Reproducible Method for Fabricating Fused Biconical Tapered Couplers Using a CO_2 Laser Based Process

C. McAtamney, A. Cronin, R. Sherlock, G. M. O'Connor, T. J. Glynn
National Centre for Laser Applications, National University of Ireland, Galway, Ireland*

Abstract

Fused biconic taper (FBT) couplers are essential elements in any fibre-optic communications network. We describe two prototype manufacturing process that produces low-loss fibre tapers and fused FBT coupler devices using CO_2 lasers as the heat source instead of a flame, as is the norm in modern manufacturing methods. The methods could potentially be exploited to increase the degree of automation of manufacture of these important devices.

Keywords: CO_2 laser; fibre optic couplers; multiplexers; automated manufacture

1 Introduction

Fused biconic tapered (FBT) couplers are passive optical components used in telecommunication networks for branching or combining optical signals. The simplest case is a 1 × 2 device which is fabricated by placing two stripped, standard single-mode optical fibres in close contact over 30 mm or so of their length. The contacting region is then heated and fused while simultaneously elongating and tapering the assembly. Typically, a "signal" source is connected to the input port, which will be distributed among the output ports within the fused, tapered region. During manufacturing the outputs ports are monitored and when the desired coupling ratio has been reached heating and elongation is halted. This basic technology has been used to create a variety of fibre devices including fibre tapers, couplers, wavelength independent couplers and wavelength division multiplexers (WDM).

The majority of contemporary manufacturing processes for FBT couplers utilise various types of flames to heat the fibres, with a hydrogen-based flame being the most widely used. The main drawback of this method of fabrication is the strong dependence of flame properties on environmental conditions. These properties are difficult to model and as a result fabrication is often described as a black art. In addition, the flame can lead to contamination of the coupler with combustion by-products – in particular water vapour – which affects the range of wavelengths available for data transmission [1].

Laser heating has been reported as an alternative method for heating the fibres, with CO_2 lasers as the heat source [2]. CO_2 lasers are used due to the high absorption efficiency of the optical glass fibre at this wavelength.

In this paper we present two different approaches to using CO_2 lasers as an alternative to producing fibre tapers and FBT couplers. The first is based on a scanning laser beam while the second employs a diffractive optical element (DOE) to provide a uniform heat distribution over the fibre.

2 Experimental Design

2.1 Scanning beam set-up

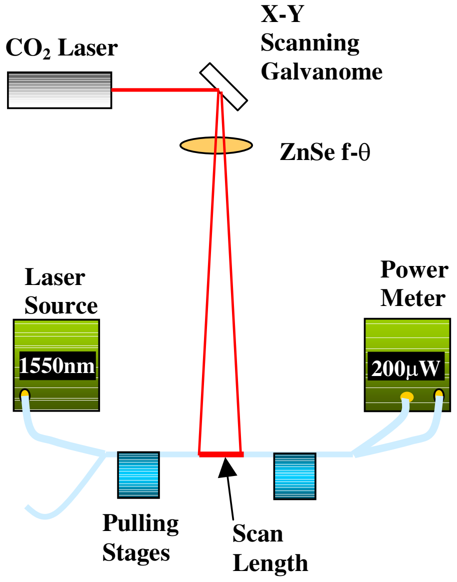

Fig. 1: *Experimental set-up employing a scanning beam*

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A laser-based development rig was constructed from a commercial rig used for flame-based manufacturing of FBT couplers with a 25 W CO_2 laser integrated into the system to replace the hydrogen flame. Beam scanning with a X-Y galvanometer mirror created the desired heat zone. The experimental set-up is computer automated to provide control over the laser power, pulling stage motion and the sweep amplitude of the galvanometer scanner. It also provided real-time coupler output-port power measurements, which are required to monitor the coupling ratio and device losses. The pulling stages were stepper-motor driven with a resolution of 1 µm. Devices were made with a range of pulling velocities up to 0.1 mm/s. The spotsize of the laser beam at the fibre was estimated to be 1 mm. Sweep speeds were varied up to a maximum of 3mm/s , while the scan length was varied between 4 and 10 mm.

