, inscribe grating structures and for the rapid prototyping of arbitrary optical structures [4]. The process is initiated by scanning a tightly focused beam from a femtosecond laser into a bulk transparent material, whereupon the process of non-linear absorption occurs to modify a material. A main advantage of this technique is that it does not require a sample with photosensitivity and as such has the capability of producing waveguides in three dimensions compared to the direct UV writing

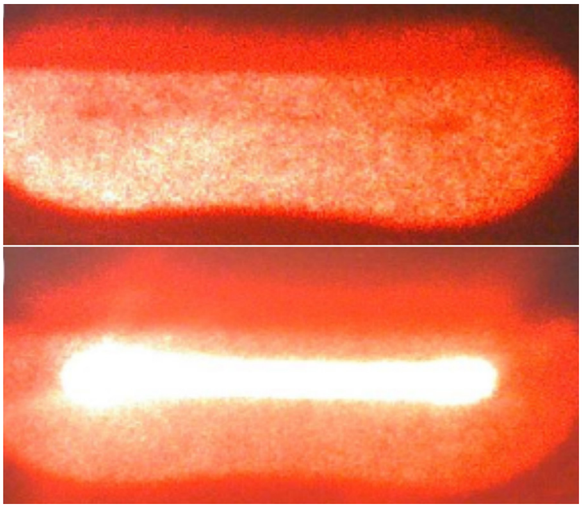


Fig. 4. Near-field images of the fibre output (a) before and (b) after coupling light to the core.

technique within a two-dimensional plane. Using this technique it is possible to produce channel waveguides with high refractive index contrast ($\Delta n = \sim 0.035$) in glass [7]. The induced refractive index change depends on the translation speed of the sample and the laser pulse energy. In femtosecond laser written waveguides in a fused silica, waveguide propagation losses of 0.8 dB/cm are typical [8]. Moreover, this technique has been demonstrated in active media [8,9].

We used a femtosecond laser operating at a wavelength of 1030 nm (HighQ femtoREGEN laser) that generate 300 fs laser pulses. The laser repetition rate was adjusted from 1 to 100 kHz according to our inscription requirements. Having passed through a shutter the laser beam was focused onto the flat-fibre sample with a 50× objective lens. A CCD camera was used to monitor the inscription of the structure at or below the surface of the flat fibre in real-time, as the sample was moved perpendicular to the machining lens on an XY air-bearing stage system (Aerotech). The movement of the stages was programmed using customised G-code. It was important to be able to write any desired structure from straight lines to other more complicated structures, rapidly and with user defines properties. Hence the conversion of bitmaps to G-code was slow and undesirable, offering crude results. Our custom coding afforded accurate and user-selected programming of the translation stages; precisely controlling the speed and the movement of the stage using the appropriate equation. Writing software was designed as concatenated building blocks, so that the user can select a ring structure, a grating structure, curves, grid arrays, straight lines, etc., and then select the lengths, number of passes, velocity, etc. for the output. Furthermore, the G-code is also used to control auxiliary items such as the mechanical shutter of the laser. In Fig. 5 we observe the laser-induced plasma in the bilk volume and at the surface of the flat fibre, which were used to help identify the correct height for inscription and micromachining of the samples.

Furthermore, the morphology of the developed channels was characterised using an optical microscope (Zeiss M1) and a 3D optical profilometer (WYKO NT9100). Several micro-optical structures were inscribed, first above the surface of the fibre, then just below the surface in order to access via evanescent filed the surface environment, and also buried in to the bulk silica of flat fibre. In surface ablated induced structures, different functional sensing materials [3] were deposited inside the fabricated channels allowing the demonstration of sensitive chemical sensors and bio-sensing devices. Microfluidic channels and devices with potentially enhanced functionality were also demonstrated constituting of three inputs, a sinewave-like channel for the delay (Fig. 6(a)) and control of liquids and a block of channels for liquid mixing. In the latter case velocity control is an important way to define channel properties, Fig. 6(b); the velocity of sample motion is increased from 100 μm/s to 1000 μm/s leading to a significant reduction in channel width. We present specific details in the sections that follow.

3.1. Direct Bragg grating waveguides

In this section we demonstrate the inscription of Bragg gratings as waveguides using femtosecond laser pulses. For much of this work the laser pulse energy was set to 1.6 μJ/pulse and the repetition rate was changed to 1 kHz. As an example of the available precision, the sample velocity and laser repetition rate are synchronised so that the laser pulses can produce index modulated points that are precisely touching, as in Fig. 7, in a process similar to that in [10]. Fig. 8(a) shows the direct writing of a 4th order structure as part of initial trials; the pitch of the structure was ∼4 μm whereas the spot size was ∼1 μm. In Fig. 8(b) and (c) we see the result once the spots are overlapping, in which case the light "sees" an average refractive index because the period is shorter than the wavelength of the light and waveguiding and reflection can occur. The Bragg structure inscribed 33 μm under the polished surface. The length of the grating was around 8 mm and the pitch ∼1.1 μm.

