High precision 9.6 µm CO_2 laser end-face processing of optical fibres

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Abstract: Reproducible, precise cleaving of optical fibres is of great importance to the fibre laser and telecommunications industries. We present a novel approach to the end-face processing of optical fibres using a 9.6 µm CO_2 laser to produce flat, smooth and symmetric fibre end-face profiles with no rounding or melting at the edges of the fibre. As a demonstration, precision cleaving of a 400 µm diameter optical fibre is reported. For this fibre a topographical profile height of <400 nm (0.06°) and a reproducibility better than 200 nm (0.03°) was achieved. To the best of our knowledge this is the first demonstration of a CO_2 process that has generated a fibre end-face topography substantially smaller than a typical mechanical cleave. Highlighting the flexibility of this system, we have also demonstrated the generation of near arbitrary fiber end-face profiles such as discrete phase steps and non-spherical surface profiles.

OCIS codes: (120.4610) Optical fabrication; (140.3390) Laser materials processing; (220.5450) Polishing.

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1. Introduction

Reproducible and precise cleaving of optical fibres is of significant importance to the fibre laser manufacturing and telecommunications industries. With the advent of complex optical fibre designs, including non-circular claddings, microstructures and interfaces between materials of substantially different dopant concentrations, mechanical cleaving techniques which rely on crack propagation often result in a poor surface quality and a low process yield. A large variety of solutions and products are available that aim to minimize cleave angles, yet the typical quoted value from various manufacturers is ~0.3° for a 400 µm diameter fibre [1–3]. This corresponds to a deformation of 2 µm across the surface. In addition, there are process features such as the blade initiation site, misting and hackle that can lead to scattering losses and potentially cause catastrophic damage in certain applications [4]. Other applications such as lensing of fibres to improve diode laser coupling efficiency or to act as monolithic collimators or mode-converters require more advanced processing techniques.

CO_2 laser processing of silica glass is an important tool for the rapid fabrication of high precision custom optical components [5–7] due to the high absorption of silica at the output wavelengths of CO_2 lasers [8, 9]. In addition to controlled shaping of silica glass through ablation, the CO_2 laser can also be used for polishing [10–13] resulting in ultralow scattering loss and increasing the laser damage resistance of surfaces [13–15]. CO_2 laser polishing promises a non-contact approach with fast preparation times and high quality surface finishes for silica glass fibres.

Despite the many advantages of CO_2 laser preparation techniques, uptake of CO_2 laser cleaving has been slow with the majority of fibre laser manufacturers still relying on conventional mechanical cleaving in order to prepare optical fibres prior to splicing. This is largely due to a strong thermal component to the process that commercially available CO_2 laser fibre processing systems tend to utilize [16]. A characteristic of strong thermal processing is substantial rounding at the edges and in the centre of the fibre with state-of-the-art systems producing a topography >4 µm over a 125 µm diameter fibre [16, 17]. This rounding is substantially worse for larger fibres, and creates a large cylindrical defect when attempting to splice two fibres. This weakens the mechanical strength of the splice and induces loss for light propagating in the cladding. A high level of heat deposition during the cleave process will also cause substantial diffusion and potentially deform the core, which will contribute to splice loss and mode-coupling effects. Consequently, current CO_2 laser fibre end-face preparation is more suited for use in free-space propagation applications, for use in fibre connectors or for the preparation of fibres prior to subsequent mechanical polishing [16–19].

In this article, we present a CO_2 laser processing technique that allows for highly reproducible fibre end-face preparation with sub-micron control over the topography. We begin with a detailed description of our approach, highlighting the key features that enable high precision and high reproducibility in the process. We then experimentally investigate the control we have over the ablation depth, profile symmetry, cleave reproducibility and demonstrate the capability to fabricate flat angle cleaves. We demonstrate a surface topography of <400 nm over the entire diameter of a 400 µm fibre with minimal edge-rounding effects – this is more than an order of magnitude improvement on currently reported

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state-of-the-art CO_2 laser processing solutions [16–19] and also an improvement by a factor of 5 on typical state-of-the-art mechanical cleaving solutions [1–3]. We also demonstrate a reproducibility of better than 200 nm in fibre surface preparation.

