Optimized Process for Fabricating Ultrashort Tapered Long-Period Gratings

Kevin Mullaney, Stephen E. Staines, Stephen W. James, and Ralph P. Tatam

***Abstract*—The CO_2 laser based fabrication of tapered long period gratings (TLPGs) is optimized so that their transmission spectra are comparable with those made using the arc-discharge technique, which typically exhibits transmission losses below 2 dB. The reduction in transmission loss was achieved by optimizing the micro-taper geometry and the duty-cycle of the device. A 6-period TLPG of period 378 μm exhibited a pass-band transmission loss of 0.6 dB, resonance band extinction values of 3 dB and had a physical length of 2.27 mm. The average refractive index sensitivity of a 6 period TPLG was measured and found to be 372 nm/RI.**

***Index Terms*—CO_2 laser, laser material processing, long period grating, optical fiber sensor, optical fiber taper.**

I. Introduction

OPTICAL fiber long period gratings (LPGs) were developed as devices for optical communications [1], where they have been used as band rejection filters, gain equalizers and wavelength tuning elements in fiber lasers [2]. They have also found many applications in the field of sensing [3], [4], where they have been for gas sensing [5], as biosensors [6] and for the detection of water contamination [7]. A number of approaches to the fabrication of LPGs have been reported: LPGs can be fabricated by exposure to UV or femto-second laser irradiation [3], [8], can be mechanically induced [9] or can be created by the spatially periodic application of heat. The necessary heat source can be either the output from a CO_2 laser [10], an arc-discharge [11] or resistive heating [12]. The use of CO_2 laser irradiation is attractive, as its use is flexible, is repeatable and produces less contamination on the fiber surface compared to alternative techniques [10].

Tapered long period gratings (TLPGs) are formed by periodically micro-tapering the fiber. This is usually achieved by locally heating and stretching the fiber. For this type of device [10], [13], the taper waist diameter is usually between 70 μm and 120 μm. One of the key advantages of such thermally induced gratings is their ability to retain their spectral properties at higher temperatures, as compared to UV written gratings, which start to degrade at temperatures in excess of 200 °C [14]. Thermally formed gratings typically start to degrade at temperatures close to the melting temperature of the fiber, ∼1000 °C [14]. Another advantage of thermally generated gratings is that larger mode coupling coefficients can be achieved, as the magnitude of the core index modulation is greater [14]. Spectral resonance bands of a given extinction can therefore be produced with fewer grating periods, so that the overall grating length can be much shorter than that of a UV-written LPG with a comparable spectrum.

A review of thermal approaches to LPG fabrication shows that high quality LPGs with well-defined resonance bands and low insertion losses have been fabricated previously using either index modulation of the fiber using a CO_2 laser (without micro-tapering) [10], [13], [15], [16] or using arc discharge heating to both index modulate and geometrically micro-taper the fiber [11], [17]. The insertion losses previously reported for CO_2 fabricated tapered LPGs are >10 dB [10], [13], while those fabricated using the arc-discharge technique typically exhibit insertion losses below ∼2 dB [11], [17]. Using the arc-discharge technique, the dimensions of the electrodes in fusion splicers currently limits the minimum achievable grating period to ∼220 μm [17], whereas the use of CO_2 laser irradiation allows TLPGs to be fabricated with periods of ∼175 μm [2]. This is shorter than can be obtained with arc-discharge techniques. The ability to fabricate gratings with periods less than 200 μm is important as it allows gratings to be fabricated with resonance bands near the phase matching turning point, where they exhibit increased sensitivity to environmental perturbation [18].

The aim of this work is to develop the CO_2 laser-based fabrication of TLPGs so that their spectral characteristics are comparable with those produced using an electric arc as the heat source. In this paper, expanding on work first reported at the 25th Optical Fiber Sensors Conference, OFS-25 [19], we describe the improvements achieved by optimizing the micro-taper geometry and grating duty-cycle, so allowing insertion losses below ∼2 dB to be realized. The device geometry has also been optimized to enhance their capability as ultrashort optical sensors.

