Deep ultraviolet laser micromachining of novel fibre optic devices

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Deep ultraviolet laser micromachining of novel fibre optic devices

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Abstract. A deep ultraviolet F_2 laser, with output at 157-nm wavelength, has been adopted for micro-shaping the end facets of single and multi-mode silica optical fibres. The high energy 7.9-eV photons drive strong interactions in the wide-bandgap silica fibres to enable the fabrication of surface-relief microstructures with high spatial resolution and smooth surface morphology. Diffraction gratings, focusing lenses, and Mach-Zehnder interferometric structures have been micromachined onto the cleaved-fibre facets and optically characterized. F_2-laser micromachining is shown to be a rapid and facile means for direct-writing of novel in-fibre photonic components.

1. Introduction

Silica-based optical fibres are pervasive in industry, health care and research serving widely diverse applications in telecommunications, sensing, surgery, optical imaging and material processing. For these applications, the packaging and assembly of optical fibre systems demand increasing novel solutions for integration with specialized micro-optic components, that are otherwise challenging to fabricate on such small core diameter (8 - 100 μm) fibres with inconvenient cylindrical geometry. Traditional fabrication methods such as grinding, polishing, thermal melting, lithographic and non-lithographic chemical etching are not well suited to processing delicate glass fibres. Laser micromachining, on the other hand, is widely employed for rapid, facile and precision fabrication of microstructures with few restraints on the feature size, surface morphology, and structure geometry. The deep-ultraviolet F_2 laser is most promising amongst commercial excimer laser systems for the precise micro-structuring of transparent glasses [1-6]. The short 157-nm radiation drives strong one-photon interactions even in the most robust UV-grade fused-silica glasses to enable smooth and crack-free etching with high spatial resolution of ~250-nm and precise depth control of ~10 nm [1]. This opens a wide range of possible applications for micro-optics fabrication in silica-based glasses.

In this paper, we extend F_2-laser microprocessing to fabrication of micro-optic devices directly onto the cleaved facets of single and multi-mode optical fibres. Laser processing parameters for defining diffraction gratings, microlenses and Mach-Zehnder interferometers are presented together with the optical characterization of these novel fibre-tip micro-optic devices.

2. F$_2$-laser processing system

Details of the F$_2$-laser microfabrication station has been described elsewhere [1-3]. In summary, a deep-ultraviolet optical homogenizing system (MicroLas Laser Systems) converts the non-uniform 10 mm × 25 mm laser beam to a uniform (±5%) beam of 5 mm × 5 mm area at the projection mask plane. Here, a mask patterns the beam, which is then demagnified 25× onto the target surface with a Schwarzschild objective (NA = 0.4). Targets were positioned on high-resolution (100-nm) XYZ motion-stages (Newport, TSPI) offering three-dimensional sample movement. The whole laser path was purged with high-purity nitrogen gas for the 157-nm transparency. The on-target laser fluence can be varied up to a maximum of 7 J/cm^2 with a dielectric coated attenuator and/or by adjusting the laser operating voltage. An imaging system sharing the Schwarzschild objective was used to spatially align the targets and observe micromachined surfaces.

