LOW COST TAPER-RIG AND LPG IMPRINTING (TWO-IN-ONE) SYSTEM USING A CO_2 PULSED LASER

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Abstract: A system is proposed to be configured via software and minor optical changes into a taper rig or a long period grating imprinting system. With it, production of assymetric (non-biconical) silica fiber tapers using the stepwise technique[1] has been demonstrated. It is suggested how this technique may be adapted for the POF tapers[2] fabrication. In addition, when imprinting LPGs, the lowest cost was established for the system to be used as a two-in-one machine, containing a minimal set of accessories.

Key words: Tapers, LPGs, taper-rig, CO_2 laser, stepwise technique

1. Introduction

The techniques for the fabrication of tapers in silica optical fibers form a mature field[3] as one can equally cite the case of the techniques for the fabrication of long period gratings[4,5,6]. The two fabrication processes may share a common tool, namely, a CO_2 laser operating as a heat source or as the tool to modulate the refractive index in the optical fiber or to soften the fiber and allow it to be stretched and produce fiber tapers or couplers [5]. One of the major methods to fabricate tapers in silica fibers is based on the flame-brush technique [3]. Its use can result in the production of bi-conical tapers allowing the production of known transition profiles. Recently the exploitation of nonlinear effects in tapers aroused the need to produce different transition profiles connected by a usually uniform waist in the fiber taper device. This resulted in a technique that required a complex control in the taper rig translation stages to produce non-biconical tapers[7].

A simplified technique has been proposed by the authors which reduced the complexity of the taper rig by using only two translation stages and constant speeds, and was named stepwise technique since it used the idea of superposing step-tapers to build non-biconical taper transition profiles[1]. The development that followed the previous result used a CO_2 laser beam with a milimeter wide spot size to laterally heat the fiber and allowed the same configuration of movements that was used in the translation stage to produce non-biconical tapers with the flame-brush[8]. In order to explore the use of non-biconical tapers in plastic optical fibers, and considering that the used heat source in POF taper-rigs need lower temperatures, the search for a stretching speed in the translation stages may be the parameter to be found for the fabrication of minute step reduction in POF tapers. In this case, the diameter reduction occurring after a single sweep of the heat source should produce a minute step taper and the superposition of such step-tapers would in theory produce arbitrary tapers in a controllable manner. If this situation happens, the stepwise technique, which has been already demonstrated using a flame-brush and a CO_2 laser beam in silica fibers, would be useful with an electrical resistance to heat a plastic fiber and produce a non-biconical taper. For this to happen, an indication on how to adapt the stepwise technique is going to be described in this work for the interested researcher that has a taper rig to be modified to produce arbitrary or non-biconical POF tapers. In addition to this development, it must be stressed that recent literature cite the use of non-adiabatic tapers[9] in sensing applications and also indicate the characteristics of the biconical taper profiles on the POF taper transition in this area of research[10,11].

As a result from the machine discussed in this work, one can cite the low cost system and the possibility of its use to imprint long period gratings by only repositioning the convergent lens in the rig for silica fibers. The system is programmed according to the previously mentioned stepwise technique to fabricate tapers. When imprinting LPGs with the same system in silica fibers, the lowest possible cost was established in a way that the system could be used as a two-in-one machine, containing a minimal set of accessories (ordinary lens, beam expander and mirror with two translation stages). Examples of silica LPG are fabricated to demonstrate the feasibility of the system as well as an illustrative optical characterization of the device. The contributions of the work can be summarized by the ideas involving the construction of a low-cost system for a two-in-one machine, and a simple description of the stepwise technique such as to be adapted for the fabrication of POF arbitrary non-biconical tapers.