After the Bragg grating inscription, we used a broadband source operating in the C-band to observe if the structure was good enough to provide a reasonable reflection. Fig. 8(c) shows the Bragg reflection at 1547.82 nm with an intensity of ∼5.2 dBm. The coupling of the light into the core required great care as we could not observe either the core mode or the side scattering from the inscribed structure for the infrared wavelength of illumination.

3.2. Ring resonator inscription in flat fibre

We demonstrate the inscription of ring resonators on and sub-surface in polished fibre, where light from the core can more easily interact with the inscribed structures. The following structures were created at the edge of the fibre where there is the possibility of filling the structures with active and sensitive

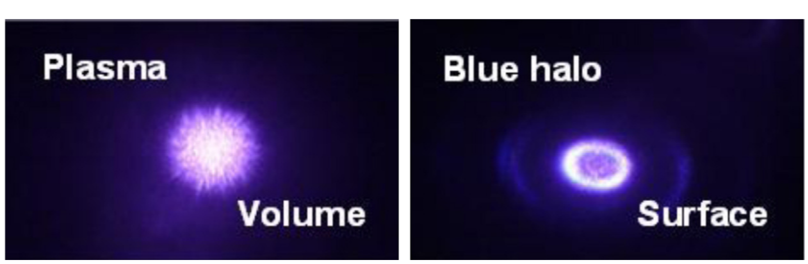
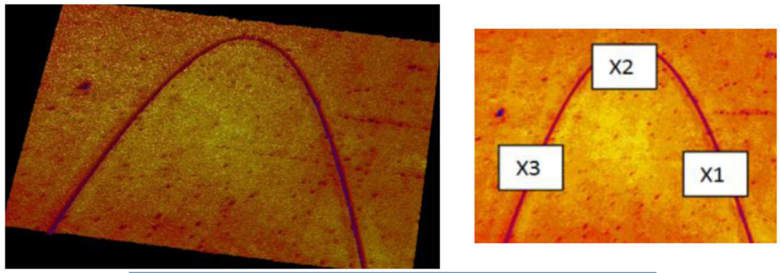


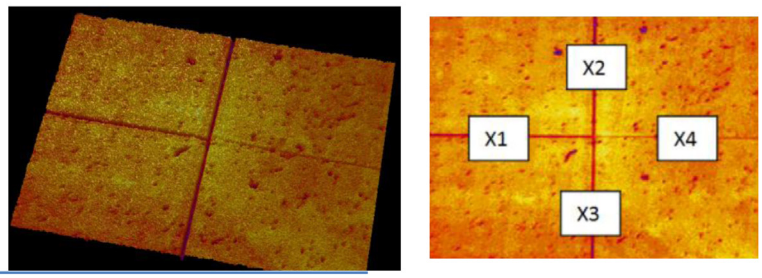
Fig. 5. Images of the laser-induced plasma, when the focus is within the bulk volume of the sample or at the sample surface.

a



A/A	Sine wave channel width (μm)
X1	24.3
X2	24.27
X3	24.3

b



A/A	Channel width (μm)
X1	20.246
X2	22.3
X3	20.2
X4	10.12

Fig. 6. (a) Uniform channel width for a sine wave, which is a complex structure for which there is an almost constant change in velocity profile. (b) Velocity change inscription results in a markedly different channel width – straight lines.

materials [11], although here commercially available materials, such as doped PDMS (polydimethylsiloxane) or PVK (poly-N-vinyl carbazole) were used. The programming code provides the ability to define the radius of the ring, the distance between the channels/waveguides and the ring resonator and the length of the final resonator structure.

Fig. 9 shows two resonators structures fabricated with a different number of writing steps, the first (top) resonator using a single step, whereas the second underwent 10 inscription repeats. The widths of the channels are ~10 μm and the diameter of the ring 100 μm. On initial inspection it appears that both channels nearly identical, but on closer inspection using the optical profilometer we observe subtle differences. The number of repeats affects the inscription width and despite the fact that the pre-default distance between the channel and the ring was defined at 5 μm, it is clear that for the case of 10 repeats the channel collapsed with

Fig. 7. Demonstration of control degree of laser repetition rate and sample velocity allowing definition of highly controllable index modulation points.

the ring creating different features, Fig. 10. The energy used for the inscription was ~6.7 μJ/pulse at 100 kHz repetition rate while the inscription speed was 50 μm/s. The measured depth of the first resonator was ~9 μm while in the second resonator was ~15 μm.

We further inscribed five cascaded ring resonators starting the inscription from the surface of the fibre going down to the cladding of the fibre at depths of 5, 10 and 20 μm in order to investigate the possibility of creating the structures several microns under the surface. Fig. 11 shows optical images (all focused on the surface of the fibre) of the inscribed resonators at different depths. The last two resonators (bottom image) show the difference between the 5 and 10 times inscription repeats.