To initiate an experiment two fibres were brought into close contact at the required tension by being automatically twisted around each other twice using a stepper-motor driven rotation-stage – the double twist results in a straight central region of contact. It is known that at constant CO_2 laser output power the temperature of the assembly will decrease as it is elongated due to the reduced cross-section intersecting the beam [3]. For this reason the laser power was increased throughout the process according to a two-segment linear function with an increase in slope for the second segment.

2.2 Diffractive Optical Element

An alternative to the scanning beam approach is to heat the fibres along an extended length with a stationary beam. This could be achieved by employing a cylindrical lens, aligning the converging axis perpendicular to the fibre axis. However, the gaussian nature of the beam would be preserved, which would result in non-uniform heating of the fibre, as well as requiring a high degree of repeatability when placing the fibre in the beam path. It was anticipated that better results could be achieved by producing a uniform heat zone through the use of a DOE.

The illumination pattern required to produce a uniform heat zone in the fibre was determined using one-dimensional numerical analysis of the standard heat conduction partial differential diffusion equation [4]; see equation 1. In the model, the fibre was divided into cells and the partial differential equation solved for each cell using a simple one term Taylor series expansion. Further terms accounting for absorbed laser power, radiative losses and convection losses were added as shown in equation 2

$$\frac{\partial T}{\partial t} = \kappa \nabla^2 T \qquad (1)$$

$$\begin{aligned} T_i(t) \; = \; & T_i^{\prime} + \frac{\Delta t}{\Delta x^2}\frac{k}{\rho C}\left(T_{i-1}^{\prime} - 2T_i^{\prime} + T_{i+1}^{\prime}\right) + P\left(\frac{\Delta t}{mC}\right) \\ & -\sigma A\left(T_i^{\prime} - T_{room}\right)^4\left(\frac{\Delta t}{mC}\right) \\ & -HA\left(T_i^{\prime} - T_{room}\right)\left(\frac{\Delta t}{mC}\right) \qquad (2) \end{aligned}$$

where κ is the diffusion constant; ρ the fibre density; C its specific heat capacity; k thermal conductivity; m is the mass of fibre within a single finite element, P is the laser power absorbed by the element; and A its surface area. H is the surface conductance/heat transfer coefficient, and σ is the Stephan-Boltzmann constant. $T^{\prime}$ represents the temperature calculated in the previous iteration.

Equation 2 was numerically integrated until the solution converged to a steady-state condition. However, the model lacked accurate estimates of either the irradiance absorption of the fibre or the heat transfer coefficient H. These values were arbitrarily varied to produce a meaningful final equilibrium temperature and it was found that the predicted temperature profile was not overly sensitive to this variation.

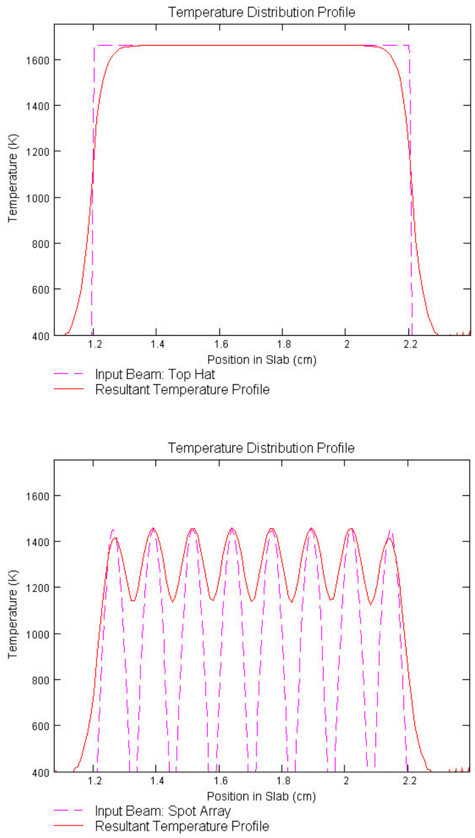

***Fig. 2**: 1D simulated temperature distribution profile across the axial length of the fibre, for incident beam profiles of a) Top-Hat and b) Spot Array.*

A number of different irradiance profiles were inputted into the simulation. Figure 2 shows the results for a “top-hat” and a spot array profile. The top-hat resulted in a uniform heat zone within the fibre, apart from a tail off at the edges, whereas the peaks in the spot array were reproduced in the temperature profile. On the basis of these simulations the design of the DOE was chosen to produce uniform illumination over a rectangular 15 mm × 1 mm area.

