FABRICATION OF PERIODIC, RESONANT FEATURES IN OPTICAL FIBRES USING A CO$_2$
LASER MICRO-TAPERING SYSTEM

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Abstract

We report on novel devices fabricated using an optical fibre micro-tapering facility based on a CO$_2$ laser and high precision translation stages, all of which are computer controlled. The use of a laser to heat the fibre is advantageous over standard flame-tapering systems as it allows greater control over the tapering parameters, namely the size of the irradiated zone, the heating rate and the exposure time. Mounting the fibre on computer-controlled stages gives programmable dynamic control over the fibre tension, as well as the ability to control the position of the tapered section with an accuracy of ±0.5 µm. Using this system, taper regions as short as 150 µm were achieved with a fibre diameter reduction of 50%. Furthermore, periodically tapered fibres and fused tapered microcouplers have been fabricated using this method. Fibres perturbed in this fashion are useful in furthering our understanding of cladding mode interactions and radiation dynamics in optical structures with a non-uniform profile.

Introduction

Tapered optical fibres have several significant applications in photonics. Fibre tapering is a means of miniaturising photonic components such as 2x2 couplers [1]. Tapered fibres have also been used successfully to couple light into photonic crystal waveguides with high efficiency [2], as well as being used as probes for Near-field Scanning Optical Microscopes [3]. It is therefore of interest to be able to fabricate tapered fibres cheaply and rapidly for a desired taper shape.

Optical fibre is tapered by heating a section of the fibre and applying tension to the fibre. If the fibre is hot enough, it will become soft enough to draw into a taper. The two major considerations for any tapering system are how the fibre is heated and how the tension is applied to the fibre. Heating is done using either a flame source or a CO$_2$ laser source. These sources rely on different mechanisms to transfer heat into the fibre, and this will directly affect the capabilities and limitations of the system. Tension is commonly applied to the fibre using a pipette puller or a solenoid plunger; however these methods offer little user control.

In the system we have developed a CO$_2$ laser is used as a heat source. The laser emits at a wavelength of 10.6 µm and is readily absorbed by standard optic fibre. Tension is controlled using computer-driven, high-precision translation stages.

Experiment

The significant components in this system shown in figure 1 are the CO$_2$ laser and the Physik Instrumente translation stages.

![Figure 1 – Tapering system layout.](image)

The CO$_2$ laser is the ML30 model manufactured by Millennium Lasers. The laser has a maximum output power of 38 Watts and a beam diameter of 4.5mm at the output aperture. The fibre is mounted at the focus of the beam. The beam diameter at the focus is ~1mm.

A CO$_2$ laser source was chosen over a flame source for several reasons. Firstly, the heat is generated from within the fibre itself, meaning the fibre heats quickly and homogeneously, allowing rapid tapering. Secondly, the size of the heated region can be controlled with precision through a combination of focusing the beam with a lens and using a mask machined from brass shim. Finally, the output of the laser can be dynamically controlled using a computer. The laser can be programmed in unison with the stages to give precision control over exactly where and when heat is delivered to the fibre.
The fibre (Corning SMF28) is mounted on a pair of PI stages, with axes set parallel to one another. The stages can be used to translate the fibre, as well as apply tension, simultaneously if desired. The stages have a positional accuracy of ±1 µm.

The stages and the laser are both computer-controlled and interfaced using LabView. The stages and laser can be programmed, which allows the user to devise more novel tapering schemes, in addition to standard tapering schemes. The user is able to control the system using a LabView user interface, making the system very user-friendly.

**Theoretical Analysis**

The final taper shape is determined by the length of the tapered region and the size of the hot-zone. The taper length can be indirectly controlled by varying the parameters of the tapering process. These parameters are as follows;

- **Draw length** – The total distance translated by each stage during the tapering process.
- **Draw rate** – The velocity of each stage during the tapering process.
- **Laser power** – The total power output of the laser.

The simplest way to determine whether a taper is low-loss is to apply the Adiabaticity criteria [4]. Using the length-scale criterion is most convenient, as it allows us to infer whether the taper is low-loss directly from the geometry of the taper. To verify that our tapers, such as that shown in figure 2 are low-loss, we must apply this criterion.

Figure 2 – Standard taper analysed using the Adiabaticity criterion.

![Length-scale delineation curve](image)

**Figure 3** – Length-scale delineation curve for a typical tapered fibre fabricated using this system.

It is evident from figure 3 that the geometry of the tapers fabricated using this system satisfy the length-scale criterion, since the taper gradient (blue curve) is less than the value required by the length-scale criterion (red curve) for the entire taper.