II. TLPG Fabrication System

The TLPG fabrication system used is shown in Fig. 1. The output from a Synrad 48-2 CO_2 laser with an output power of 5 W was used to heat the fiber (Fibrecore SM750) to its melting point and allow a micro-taper to be formed. The laser was cooled with an external water chiller at a temperature of $18.0 \pm 0.1\,^{\circ}$C,

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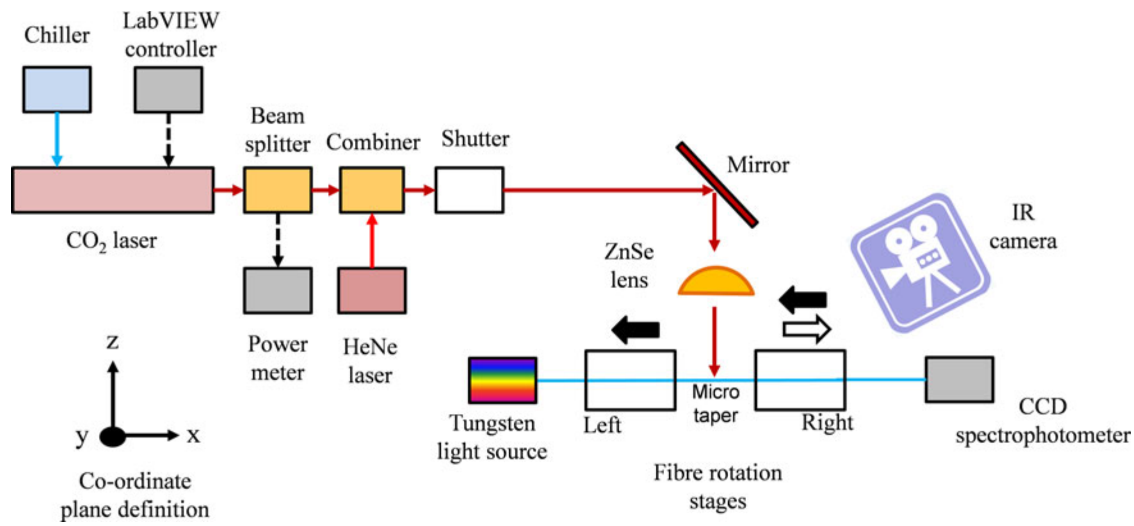

Fig. 1. Schematic of the TLPG fabrication system. When the micro-taper is formed the stages rotate in opposite directions. During fiber translation the stages rotate in the same direction.

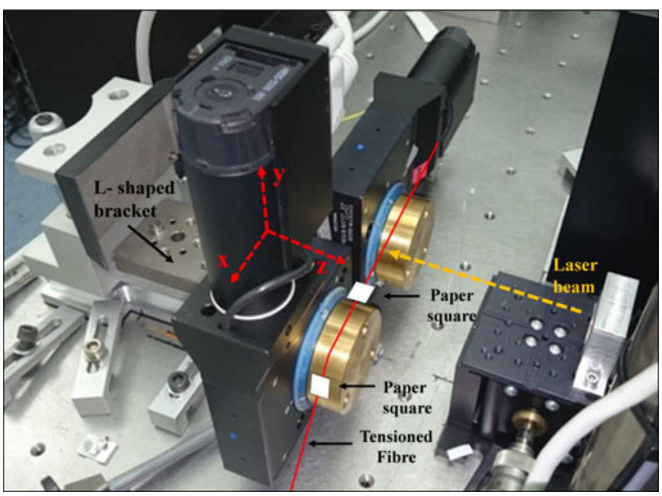

Fig. 2. Experimental arrangement for fabricating TPLGs. Paper squares are used as an aid to reduce torsional strain on the fiber during the fiber attachment process.

so ensuring the laser power stability was ±2.75%, which has been shown previously to be an important parameter in the fabrication of optical fiber tapers [20]. ZnSe optical elements were used for power tapping and for injecting the HeNe alignment laser into the path of the CO_2 laser beam. A ZnSe plano-convex cylindrical lens with a focal length of 100 mm was used to produce an elliptical focused spot on the fiber. The minor axis of the ellipse was 355 ± 30 μm in length and was oriented parallel to the fiber axis, while the major axis was of length 3.5 ± 0.03 mm and oriented perpendicular to the fiber axis. These values were determined by melting the frosted surface of acrylic test-pieces with the laser operating at a power of 4 W.