A custom DOE meeting the required profile was sourced and manufactured externally for this application. The lens structure has an adjusted Fresnel zone micro-relief pattern imparted on the plano side of a plano-concave lens to provide our required beam profile [5]. A computer simulation, based on scalar-diffraction theory, of the expected beam profile was generated as part of the manufacturing process. A 3-D representation of the beam profile resulting from the model is shown in figure 3. The predicted overall percentage standard deviation from the mean intensity value at simulated focus was calculated to be about ±10%. However, if we consider the central 10 mm x 0.48 mm portion of the beam the deviation drops to ±2.8%.

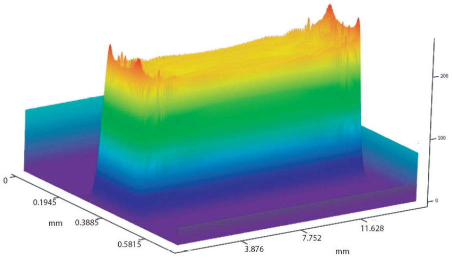

Fig. 3: *3D simulated intensity distribution of the DOE at focus, giving a 15mm × 1mm beam with a simulated transmission efficiency of 93.8 %.*

2.3 DOE set-up

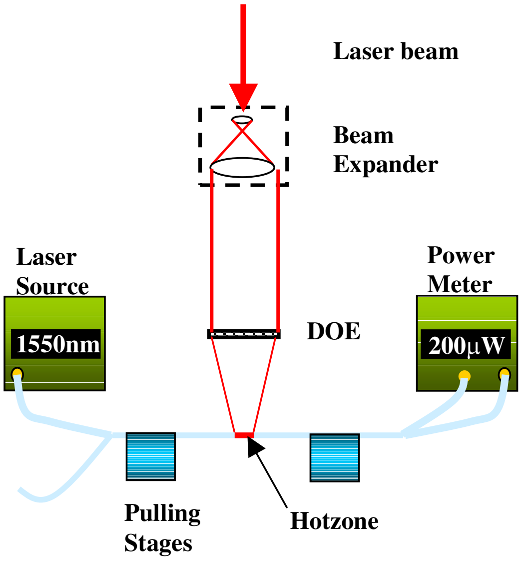

Fig. 4: *Experimental set-up for producing low-loss tapers by DOE method.*

A schematic diagram of the set-up, utilizing the diffractive optical element used to fabricate tapers is shown in figure 4.

In this case the laser was a 250 W CO_2 laser, with a beam waist diameter ($1/e^2$) of 8mm. The beam is expanded ×3 to 24mm prior to incidence on the DOE lens. As was the case with the scanning beam rig, the apparatus is computer controlled.

An aperture was placed between the DOE and the fibre to mask off the peaked edges of the profile seen in figure 3 and also to vary the length of the heated zone within the fibre.

To produce tapers, a fibre is placed manually into the pulling stages and held with a required tension by a vacuum. The laser and pull both start simultaneously. The process stops once a desired pull length has been reached.

3 Results and Discussion

3.1 Scanning rig

Fibre tapers and couplers made with reference to the adiabatic approximation [6,7] should exhibit low losses for the device. This is as a result of ensuring that mode propagation is confined as much as possible to the fundamental mode, LP_{01} along the taper regions. According to the extensive discussion by Love *et al.* [6,7,8] the condition can be met by fabricating devices in which the cladding taper angle is maintained approximately 10 times lower than the $V = V_{cc}$ curve, where V is defined as the core guidance parameter. Figure 5. shows that this criteria was met for tapers fabricated with the scanning rig.