3.3. Disc resonator inscription in flat fibre

By creating many homocentric circles having decreasing diameters and a very short distance between them, there is the possibility of overlapping the circles thereby creating a disc resonator. All the parameters of the laser and the characteristics of the disc remained the same as before. Fig. 12(a) shows the optical image of the disc resonator and Fig. 12(b), the corresponding 3D image from the profilometer.

3.4. Deposition of active material (PDMS) on the ring resonator

In this section, we present an example of the successful deposition of PDMS (polydimethylsiloxane) inside the channel of a resonator. PDMS was synthesised by mixing 10:1 the elastomer with the curing agent. First we drop-casted the material on the top surface of the fibre and then removed the remaining PDMS using a razor-blade. We subsequently annealed the fibre with the

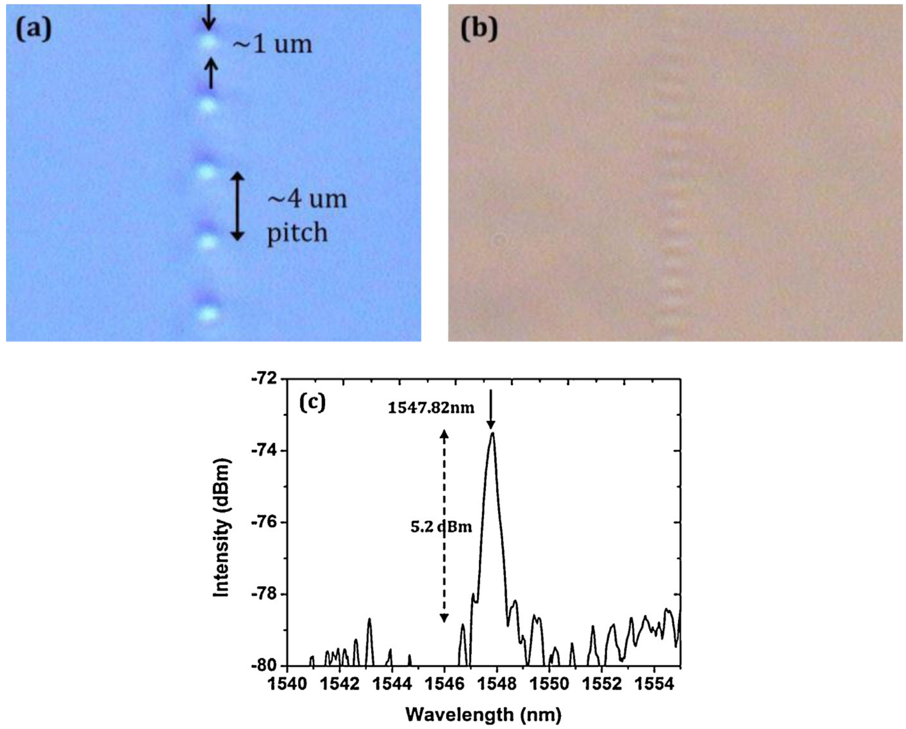


Fig. 8. (a) Laser inscribed points having a 4-μm spacing and 10-μm depth and (b) the 1.1 μm-spaced points that resulted in the reflection response in the C-band, inscribed at a 33-μm depth. (c) The recovered Bragg grating spectrum at 1547.82 nm.

deposited material at ~70 °C for ~2 h. Figs. 13 and 14 show the optical images as well as the 3D pictures from the profilometer before and after PDMS deposition, confirming the existence of the material in the channel of the ring resonator. It should be noted that in Fig. 13 both images are focused on the surface of the fibre where the difference between the two cases is clear indicating the existence of the material inside the channel of the resonator.

In order to further confirm the successful deposition we used the optical profilometer to determine the depth of the channel before and after the PDMS deposition. The initial depth of the resonator was around ~5 μm, whereas following the deposition the depth was just a few nanometers. However, as can be seen from Fig. 14 there is a small part of the resonator unfilled (indicating with white dashed circle) due to the high viscosity nature of PDMS.

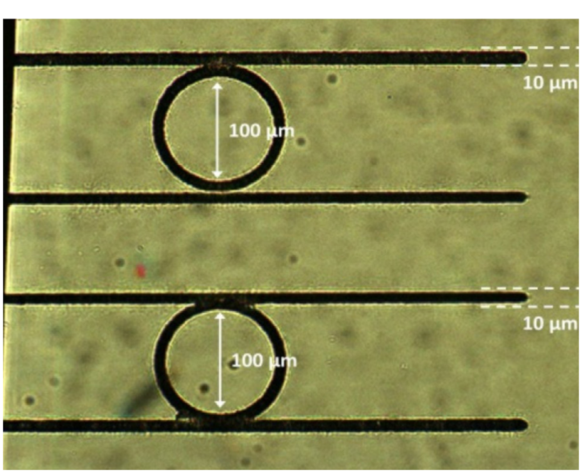


Fig. 9. Two resonators fabricated with a different number of writing steps, (top) resonator using a single step, (bottom) resonator underwent 10 inscription repeats.