3. Micro-optics fabrication and characterization

3.1. Diffraction grating

A chrome-on-CaF$_2$ photo mask with a 50-μm period grating and 50% duty cycle was used for generating 2-μm surface-relief gratings on fibre end facets. Figure 1a shows an optical image of a highly uniform grating formed fully across both the 50-μm core and 125-μm cladding of a multimode silica fibre. The surface-relief profile in figure 1b, recorded by atomic force microscopy (AFM), reveals a smooth sinusoidal-like modulation of 1.3-μm depth. This grating was excised with 36 laser pulses at a single-pulse fluence of ~ 4 J/cm^2. For this 2-μm grating period, modulation depth was controllable from ~10 nm to 2 μm by varying laser fluence or exposure pulse number. A 633-nm He-Ne laser beam was lens-coupled into the multimode fibre at various angles to excite low or high-order modes, which yielded the far-field grating diffraction patterns in figures 2a and 2b, respectively. The measured first and second order diffraction angles of 18.7° and 39.9°, respectively, are expected for the 2-μm grating period. The zeroth order and combined first-order diffraction efficiencies were 25% and 50%, respectively, of the input power. The diffraction efficiency of various orders could be readily manipulated by controlling the laser-etch depth. This fabrication process also provides sub-micron gratings on single-mode fibres, while blazed diffraction gratings can also be generated, for example, by direct write scanning with triangular-shaped amplitude masks.
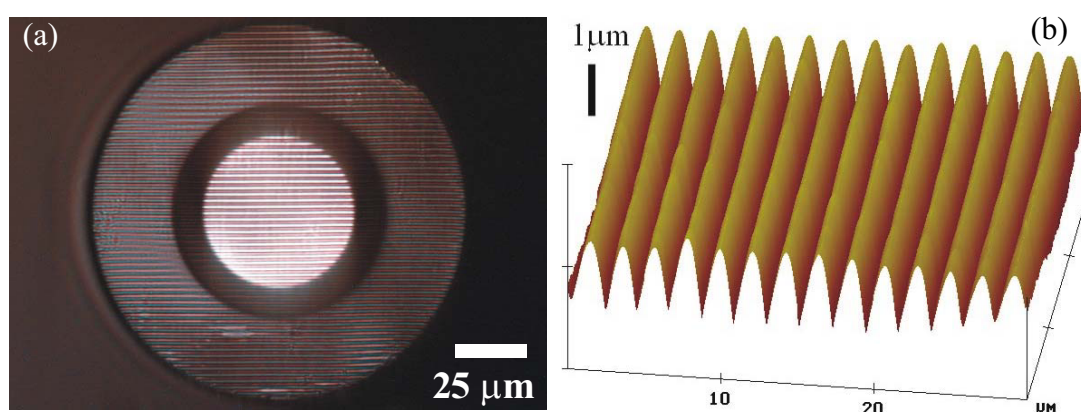

Figure 1. An optical microscopy image of a diffraction grating fabricated on the end facet of a multimode silica optical fibre (a) and an atomic force microscopy image of part of this grating surface (b).

3.2. Micro-lens

Both mask-projection and direct-write approaches were tested in shaping micro-lenses directly on fibre-end facets. In the former, the optical fibre was placed perpendicular to the laser beam and rotated

around its axis while the F_2 laser beam, shaped by the mask shown inset in figure 3, cut the rotating fibre with a conical shape. The optical microscopy image in figure 3 shows an example of a micro-lens formed on a multi-mode fibre with a 120-μm radius of curvature. In the direct-write approach, the fibre was aligned along the laser axis and rotated axially while a small laser spot was synchronously scanned under computer control normal to the facet at various radial positions, up to 30-μm for single mode fibre or much larger for multi-mode fibre. This arrangement provided wide latitude for varying the lens curvature while also correcting lens aberration simply by tuning the computer-controlled exposure script and varying the rotation speed, laser fluence, beam spot size, and laser repetition rate. Figure 4a shows a micro-lens of 10 μm radius of curvature positioned over the core of a standard single-mode silica optical fibre (SMF-28). The beam profile recorded at the focal plane for 1550-nm light is shown in figure 4b. The focussed beam is highly symmetrical with little scattered loss, while the spot diameter closely matches the 2-μm diameter diffraction limit.
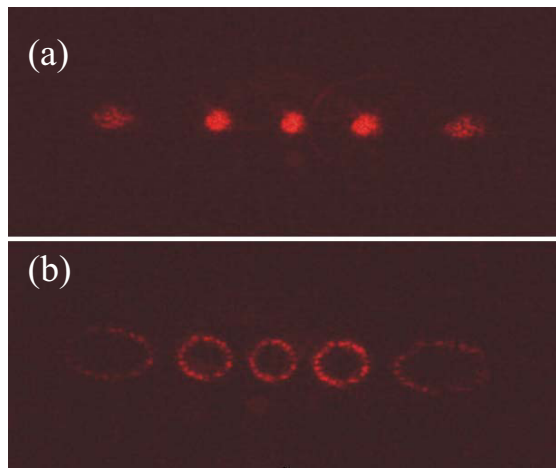