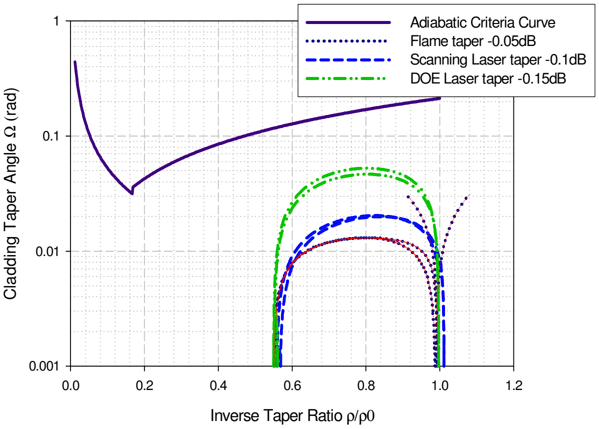

Fig. 5: *Length scale delineation showing adiabatic tapers fabricated with scanning beam and DOE apparatus.*

The low loss tapers were fabricated with a pulling speed of 75 µm/sec, scan length of 10mm, scan speed of 2 mm/s and a pull length of 20 mm. The final taper diameter was 45 µm. For a consecutive run of 10 tapers, the average excess loss was 0.056 ± 0.026 dB.

Fused fibre couplers of specified coupling ratio were obtained by monitoring the output of the fibres and stopping the pull when the desired ratio was reached. It was experimentally found that better yields for low-loss coupler devices resulted from longer sweep amplitudes, up to the maximum of 10 mm used in our experiments. Figure 6 shows an example of coupler output powers for a pulled a length of 23 mm. Interferometric-type beating between modes created in the coupling region [9] is indicated by 12 power transfer cycles.

A number of fused couplers, with a coupling ratio of 50:50, were fabricated with low excess losses. For a run of 5 consecutive couplers, the pull length required for 3 dB splitters was shown to be 11.46 ± 0.43 mm. These couplers had excess losses of 0.44 ± 0.03 dB, which is somewhat higher than the commercially acceptable value of 0.2 dB. Individual coupler devices have been made with excess loss values below (such as the coupler in fig. 6, for example), but the further work is required to improve the reliability of the process.

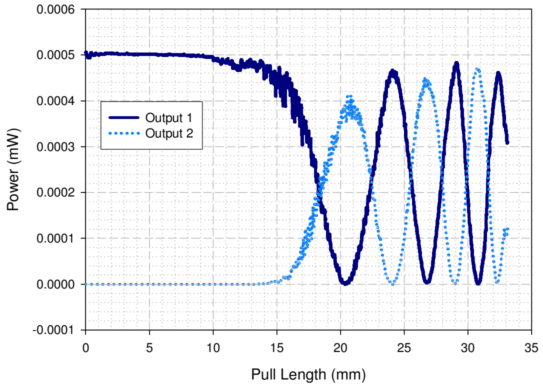

Fig. 6: *Output-port power as a function of pull length for a coupler made with CO_2 laser process, showing the interferometric-type beating between modes created in the coupling region.*

In addition to 50:50 couplers WDM devices were also produced. (WDMs are widely used devices in the telecommunications industry enabling multiplexing and demultiplexing of two wavelengths, commonly 1310nm and 1550nm). As can be seen in table 1, we fabricated devices that efficiently separate 1310 nm and 1550 nm wavelengths with isolation values in excess of 15 dB. This compares well with commercially available devices, for which isolation specifications in the 12 – 17 dB range are typically quoted [10,11].

Tab. 1:

Wavelength	**1310 nm**		**1550 nm**	
	Port 1	***Port 2***	***Port 1***	***Port 2***
Power (µW)	11	356	341	9
Power (dBm)	-19.6	-4.5	-4.8	-20.5

3.2 DOE rig

3.2.1 Beam Shape

Mode burns of the CO_2 laser profile were taken in perspex block to determine the beam profile. Although a perspex mode burn is not a true reflection of the beam shape but more of an approximation, this is a widely used method for determining the shape of a CO_2 laser beam in the absence of an infrared laser beam profiler.

Figure 7a. shows a mode burn of the full beam (no aperturing). The beam shape is largely that predicted by the software simulation with a flat central zone and peaked regions on either end. By using the aperture the peaks were masked off and a flatter part of the beam was used for making tapers. Figure 7b. shows a typical beam profile for taper fabrication. Figure 7c shows the plan view of the same mode burn. It was found to be 4mm long and 1mm wide. When viewed through a microscope, the bottom of the mode burn was found to be flat in both x and y directions.