One possible to avoid this effect is to further dissolute PDMS in toluene in order to reduce the viscosity of the material.

3.5. Mach-Zehnder structures

Another structure of increased importance for sensing or telecommunication applications is the Mach-Zehnder interferometer. Fig. 15 shows optical microscope images of two Mach-Zehnder interferometers inscribed on the top surface of the fibre. The laser energy was 3.5 μJ/pulse and the speed of inscription 50 μm/s; the difference lies in the number of inscription repeats. The 3D image from the profilometer indicates smooth transition to the two arms of the Mach-Zehnder.

The flexibility offered using the direct write femtosecond laser inscription allows for far more complex structures to be made, Fig. 16, with small changes to the G-code program. It is relatively straightforward to create a double Mach-Zehnder structure or a complex interleaved Mach-Zehnder having several interferometers inside each other. The points A and B in Fig. 16 indicate the location where we measured the quality of the channel using the profilometer. In case (A) the quality of the channel is affected by the presence of debris due to the low inscription speed that was used (50 μm/s), while in the second case, where the speed was 1000 μm/s the quality of the channel was significantly improved. The laser parameters were maintained as previously. In addition, it should be noted that in a similar way as presented for the case of the ring resonator we deposited and filled the fabricated Mach-Zehnder channels with PDMS, to verify that the drop-casting technique is a proper method for filling the micro machined channels with the desired material.

3.6. Fabrication of microfluidic structures

In this final section we combine several surface microfluidic channels and structures as a demonstration of the potential of the