Figure 2. Far-field diffraction patterns generated by the grating-tipped multimode fibre shown in figure 1 for low-order (a) and high-order (b) mode excitation.
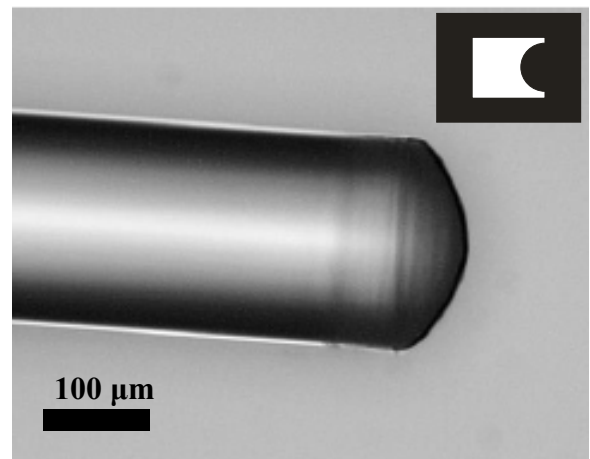

Figure 3. An optical microscopy image of a micro-lens-tipped optical fibre. The inset illustrates the amplitude photo mask used for laser-projection machining of the micro-lens.
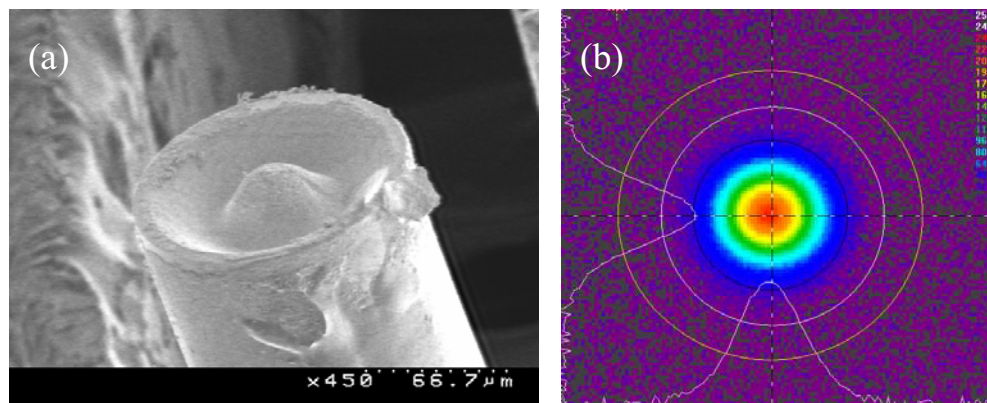

Figure 4. SEM image (a) of a micro-lens-tipped single-mode silica optical fibre (125-μm diameter) and the focussed-beam profile (b) at 1550-nm wavelength (2-μm diameter).

3.3. Mach-Zehnder interferometer

A miniature in-fibre Mach-Zehnder interferometer was fabricated by laser-etching a rectangular microchannel across one-half of the guiding core of a single-mode fibre (Corning SMF-28) as shown