2. Approach

In many processing applications, it is advantageous to prevent volume heating of the fibre due to the potential for dopant diffusion, surface melting, surface deformation and unwanted bulging of fibre surfaces. To avoid operating in this regime, processing using a wavelength with a much shorter absorption depth in silica limits the deposition of energy to the fibre surface and enables the fabrication of smaller features. As a result, a wavelength locked CO_2 laser operating at the wavelength of 9.6 µm (Coherent GEM 100L) was chosen to enable the production of high precision optical fibre end-faces. At this wavelength, silica has an absorption coefficient an order of magnitude larger than at the more conventional wavelength of 10.6 µm [9] which has a measured absorption depth of 35 µm at 25°C [8].

A schematic of the CO_2 laser fibre processing set-up is shown in Fig. 1(a). The fibre is held in a rotary stage that can be linearly translated in three orthogonal axes and tilted in the plane of incidence of the laser. A 100 W pulse width modulated 9.6 µm wavelength CO_2 laser beam is focused on to the optical fibre using a 25 mm focal length ZnSe aspheric lens. The beam diameter of the CO_2 laser at the laser exit aperture is ~3.8 mm with a full angle divergence of 3.6 mrad and an M^2 ~1.2. The beam expands to a diameter of ~7 mm at the ZnSe lens, which focuses the beam to a spot diameter of ~50 µm at the focus. This is confirmed using a 90/10 knife-edge measurement technique. A visual indication of the spot size is shown in Fig. 1(b) where the process feature is about a factor of 10 smaller than the diameter of the 400 µm fibre.

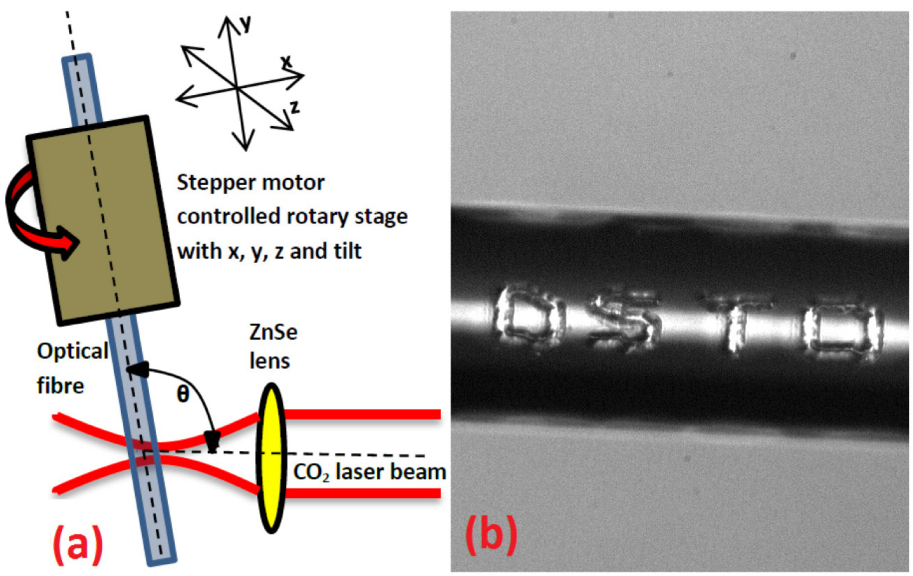

Fig. 1. (a) Schematic of the CO_2 laser cleaving experimental setup: An optical fibre is held in a removable chuck. Translation in the x, y and z axis, as well as tilt is achieved through a series of stepper motors. The CO_2 laser beam is focused onto the optical fibre using a 25 mm ZnSe aspheric lens. (b) An inscription on the surface of a 400 µm diameter fibre illustrating the ~50 µm spot size of the CO_2 laser beam.

The fibre was rotated at 60 revolutions per minute while individually controlled pulses from the CO_2 laser were triggered at prescribed angles. Tilt, rotation and 3D translation of the fibre during processing was possible using 5 stepper motors. A microscope camera was used to monitor the process in situ.

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In all configurations, the fibre was positioned as shown in Fig. 2(a) – there is no prior preparation of the fibre other than the removal of the polymer coating. The processed fibre is shown in Fig. 2(b) and a movie of the cleaving process is provided in Media 1. The video shows that a large fraction of the glass is ablated during the first few rotations of the fibre. The temperature of the irradiated zones then drops below the evaporation temperature of silica glass (2700°C [13]) because the fibre is no longer in the direct path of a focused Gaussian beam. At this point, the process is dominated by laser polishing of the fibre end-face surface. In this regime, the fibre end-face only interacts with a small portion of the CO_2 laser beam. This allows for very fine control of the material removal and the subsequent production of smooth features with dimensions an order-of-magnitude less than the CO_2 laser wavelength.