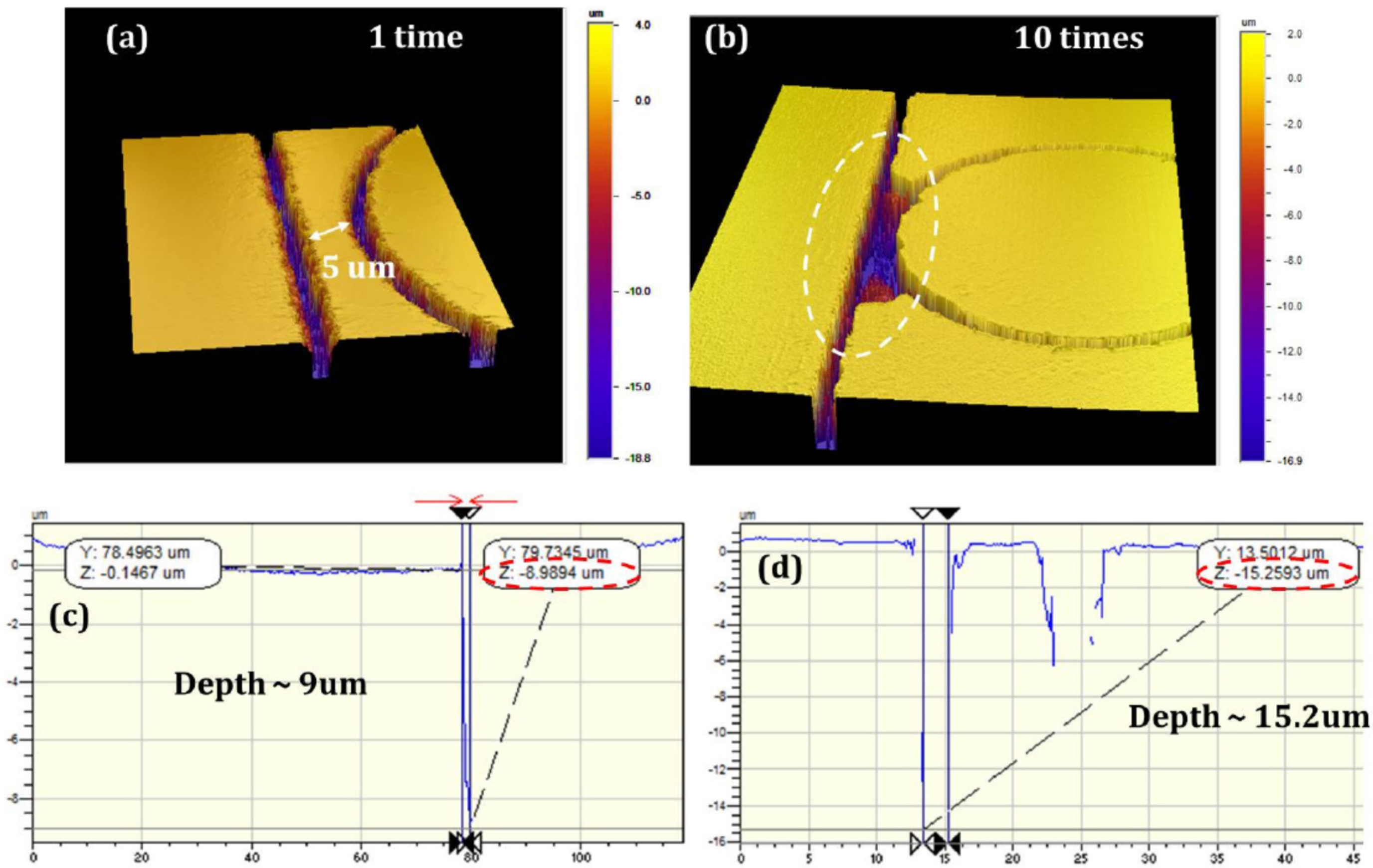


Fig. 10. (a) 3D image of the ring resonator inscribed once showing the distance between the channel and the ring. (b) Ring resonator after 10 repetitions showing channel collapse with the ring. (c) Depth measurement of the first resonator and (d) the second resonator.

flat fibre to accommodate such diverse and complex structures. The design of the microfluidic device constitutes three inputs, a sinewave-like channel for the delay of the fluids and a block of channels for liquid mixing. The depths of the channels were about 4 μm while the dimensional parameters are shown in Fig. 17. The laser energy was 6.7 μJ/pulse at 100 kHz repetition rate. This final structure indicates the great potential of the combined flat-fibre platform and femtosecond laser inscription process.

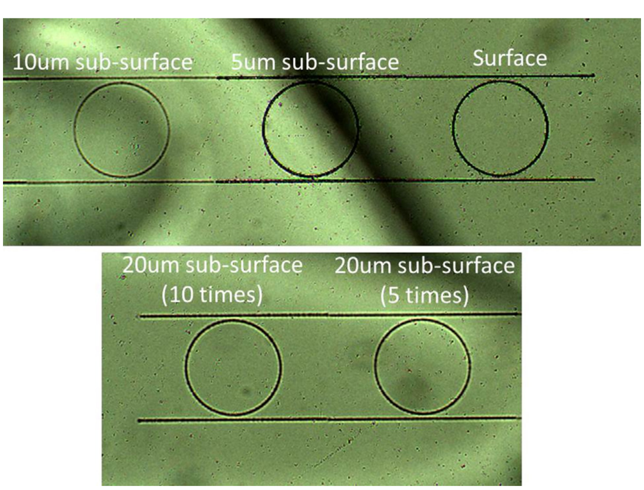


Fig. 11. Inscription of 5 cascaded ring resonators at different inscription depths (surface, 5, 10 and 20 μm sub-surface). The last two resonators inscribed 5 times and 10 times respectively.

In most of the above demonstrated structures (ring resonators, Mach Zehnder interferometers, microfluidic channels, etc. a common fabrication quality factor is the exhibited sidewall roughness which can affect the waveguide propagation losses and consequently the performance of those devices. The laser fluence and the height of the laser focus relative to the flat fibre surface have an impact on quality of the inscribed channels, regarding their depth and roughness. Here are presented initial results while further detailed investigation is in progress. For the case of high fluence, as we have used in this work, we have the greatest exhibited roughness with an average roughness of 400–500 nm being typical, results that agree with existing research [12]. By using laser energies below 3.5 μJ/pulse can reduce the average roughness to levels of 100–350 nm. The inscription procedure can therefore lead to markedly different results, and methods can be employed to improve or control roughness, such as overwriting existing channels, optimise the laser inscription energy and write velocity, in addition to control of the height of the laser focus point relative to the sample surface. Furthermore, these levels of average roughness can be significantly improved by post processing the samples, for example, coating the channels with hydroxyethyl methacrylate (HEMA) polymer coating that can lead to coated channels with an rms roughness of 10–50 nm [13]. Methods that introduce glass reflow in the femtosecond laser processed areas of the samples can also be used to improve levels of roughness, such as the use of optical polishing with CO_2 lasers or processing in a high temperature oven [14,15]. The use of wet tech techniques is widespread, with the selective etching of silica using hydrofluoric acid to preferentially remove regions of glass exposed to the femtosecond laser pulses, where the laser-exposed areas react rapidly with the acidic