2. Methodology

This section describes the stepwise technique to fabricate fiber tapers having different transition regions in the reduced taper diameter. The section of the taper between the original diameter and the waist diameter in the optical fiber may have a profile given by a desired monotonic function. The input parameters usually provided by the user are the waist length and diameter and the transition functions of the left and right sides in the taper, which connects the waist to the left and right original diameters in the optical fiber. The fiber is usually fixed to a fiber holder on a translation stage that is capable to stretch it while a heat source heats a section of the fiber that has its viscosity altered in a region called hot-zone. The hot-zone has the size of the flame-brush or the spot size width in the case of heating with a laser. The heat distribution must be observed if a resistance is used such as to have this same size. Usually, the size of the hot zone must be in the range of a few units of millimeters. The speed of the translation stage is in the range of a few millimeters per minute and the heat source in the range of a few millimeters per second. With this in mind, after a single pass of the heat source, the taper rig cause a minute change in the diameter of a silica optical fiber. The same behavior is to be expected in a POF. The profile of this taper after a sweep of the heat source characterizes a step-taper. If the size of the hot zone has infinitesimal width, the change in diameter is abrupt and the device is an ideal step-taper. Otherwise, with a millimeter sized hot zone, the step-taper has smoothed transitions[1]. To calculate the size of the diameter reduction after a heat source sweep, one can use volume conservation in the hot zone, as indicated in the following equation:

$$A_n = \begin{cases} \left(\frac{V_B - V_R}{V_B}\right) A_{n-1}, & \text{if heat-source moves to the right;} \\ \left(\frac{V_B}{V_B + V_R}\right) A_{n-1}, & \text{if heat-source moves to the left.} \end{cases} \tag{1}$$

Where V_B is the heat source speed, V_R is the stretching speed to the right, A_n is the cross-sectional area of the taper after the *n-th* sweep of the heat source, as schematically illustrated in Fig. 1. If the heat source sweep is to the left side of the fiber, the volume reaching the hot-zone while the fiber is being stretched is proportional to $V_B A_n$ and the volume that leaves the hot-zone is proportional to $(V_B + V_R)A_{n+1}$. When the heat source moves to the right, the volume arriving in the hot-zone is $(V_B - V_R)A_n$, the volume leaving it is $V_B A_{n+1}$. It is natural to think that after every sweep of the heat source, at the point of direction change in the heat source, the diameter change is building a profile in the transition region in the taper and a desired input profile function can be compared to the expected instantaneous diameter at the *n-th* heat source sweep. The next length of the heat source course can be calculated to build the next step of the taper profile. In this case, the number of heat source sweeps must be previously calculated and the list of movements to the heat source while the fiber is stretched must be used as input parameter to the translation stage controller. A video and an illustration of the simulated process for a silica fiber taper is presented in the published literature[1]. In the case of the heat source temperature, it must be set such as to produce a smooth step-taper transition profile.

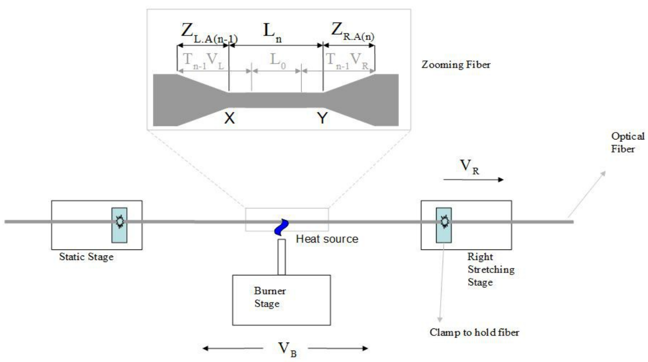

Fig. 1: Schematic description of the taper rig operating to produce a fiber taper with one static translation stage (left), a moving stretching stage to the right, a heat source stage heating a length L after the n-th sweep, and a zooming of the taper region depicting a step-taper with linear transition regions and a uniform waist between points X and Y.

The course length of the heat source is defined by L_n, as in eq.(2), and x_0 is the size of the fiber used to produce the desired taper, while T_n is the time spent by the heat source stage to perform n sweeps, $\Delta T(L_n)$ is a time interval that depends on the stage controller[1], and Z_L and Z_R are complementary distances functions of the cross-sectional areas, and are used to determine the start and end of the heated fiber. V_L is the speed of the left stage, which is null in this case. This would gradually shift the heated lengths towards the direction of the moving stage.

$$L_n = \begin{cases} x_0 + \; V_R T_{n-1} - Z_R(A_n) - Z_L(A_{n-1}) + V_R \cdot \Delta T(L_n), & \text{when heat source to the right;} \\ x_0 + \; V_R T_{n-1} - Z_L(A_n) - Z_R(A_{n-1}), & \text{when heat source to the left.} \end{cases} \tag{2}$$