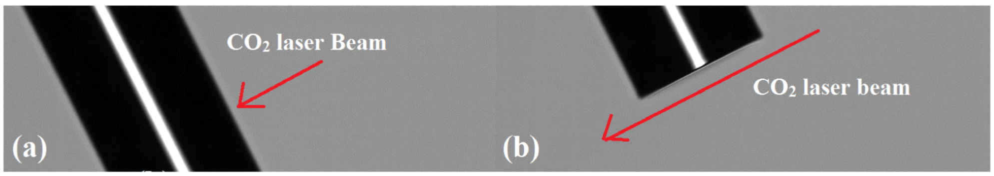

Fig. 2. (a) Fibre prior to processing with an indication of the direction of the CO_2 laser beam propagation (b) Flat end-face process completed. A movie of a typical process is provided in Media 1.

Due to the cylindrical nature of the optical fibre, inspection using side illumination can often give misleading results. With this in mind fiber end-face surface profiles where measured with a phase shifting interferometer operating with a LED source at ~650 nm (Nyfors, Cleavemeter 3D).

3. Optical fibre end face profile control

The curvature of the fibre end-face was found to be dependent on the fibre pitch angle relative to the incident laser beam, as well as the pulse duration and pulse energy. To investigate this effect the residual curvature of the optical fibre end-face was measured as a function of fibre pitch angle for pulse durations of 80 and 90 µs as shown in Fig. 3. From these measurements, it is clear that there is an optimum fibre pitch angle that yields a flat surface profile, as well as regions where the end-face is convex or concave. Figure 4 also shows that the optimum pitch angle varies for different pulse duration settings.

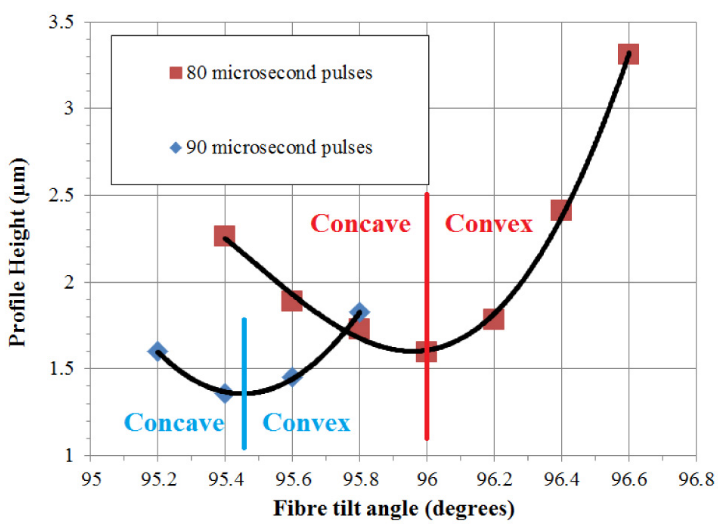

Fig. 3. Profile height as a function of fiber tilt for pulse durations of 80 and 90 µs.

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To investigate the effect pulse duration has on the radial slope of the optical fibre for a fixed fibre tilt angle, we processed a fibre with pulse durations that linearly increased every 1.8° of spindle rotation from 40 μs to 50 μs. The results of Fig. 4 show that the slope changes from positive to negative in approximately a linear manner.

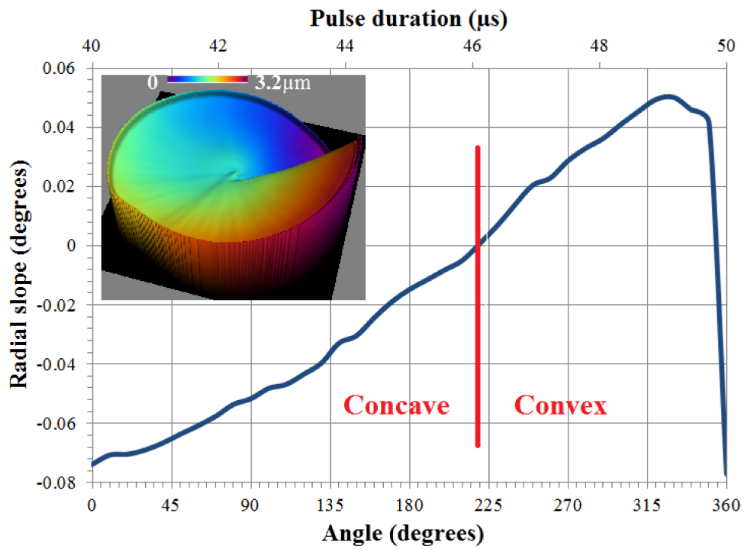

Fig. 4. Radial slope measured for a ramp created using pulse durations which increased linearly from 40 μs to 50 μs every 1.8 degrees, with the fibre held at a tilt angle of 110°. For pulse durations below 46 μs the slope is negative and the radial profile is concave, while above this value the slope is positive corresponding to a convex profile. The insert shows the reconstructed 3D profile of the ramp with a maximum profile height of 3.2 μm.