Two programmable rotation stages (Physik Instrumente) supported and located the fiber to be heated and stretched. The capstans mounted on the stages were inscribed with v-grooves to ensure reproducible fiber placement in the focal plane of the ZnSe lens (see Fig. 2).

The operation of the laser and rotation stages was controlled using a program written in LabVIEW, which provided the requisite driving waveforms to control the laser power and the motion of the rotation stages. In addition, the program provided the necessary synchronization between the process steps, such that the process was repeatable. To fabricate a micro-taper, the system was programmed such that the output power of the laser was ramped linearly from 0.25 to 5 W over a 1 s time period and then remained constant at 5 W during the time the taper was pulled. The initial power ramp ensured that the CO_2 laser power output remained constant while the taper was pulled. The rotation stages pulled the heated fiber in opposite directions with a tangential velocity of 6 μms^{-1}. The laser power was then reduced to zero and the rotation of the stages stopped. Using the rotation stage angular data to determine the micro-taper length, the fiber was then translated by moving both rotation stages in the same direction to arrive at the position for the formation of the next micro-taper. This sequence of stretching and translating was repeated until the requisite number of micro-tapers was formed.

To optimize and to ensure the repeatability of the TLPG fabrication process, the following monitoring techniques were used [21]; a NIR camera (Vosskuhler NIR-300 P) was used to aid the alignment of the heated fiber within the focused laser spot and to observe the thermal intensity distribution along the fiber; a charge coupled device (CCD) spectrophotometer (Ocean Optics—S2000) and a tungsten-halogen light source (Ocean Optics—HL-2000) were used to facilitate the measurement of the transmission spectrum of the TLPG over the wavelength range 625–1100 nm during the fabrication process. This wavelength range allows the use of a low cost light source and CCD spectrophotometer.

III. Experimental Results and Discussion

Initial TLPGs produced by this system exhibited high attenuation (~17 dB) and had poorly defined resonance bands. The potential causes of this inferior performance were identified as: a

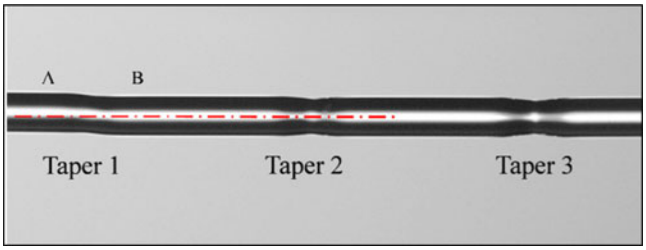

Fig. 3. Micrograph of a TLPG with 3 micro-tapers. Taper 1 has a distorted profile. The fiber at position A is offset from the fiber axis compared to position B. The center axis of the fiber is shown as a dashed red line. SM750 fiber was used (magnification × 10).

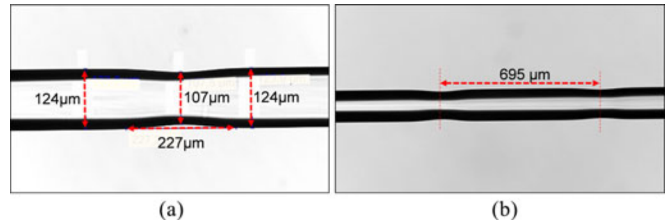

Fig. 4. Micrographs of (a) a 227 μm long micro-taper, magnification × 20 (first taper) and (b) of two micro-tapers separated by 695 μm (magnification × 10), using revised fiber attachment process.