It must be noted that the length-scale criterion assumes that cylindrical symmetry is maintained. Images of tapers fabricated using this system show slight asymmetry in some tapers, we expect these tapers to exhibit greater loss than the length-scale criterion indicates.

**Results and Discussion**

**i) Standard Tapers**

Standard tapers are tapers considered to be low-loss, since most applications for tapered fibres require that the loss be minimised. When fabricating a standard taper, the mask is removed from the system, as it is desirable to have a large hot-zone to ensure a gentle taper angle and minimise the chance of breaking.

When the laser beam hits the fibre, tension causes the fibre to bend slightly. This requires tapering to occur over several seconds as time is required for the stages to apply tension to the fibre and straighten out the bends so that further tapering can continue.

The following graphs illustrate how the system parameters affect the eventual length of the tapers.
ii) Fused-Tapered Microcouplers

Fused-tapered Microcouplers can be fabricated in a similar manner to standard tapers. Firstly, two fibres are mounted in contact with one another. The fibre is then exposed to the laser beam without drawing to fuse the two fibres together. The fibres are then exposed a second time and drawn as with the standard tapers. Figure 7 shows an image of two fibres drawn in this manner.

While an extensive analysis of fused-tapered microcouplers fabricated using this system has not been performed, a 66/33 coupler with a 6dB loss has been fabricated using this system. We are confident that with optimised parameters, the performance of these couplers could be improved.

iii) Periodic Structures

Periodic structures have been fabricated using this system comprising multiple tapered sections of fibre. These tapered sections were made as short as possible to enhance the possibility of creating resonances within the structure. In order to fabricate very short tapered sections the hot-zone must be reduced, a 100 µm mask was placed between the lens and the fibre for this purpose. Using this rather simple method, tapered sections as short as 150 µm, with a diameter reduction of 50% were achieved. An example of a periodic structure is shown in figure 8 below.

Figure 4 – Taper length as a function of laser power.

There is a smooth variation of taper length for powers between 10 and 30 watts. The stages were translated 5 mm at a rate of 2.5 mm/s for each taper in figure 4.

Figure 5 – Taper length as a function of draw length.

Figure 5 shows a linear variation of taper length with draw length. This relationship between taper length and draw length makes it easy to fabricate a taper with a desired length.

Figure 6 – Taper diameter as a function of taper length.

Figures 6 shows how taper diameter varies with taper length. While it is possible to choose the taper diameter, you cannot choose both the taper diameter and taper length, as choosing one sets the value for the other.

Figure 7 – An example of a fused-tapered microcoupler fabricated using this system.

Figure 8 – A periodic structure fabricated using this system. This structure contains 20 tapered sections 200 µm apart.
Short tapers such as these do not satisfy the adiabaticity criteria, thus it is expected that significant power will couple to higher order modes. However such tapers find applications in a wide range of devices, including filters [5], sensors and modulators.

Short tapered sections were achieved by allowing the fibre to draw under its own tension only. No additional tension was applied by translating the stages during the drawing process. Multiple tapered sections were fabricated by translating and reapplying tension between each tapering process.

Structures with 10 or more tapered sections were found to have interesting spectral transmission features. An example is shown below.

![Normalised Spectral Response of a Periodic Fibre Structure](image)

Figure 9 – Spectral response of a periodic structure with 10 tapered sections.

Figure 9 shows a number of transmission peaks, most notably one at around 1560 nm and another at 1580 nm. It is tempting to compare such structures with long-period gratings, however there are differences between these structures and LPGs that are not accounted for in LPG theory, for example the variation in diameter along the length of the fibre. Also, the fact that there is no established theory for the presence of imperfections in the structure makes analysis of such structures difficult.

The overall loss of a typical periodic structure fabricated using this system is 10-20 dB. A significant portion of the loss can be attributed to fabrication errors, the most significant of which is the loss of cylindrical symmetry of the fibre. Asymmetry is introduced into the structure due to the fibre not being in the precise centre of the beam. Breaking the cylindrical symmetry increases the number of higher order modes that power can couple to, such as the cylindrically asymmetric LP1n modes.

There are several ways in which this system can be improved. The difficulty of aligning the fibre in the exact centre of the laser beam could be negated altogether by using a line focus rather than a spot focus. Additionally, a galvanometer mirror could be used to raster the beam, giving precise control over, not just the size of the hot-zone, but the actual temperature profile across the fibre. A variable aperture could also be used to reduce the hot-zone, rather than the fixed 100 µm slot currently in use.

**Conclusion**

The ability to fabricate fused-tapered microcouplers and periodic, resonant structures in standard optical fibre demonstrates the flexibility of this tapering system. While this system has so far met our needs in terms of tapering, we have identified some ways the system could potentially be improved.

**References**