2.2. Long Period Grating fabrication

In the case of silica fiber processing with the discussed two-in-one taper rig system, it is made by two translation stages, a Diamond C30A(Coherent) CO_2 laser that has its 1.8mm wide beam directed to a 7x beam expander, a ZnSe mirror and an ordinary convergent lens. By properly positioning the lens, the spot size can be set to heat the fiber to fabricate tapers or with a micrometer sized spot to imprint changes on the side of the fiber and produce long period gratings. A pulley is mounted on the side of the machine when the system is configured to imprint LPGs. When used as a taper-rig, the previously described stepwise technique is used and the taper profile equations are input to the software, while the delivered energy to the fiber is electronically controlled by a computer driven pulse-width modulator connected to the laser controller. Fig. 2 depicts an isometric drawing of the system containing the pulley, the optical accessories and indicates the laser beam. The lens is positioned on the aluminum platform in front of the mirror when the system operates as a taper rig. In this case the beam is defocused to produce a 3mm wide spot size on the fiber. When imprinting LPGs the spot size can have an estimated width of 80 to 100µm.

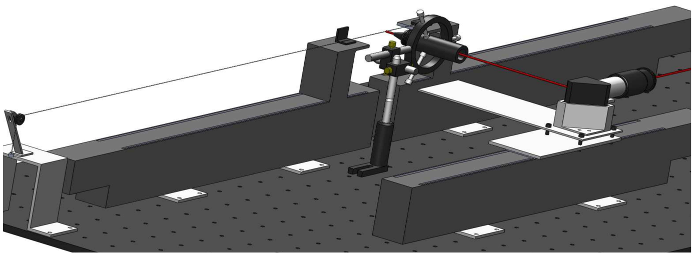

Fig. 2 Configuration of the system to imprint LPGs. Beam from the CO_2 Laser in red, stages in gray; lens, beam expander and mirror in black, while fiber is depicted connected to a pulley and weight. Convergent lens is moved to the white aluminum platform when the machine operates as a taper rig and is set to produce a 3mm spot size on the fiber. When operating as an LPG imprinting system, the spot is set at 0.08~0.85mm.

The length and position of the heat source during the tapering is another topic to be treated during this process. If one considers one of the stretching stages to be static, the movement modeling must consider this fact while determining the position of the heat source during the stretching, as described in [1]. In eq.(1), the left translation stage is maintained static during the heating process that uses a translation stage moving to the left and right and a stretching devide moving to the right with a speed of V_R. Such descriptions are given to explain the theory that may be eventually used in a taper rig for plastic optical fibers. No experiment using tapers have been inserted in this work.

2.3. Characterizing the LPGs

Standard characterization of the long period gratings that have been fabricated is performed by immersing the LPG in fluids with different refractive indexes, and illustrating its behavior as a refractive index sensor. The analysis was performed by illuminating the sensor with a super-luminescent diode with wavelength ranging from 1475nm up to 1650nm and with a deuterium lamp and a Deuterium Tungsten Halogen lamp from 200nm up to 1100nm. The periods of the LPG were chosen such as to cause mode coupling in a standard singlemode fiber (Draktel), in the near infrared region of the spectrum and in the wavelength range of 1520nm to 1580nm.

A characterization of the changes in the fiber due to the imprinting process was also performed by using an optical microscope with a moveable translation stage under the objective that could move the LPG while acquiring images. By using a custom-made software to stitch the images, the whole length of the LPG could be measured and the changes in the diameter caused by the laser was also characterized.

With respect to the parameters of the laser, the beam spot on the fiber is set at an estimated value of 90μm and the frequency of the laser pulses is set at 1kHz, with a pulse width of 140 μs for a duration of 25ms. This would correspond to a delivered energy of 105mJ for each mark in the LPG, while the fiber is kept straight with a 5g weigth through the pulley. The LPG is formed by 40 marks with a period of Λ=573μm.

3. Results and Discussion

Fig. 3 depicts the spectrum of the light transmitted by the LPG while being measured in the infrared and near infrared. The modes associated to the resonance wavelengths in the C-band correspond to lower order modes, and in the near infrared, to higher order modes. Since the modulation of refractive index in the fiber occurs in the cladding, the coupling of there is a large set of cladding modes involved at each corresponding resonance wavelength. Differently from the LPG imprinted in the core, the modulation of this LPG is also limited to a section of the cross sectional area of the cladding. As a consequence, the efficiency is not pronounced, being evidenced by the low attenuation (less than 25% at the resonance wavelengths. The sensitivity to changes in the refractive index when the LPG is immersed in water demonstrates that lower order mode coupling are more sensitive to changes in the refractive index of the environment, if this index remains below the value of the cladding index. In the near infrared, higher order modes are responsible for the dip in the spectrum centered at 960nm.