Utilising this degree of flexibility in the surface contouring the CO_2 laser fibre processing system is capable of arbitrarily shaping fibre end-faces, resulting in profiles such as those shown in Fig. 5. By varying the pitch of the fibre with respect to the CO_2 laser beam, it is possible to produce profiles transitioning from convex to concave while maintaining a high degree of symmetry as shown in Figs. 5(a) and 5(b).

The ablation depth for a fixed pitch can also be controlled by varying the pulse duration. As an example of various end-faces that can be fabricated, in Fig. 5(c) a ramp profile was created by firing the laser every 0.45° of spindle rotation, with increasing pulse durations from 40 μs to 70 μs. In Fig. 5(d) alternating pulses of 40 μs and 45 μs create submicron periodic features and in Figs. 5(e) and 5(f) alternating pulsing for half and quarter spindle angles provides alternating high and low planes.

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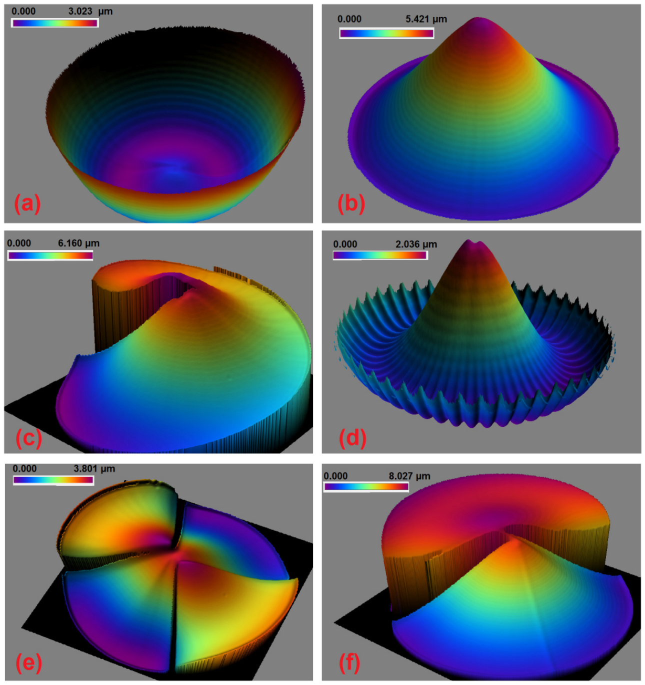

Fig. 5. Reconstructed end-face optical fibre topography measured using a 650 nm phase-shifting interferometer for a series of cleaves fabricated with a variety of CO_2 laser pulse durations as a function of rotation angle at a constant fibre tilt: (a) 40 µs pulse fired every 0.45° degrees (b) 70 µs pulses fired every 0.45° (c) ramped pulse durations from 0.45° degrees, starting at 40 µs and finishing at 60 µs, (d) alternating 40 µs and 45 µs pulsing every 7.2° spindle rotation.,(e) alternating 60 µs and 70 µs pulsing every 90° spindle rotation and (f) alternating pulsing every 180° spindle rotation.

4. Flat angle cleaving reproducibility

The reproducibility of the CO_2 laser cleaving process was tested by cleaving 10 samples of 400 µm outer diameter fibre and measuring the resulting end face profiles. Figure 6 shows the interference patterns obtained for each cleave. The variation between the surfaces had a standard deviation of <200 nm at each point (approximately equivalent to ± 0.015°).