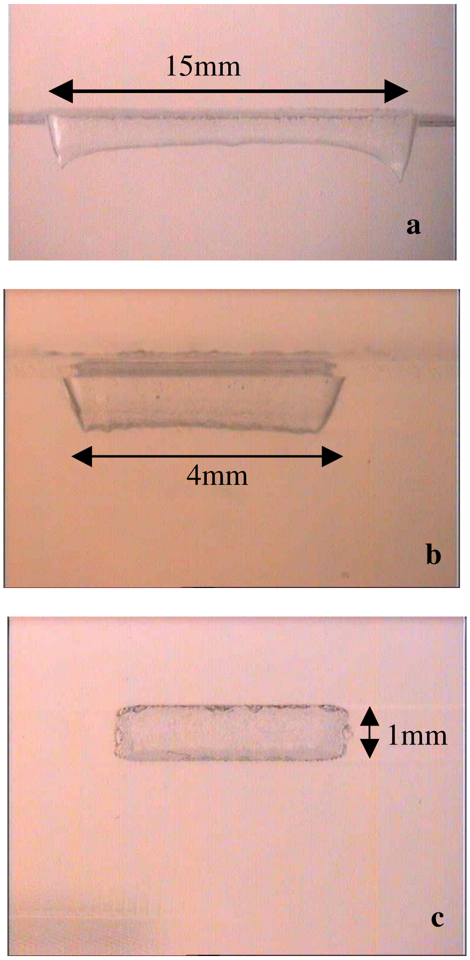

Fig. 7: *a) Full beam profile. 15mm in length.*
b) Side on view of beam shape. 4mm in length.
c) Plan view of beam shape. 1mm in width

3.2.2 Low loss tapers

Low loss tapers were fabricated using a laser beam with profile shown in figure 7b. It was found to be important to use a truncated profile in order to achieve acceptable results. A typical taper shape is shown in figure 8. This taper shape was made using 45 W of laser power, a pull length of 3.2 mm, and pull speed of 75 µm/s. For a consecutive run of 5 tapers, the excess loss was measured to be 0.085 ± 0.05 dB. These losses are somewhat higher than those measured for the scanning beam system. This is perhaps related to the adiabaticity criteria (figure 4.): the V value is not consistently a factor of 10 lower than the Vcc curve.

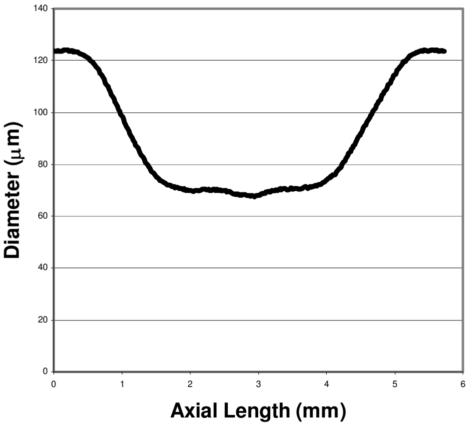

Fig 8. *Axial length of tapered fibre manufactured using the DOE laser rig, showing the reduction in diameter with length.*

4 Conclusion

We have described two alternative methods for fabricating fiber tapers and FBT couplers, utilising CO_2 lasers as heat sources. Both processes have successfully produced passive optical components with comparable characteristics to those produced with a flame-based process. Because of the greater control of the heat source, a CO_2 laser based process could potentially replace the current flame based process.

A scanning beam approach was succesfully used to fabricate low loss tapers, and FBT couplers with a 50:50 coupling ratio and excess losses comparable to commercially available couplers produced with a flame based process. Wavelength Division Multiplexer was also fabricated with isolation of over 15dB, which meets comercially available specifications.

A diffractive optical element was shown to shape the output of a CO_2 laser into a rectangular tophat profile. The beam shape is largely that predicted by the software simulation with a flat central zone and peaked regions on either end. The peaked regions were apertured to produce a flattened beam, which was then used to produce fiber tapers with losses of 0.085dB.

Improvements to the fabrication processes could be made by inclusion of an on-line temperature monitor to provide feedback control of the laser power for maintaining constant fibre temperature. It is also possible that experimental design could be used to optimise process parameters.

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