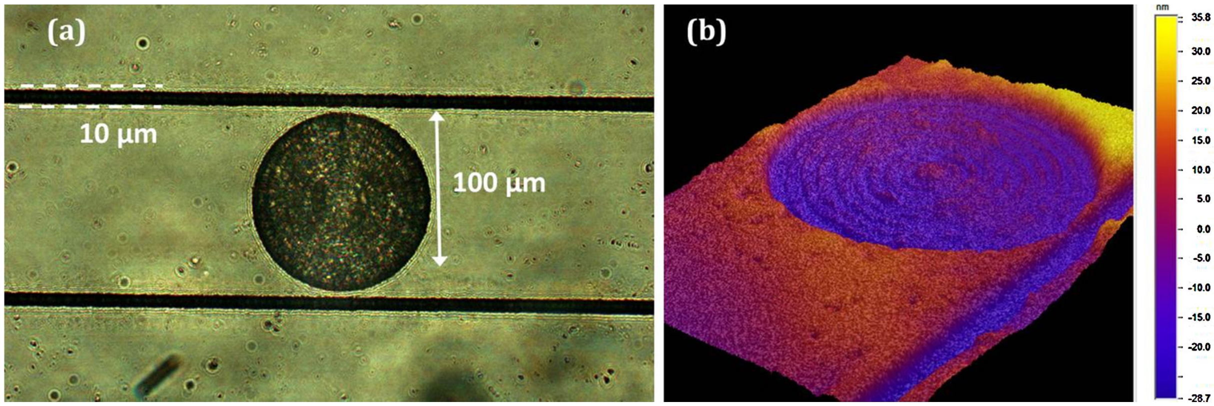


Fig. 12. (a) Optical image of the disc resonator. (b) 3D image from the profilometer.

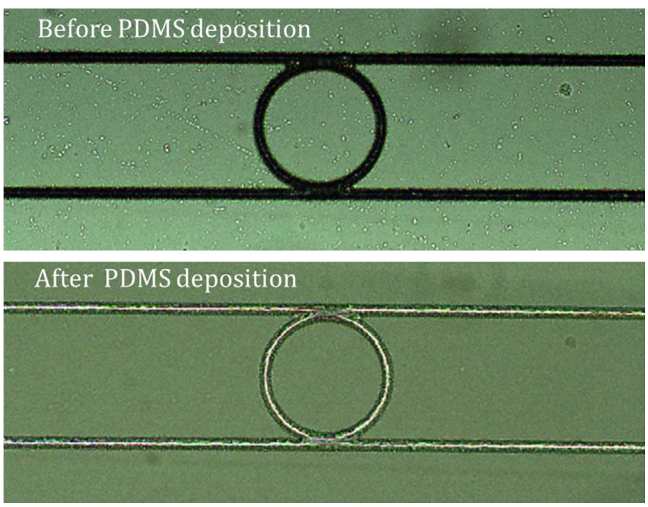


Fig. 13. Optical images of the ring resonator before and after PDMS deposition. Both images are focused on the fibre surface.

solution compared with unexposed areas [16–18]. We should also note that the degree of roughness has a different impact on different applications depending on the use of micromachined channels as for example for waveguides development (by filling them with high refractive index materials and potentially doping them) or as microfluidic channels for fluids flow control. Those different applications require and can tolerate also different degrees of side wall roughness. The above areas are currently under detailed investigation.

4. Discussion and future perspectives

The presented results demonstrate the development feasibility of flat-fibre based integrated optical circuits combined with microfluidics structures and devices, towards an integrated platform of lab-on-a-chip [19,20] or more accurately lab-on-a-fibre implementation. The infinite (in theory) length, and the highly uniform nature provided by this platform that results from the drawing process involved, could enable the optimised design [21] of more sophisticated structures that could enable multi-parametric and cross correlated sensing. Integration of multiple Bragg grating loaded waveguides [22,23] or concatenated multiple ring/disc resonators along the fibre could enable the continuous monitoring of different physical and biological processes occurred at physical cavities exposed to measured environment or microfluidic structures that are in sensing proximity with those interrogated waveguide channels transferring information.

Further to passive sensing and microfluidic components the large area of flat fibres and the customisable manufacturing process enables the development of active lasing devices by appropriate doping with erbium in suitable aluminium-doped silica material