in figure 5. An optically smooth rectangular channel, 30-µm wide and 5-µm deep, was formed by projection-mask machining with 30 laser pulses at 7-J/cm^2 single-pulse fluence. The trench was accurately positioned to bisect the ~9-µm diameter core, creating controllable phase delay between two halves of the guided beam that leads to interference fringes in the forward propagation. To test the interferometer, the etched fibre was butt-coupled to another single-mode optical fibre and probed with a multi-diode LED source (Agilent 83427A) and an optical spectrum analyser (Ando, AQ6317B). An interference spectrum is clearly demonstrated in the normalized transmission spectrum of figure 5b. The high contrast 26-dB attenuation at 1660 nm and low 2-dB insertion loss at 1300 nm is evidence of the good optical surface quality and straight trench walls defined by F$_2$-laser ablation.
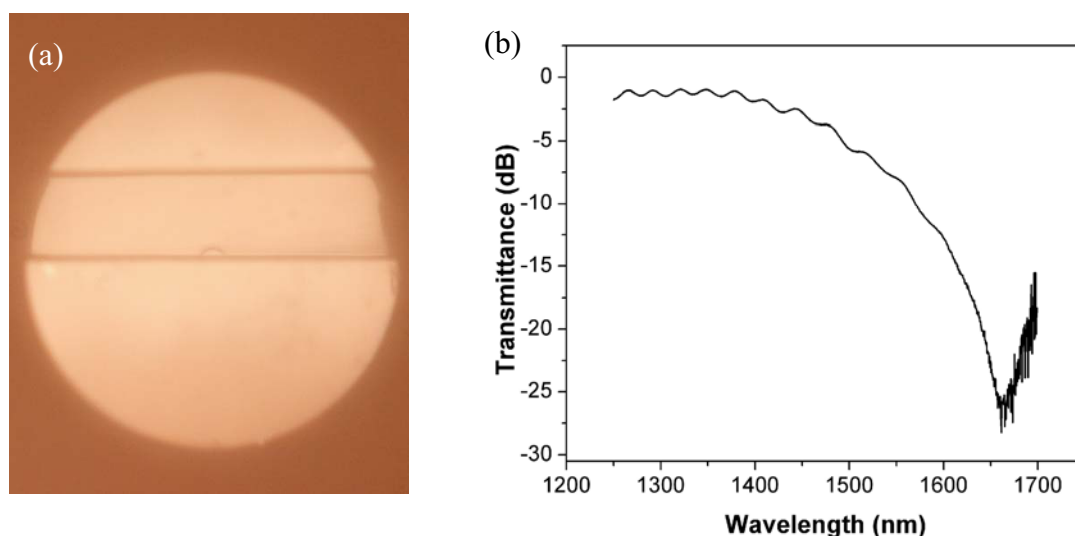

Figure 5. Optical microscopy image (a) of a single-mode silica optical fibre (125-µm diameter) with an ablated micro-trench defining a miniature wavefront-splitting Mach-Zehnder interferometer, together with (b) the normalized transmission spectrum.

4. Discussion and conclusions

Deep-ultraviolet F$_2$-laser micromachining has been applied to structuring the end facet of various optical fibres, producing various micro-optical components. The examples of focussing lenses, diffraction gratings, and interference phase masks define the basic tenets of most optics devices required in fibre systems today. Such integrated fibre-tipped optical devices are attractive in simplifying assembly and packaging in multi-element fibre optic systems by reducing the number of required optical components. Fewer optical components also improve thermal and mechanical stability. F$_2$-laser ablation provided optically smooth surface structures with high resolution (~250 nm lateral and ~10 nm depth control) and free of micro-cracks or other damage. Low insertion losses of ~2 dB were observed in several devices. Computer-controlled systems offered further flexibility for varying laser exposures conditions, adjusting write-patterns, or exchanging projection masks, which was attractive in tuning optical performance across a wide range of devices on single or multimode optical fibres across a wide spectrum of wavelengths. This approach is well suited to rapid prototyping of customized micro-optic designs.

In summary, several novel fibre optic devices have been demonstrated by the direct micromachining of optical fibre facets with a F$_2$ laser at 157-nm wavelength. Lenses, gratings, and interferometer devices were successfully integrated on single or multi-mode fibres. The low losses and compact geometry are broadly attractive in telecommunication, biophotonics, and sensor systems as wavelength multiplexers, micro-interferometric phasemask illuminators, mode-selective fibre-to-plane-waveguide couplers, beam splitters and combiners, and optical trapping.

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