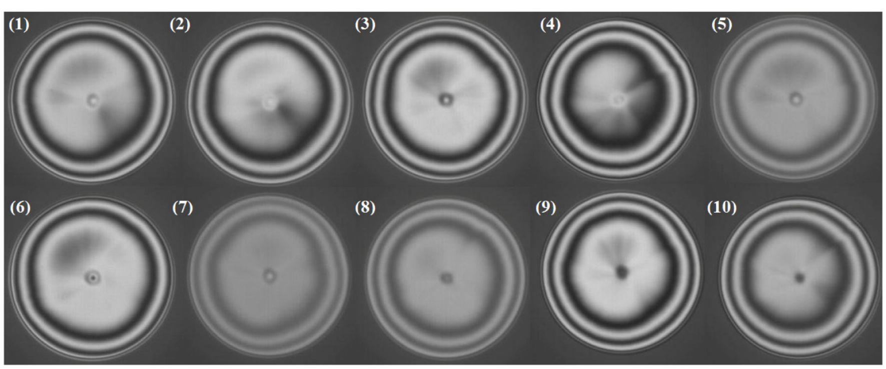

Fig. 6. A series of 10 cleaves of a 400 µm. The end-face is inspected using a phase shifting interferometer operating at ~650 nm. All samples show a large central fringe and symmetric outer fringes. The standard deviation of the surface variation was <200 nm.

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In many applications, a more convex end-face profile is desirable. Using the calibration shown in Fig. 4, pulse durations of 47 μs were chosen to produce a slightly convex profile as shown in the cleave of Fig. 7. The total material processing time for this cleave was <30 s.

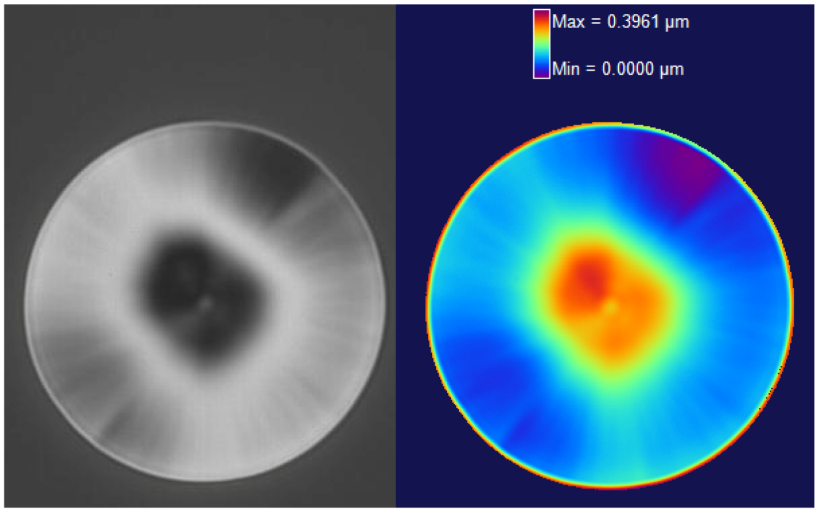

Fig. 7. A nearly flat 400 μm fibre end-face fabricated using CO_2 laser pulses of 47 μs duration fired every 1.8°, giving a slightly convex shape.

5. Conclusion

We have presented a 9.6 μm CO_2 laser processing technique suitable for the reproducible, rapid fabrication of near arbitrary fibre profile shapes. The fabrication of a number of novel fibre end-face profiles including discontinuous phase steps and aspheric concave and convex profiles demonstrates the versatility of this technique. Such complex profiles with sub-micron scale resolution cannot be fabricated using conventional cleaving or polishing techniques.

While fibre end-face preparation using CO_2 lasers has been previously demonstrated, these approaches have largely been limited to a more thermal processing of the fibre. As such the fibre end-face takes on a more rounded shape. This rounding is typically >4 μm topography over the fibre diameter [16, 17]. In comparison, we have demonstrated a repeatable process that produced end-face profile topography of less than 400 nm across the entire surface of a 400 μm diameter fibre with negligible rounding at the fibre edges and cleave-to-cleave reproducibility to within 200 nm. The magnitude of this end-face topography is equivalent to the surface deformation associated with that of a 0.06° angle cleave. This total deformation is also a factor of 5 smaller than the deformation associated with conventional mechanical cleaving [1–3]. To the best of our knowledge, this is the first time a CO_2 laser based fibre processing technique has shown superior performance in comparison to the conventional mechanical crack propagation approach for the preparation of fibre end-faces prior to splicing. Our technique also leaves no cleave initiation point, misting or hackle features that have been shown to lead to scattering losses and lower fibre damage thresholds.

The process is insensitive to the original fibre end-face condition, requiring only stripping of the polymer coating as the preparation. Other authors have investigated and demonstrated the use of CO_2 lasers to ablate and remove the polymer coating [20]. We are currently in the process of implementing this technique which should eventually allow for a completely operator independent, automated fibre end-face preparation system.

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