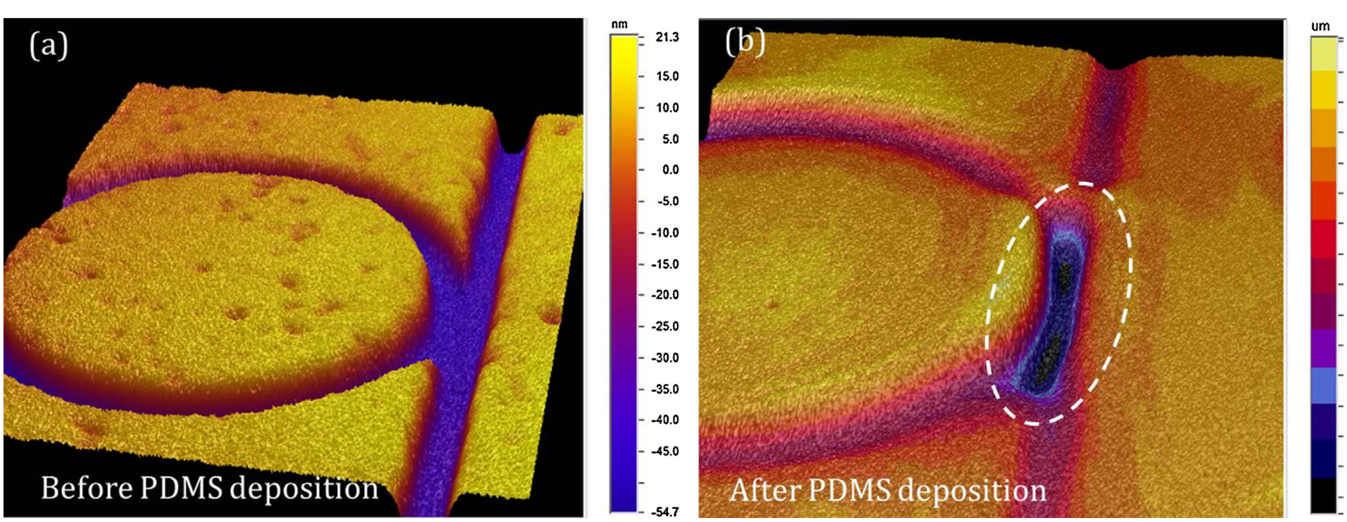


Fig. 14. 3D images from the profilometer of the ring resonator (a) before and (b) after PDMS deposition (white dashed circle indicates the unfilled region).

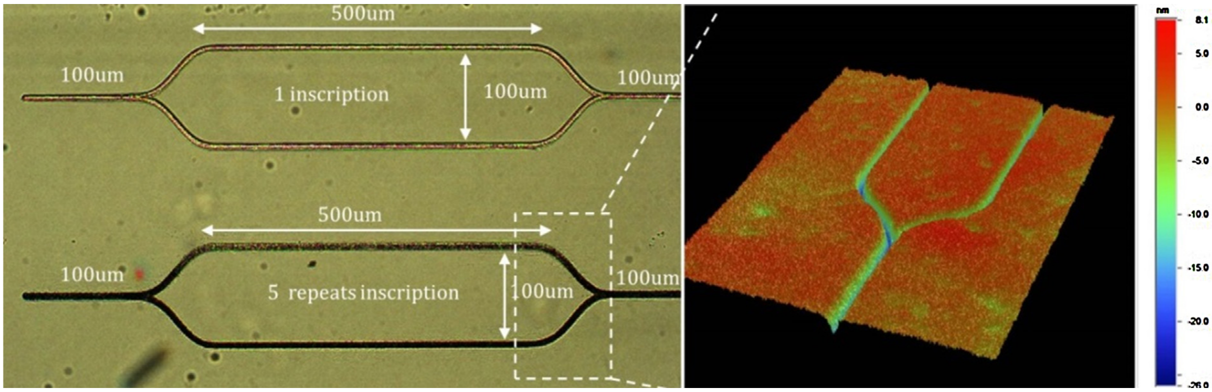


Fig. 15. Optical images of two Mach-Zender interferometers. The top structure made using 1 inscription, while the bottom has 5 repeats. Profilometer 3D image demonstrating the structures' quality (Right).

system. The development of integrated fibre laser and amplifiers could intrinsically compensate for transmission losses and more importantly allow the development of active sensing schemes. The surface physical patterning of flat fibres enables also the definition of low loss waveguides with novel polymeric materials like amphiphilic diblock copolymers [11,24] leading thus to intrinsically, by means of material, sensitive waveguides to a tailor made range of targeted analytes.

Overall, our results highlight the great potential of this new fibre type in removing the need to combine cylindrical optical fibres with planar technology, but rather having a single platform as a transport and sensing medium, directly having all the desired integrated optics "on chip". We foresee that this technology will lead the way to new sensing applications and new types of integrated devices, particularly those requiring both fully distributed and point interaction capabilities.