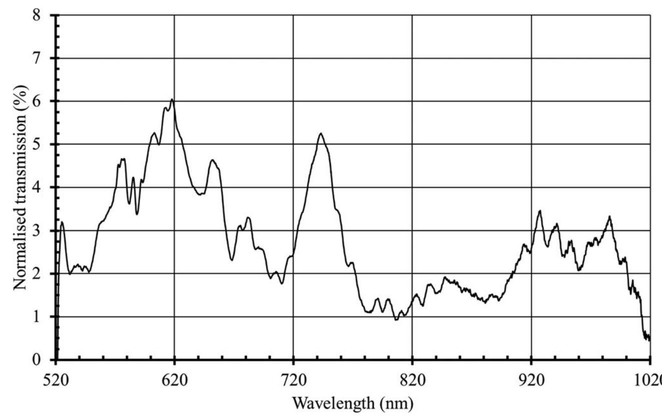

Fig. 5. The transmission of a 6-period TLPG with an average period of 697 μm. The individual taper pull time was 18 s and the fiber used was SM750.

distorted first taper, variable fiber pre-tensioning, a non-optimal taper waist diameter. A typical example of a distorted first taper is shown in Fig. 3, here the axis of taper 1 is offset with respect to the tapers 2 & 3 which are both undistorted. It was viewed that the high optical attenuation was caused by the distorted profile of the first taper, coupling a significant amount of core light into the fiber cladding. This was confirmed by observing how the TPLG transmission changed when each successive taper was formed; the first taper caused a significantly greater attenuation compared to that caused by the fabrication of the subsequent tapers.

To increase the transmission of the TLPGs, the fiber attachment process was improved to correct the distorted taper and a number of experiments were undertaken to investigate the influence of taper diameter on TLPG transmission loss. Before the fiber was attached to the stages using adhesive tape, a 6 g weight was used to pre-tension the fiber during the attachment process. The weight ensures that the fiber is repeatably tensioned prior to final attachment to the stages. Fiber tension has been shown to be an important parameter [22] as it influences the degree to which the fiber index is modulated during the TLPG writing process. During the writing process, viscoelastic strains can be frozen into the fiber when is cooled below its fictive temperature under tension. These strains can have a significant impact on the index modulation of the fiber, greater than those related to the elasto-optic effect [23], [24]. After the fiber was attached to the capstans, the weight was removed. During the fiber attachment process paper squares were also temporarily attached to the fiber and used as a visual aid to indicate any twist within the fiber during the attachment process. Any twist in the fiber would relax on laser heating and locally deform the fiber. The use of the weight also was found to reduce both the variability in the diameter and distorted shape of the first micro-taper compared to subsequent micro-tapers produced during the fabrication process. Fig. 4 shows typical micrographs of a 227 μm long micro-taper (magnification X20) and of two micro-tapers separated by 695 μm (magnification X10) using the revised attachment process. For both tapers the waist diameter is 107 μm. These measurements were obtained with an Olympus BX51 microscope.

A number of experiments were undertaken to investigate the influence of taper waist diameter on the transmission of the TLPGs. Control over the taper waist diameter was explored, for a constant laser power, by varying the taper pull times from 18 s to 13 s. The transmission of a TLPG that was fabricated with a taper pull time of 18 s and a waist diameter of 100 μm is shown in Fig. 5. This had an average transmission loss of 17 dB, several resonance bands are visible in the spectrum but these are not clearly defined.

TABLE I
TPLG OPTICAL LOSS VERSUS TAPER WAIST DIAMETER

Taper pull time (s)	Taper waist diam. (µm)	Average TLPG loss (dB)	Comments
18 ± 0.1	100 ± 2	17 ± 0.2	-
16 ± 0.1	110 ± 2	8 ± 0.1	-
15 ± 0.1	117 ± 2	7 ± 0.1	-
13 ± 0.1	121 ± 2	5.2 ± 0.1	Visibility of resonance bands decreases.

Reducing the pull-time from 18 to 16 s resulted in an increase in waist diameter from 100 μm to 110 μm, which was accompanied by an increase in light transmission through the TPLG (Table I). Further reductions in the pull time to 13 s resulted in a waist diameter of 121 μm. At this diameter, a single resonance band was observed at 800 nm and the TPLG loss reduced to 5.2 dB. This would suggest that the waist diameter determines the number of cladding modes that are excited [3] and suggests that the optimal waist diameter occurs within the range 100–117 μm for resonances observed over the wavelength interval, 650–1000 nm. At these waist diameters, cladding modes are excited while still exhibiting increased light transmission.

Using the new fiber preparation procedure and a taper pull-time of 15 s, a 6 micro-taper TLPG was fabricated. The spectral

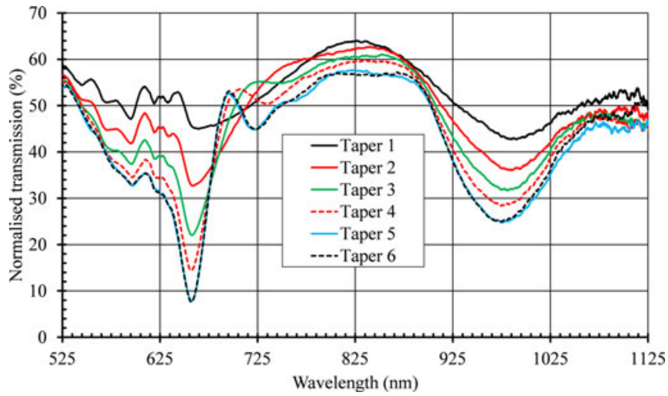

Fig. 6. The spectral characteristic of a 6 micro-taper TLPG with a waist diameter of 117 μm and a period of 418 μm, using SM750 fiber.

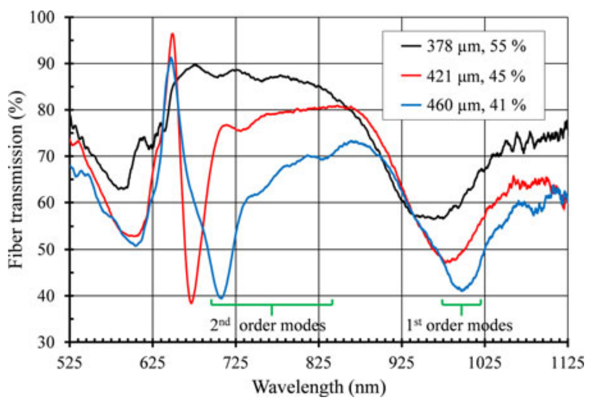

Fig. 7. Transmission of 6 micro-taper TLPGs with periods of 378, 421 and 460 μm and duty cycles of 55, 45 and 41%. The fiber used was SM750.

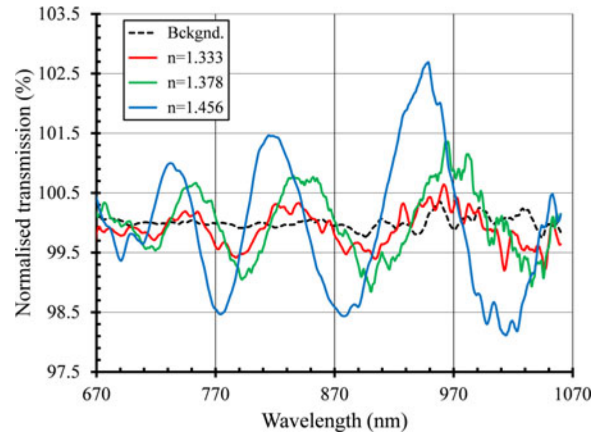

Fig. 8. Transmission change of a 6 taper TLPG with a waist diameter of 117 μm when it is immersed in liquids with an index ranging from 1.333–1.456. The fiber used was SM750.

performance is illustrated in Fig. 6. The average waist diameter of this TPLG was $117 \pm 2\,\mu$m, the average period was $418 \pm 11\,\mu$m with a duty cycle of $54 \pm 6\%$. The duty cycle is the ratio of the taper length to the grating period expressed as a percentage. The transmission at 825 nm, a wavelength at which the transmission was not influenced by LPG-induced mode coupling, was $\sim$57% and did not substantially degrade when successive micro-tapers were fabricated. Two strong resonance bands are visible at $\sim$630 nm and 980 nm and weaker bands are located at 721 nm and 770 nm.