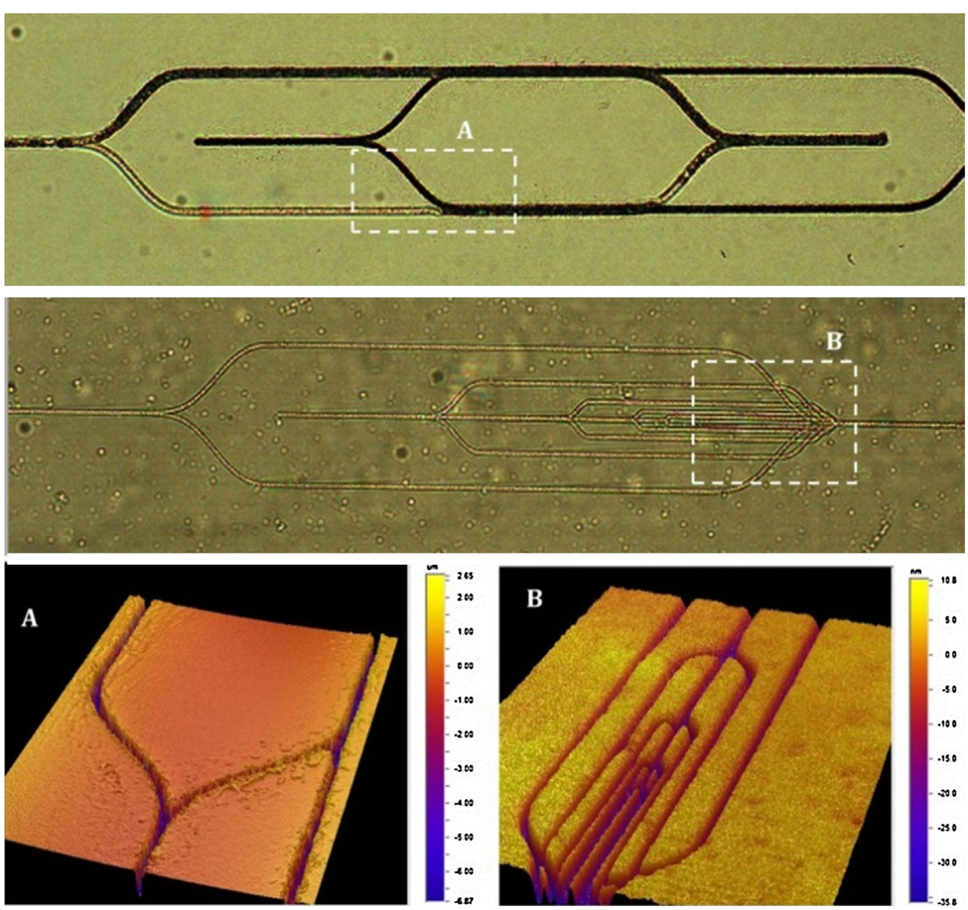


Fig. 16. Optical and 3D profilometer images of a double (top) and interleaved (middle) Mach-Zender structures.

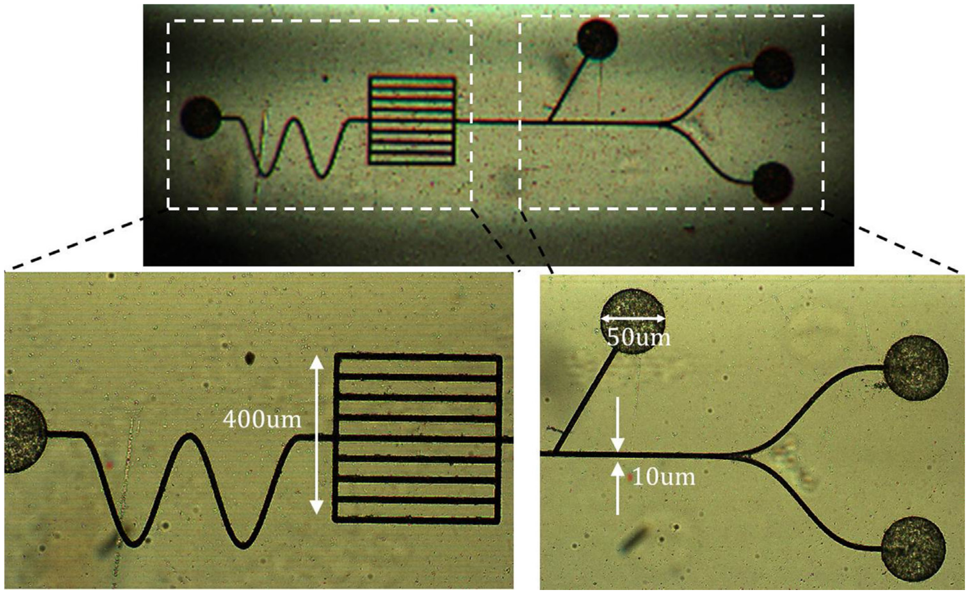


Fig. 17. Optical images of the microfluidic device on the top surface of the flat fibre.

5. Conclusions

We have demonstrated that flat optical fibre represents an exciting research field that combines many and diverse areas of science such as materials, femtosecond laser fabrication processes, integrated optics and optical fibres. More specifically we have presented, for the first time in flat fibres, the micromachining and inscription of different key optical structures (such as ring and disc resonators, Mach-Zehnder interferometers and complex microfluidic devices), and the inscription of C-band Bragg gratings (∼1550 nm) in the Ge-doped core of the flat fibre or indeed anywhere in the cladding. In addition, we have shown that it is possible to fill the channels with potentially any functional material. The flat-fibre chip offers a unique degree of freedom by allowing surface and sub-surface devices to be integrated onto an optical platform with the potential for straightforward incorporation into integrated photonic circuits or opto-fluidic devices.

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