While the duty cycle of this TPLG was measured at 54%, the target was 50%. It is known from studies of UV-written LPGs, that duty cycles near 50% can produce high transmission and increased spectral resonance band definition [18]. The estimation of percentage duty-cycle is subject to significant error $(\pm 6\%)$ as it was not possible to determine the additional contribution of laser induced refractive index modulation of the fiber and so only the geometrical modulation was assessed by measuring the total micro-taper length, using an Olympus BX51 microscope.

To examine the effect of changes in duty-cycle on the spectrum of the TLPGs, three TLPGs were fabricated in SM750 optical fiber. Each TLPG comprised of 6 tapers and the duty-cycle was varied from 41–55%. The spectra of the three TLPGs are shown in Fig. 7. As the grating period increases, the resonant bands' central wavelengths increase, as expected. The transmission in the pass-band region ($\sim$775 nm) is influenced by the duty-cycle, with a duty-cycle of 55% resulting in a pass-band optical loss of 0.6 dB. A three layer cylindrical waveguide model using MATLAB software [18] was used to predict the experimental spectra exhibited by the TLPGs shown in Fig. 7. The theoretical results suggest that the broad resonance band at $\sim$980 nm is caused by a superposition of 1st order coupling modes, while the resonance band at $\sim$680 nm is caused by the superposition of 2nd order coupling modes. Because the magnitude of the index modulation in a TLPG is significant, the spectral bandwidth of the individual cladding modes is increased and so will overlap with adjacent modes, forming the broad resonance bands observed [20]. The TLPG has a grating period of 378 μm and a length of only 2.27 mm, which is substantially shorter than conventional UV-written gratings which can be 30 mm in length [3]. The shorter length allows these devices to be used more easily as biosensors and in applications where space is limited, for example in micro-centrifuge tubes or as a localized refractometer used in composite material cure monitoring [25]. Other benefits offered by their short length include easier device packaging [26] and simplified integration with other photonic components.

The spectral changes associated with immersing the TLPG sequentially in de-ionized water (n = 1.333), isopropyl alcohol (n = 1.378) and a refractive index matching oil (n = 1.456) measured at 21 ± 1 °C, are shown in Fig. 8. These are presented as a difference spectrum, using the spectrum recorded with the TLPG surrounded by air as the reference. The dependence of the effective refractive indices of the cladding modes on the refractive index of the surrounding medium gives rise to a change in the central wavelengths of the attenuation bands [3]. The sensitivity increases as the refractive index of the surrounding refractive index approaches that of the fibers cladding. The average refractive index sensitivity of this TPLG is 372 nm/RIU over the index range 1.378–1.456. The refractive index sensitivity observed with this device is greater than that typically achieved with UV written LPGs [27] and is comparable in performance with both tapered multi-modal sensors [28], which have a sensitivity of 487 nm/RIU, and

LPGs fabricated in tapers [29], which have a sensitivity of 300 nm/RIU. The device described in this paper offers advantages, as the fabrication process is less complicated and it is more likely to be robust in use, as the minimum fiber waist diameter is greater than those reported in [28] and [29].

Further improvements to device index sensitivity can be achieved by the fabrication of gratings with periods less than 200 μm, as these produce resonance bands near the phase matching turning point, where they exhibit increased sensitivity [18] and would result in an even shorter device.

IV. Conclusions

The process of fabricating TLPGs using the output from a CO_2 laser as the heat source is described. By optimization of the micro-taper waist diameter and careful control of the duty-cycle and its uniformity along the length of the grating, TLPGs of period spacing $\geq$378 μm, consisting of 6 periods with a corresponding total physical length of 2.27 mm, were fabricated. These exhibited a low pass-band insertion loss of 0.6 dB and had resonance band extinction values of 3 dB. The average refractive index sensitivity of a 6 period TPLG was measured and found to be 372 nm/ RI over the refractive index range 1.333–1.456. This type of fiber refractometer should find varied applications due to its high sensitivity, small length, simplicity of manufacture and potential robustness.

Acknowledgment

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