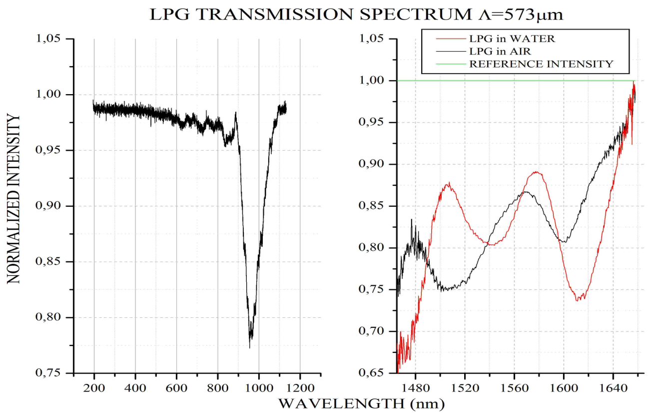

Fig. 3: Figure on the left side, the spectrum of the transmitted light in the near infrared range. In the figure on the right side, the spectrum of the transmitted light for an LPG immersed in air(black line) and in water (red line).

Fig. 4: High resolution image resulting from the stitching process of 19 images from an optical microscope. Each image was obtained after positioning the moveable platform under the microscope objective lens and was stitched to depict the whole LPG while indicating the imprinting characteristics of the system.

In Fig. 4, an image composed by a series of 19 photos taken with in an optical microscope with a moveable platform that could move the LPG in a controllable manner. The stitching was performed with a custom made software and the superposition of each image corresponded to 2μm. Since the equipment used was a confocal microscope (DCM3D-Leica), small adjustments in the focus could be automatically performed during this characterization. It has also been possible to observe a standard error of 2μm in the period Λ along the LPG length, and due to defocusing and beam misalignment, the marks in the end and beginning of the LPG happens to have caused less changes in the fiber, producing a natural apodization of the device. The use of a cylindrical lens may avoid such a behavior and allow a production of LPGs with lengths limited only by the mechanical configuration of the machine. The cost of the system would naturally increase, since the used lens in this work is an ordinary ZnSe one with 100mm focal distance.

With respect to mode coupling in the LPG, since the perturbation in the refractive index occurs only in the cladding with azimuthal dependence, such index modulation is restricted to a region in the fiber. This situation causes the coupling to occur not only between modes of specific simmetry, as it would be the case in LPG imprinted in the core, but also between sets of modes with no specific simmetry that respect phase matching conditions at the observed wavelength intervals. The relatively large bandwidth of the LPG is directly associated with the limited periods of the index modulation imprinted in the fiber.

4. Conclusions

The authors discuss the stepwise technique to fabricate tapers and indicate the possibility of using it to fabricate tapers in platic optical fibers. The discussed system was programmed with this same technique and the system that allows the fabrication of arbitrary tapers in silica optical fibers was changed to imprint long period gratings by using the same optical circuit. Since the fabricated LPG was imprinted by lateral exposure to the CO2 laser beam, a larger combination of cladding modes that participate in the coupling process at the resonance wavelengths produced the depicted spectrum. The feasibility of fabricating two types of devices (LPGs and tapers[8]) with a low cost two-in-one machine was demonstrated.

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References

[1] A. Felipe, G. Espíndola, H. Kalinowski, J. Lima, and A. Paterno, "*Stepwise fabrication of arbitrary fiber optic tapers*," Optics Express 20, 19893-19904 (2012).

[2] C. Beres, F. V. B. de Nazaré, N. C. C. de Souza, M. A. L. Miguel and M. M. Werneck, *Tapered Plastic Optical Fiber-Based Biosensor - Tests and Application*, Biosensors and Bioelectronics, 30, 328-332, 2011.

[3] T. Birks and Y. Li, *The shape of fiber tapers*, Journal of Lightwave Technology, 10, 432 –438, 1992.

[4] D. D. Davis, T. K. Gaylord, E.N. Glytsis, S. C. Mettler, and A. M. Vengsarkar, *Long Period Fiber gratings fabrication with focused CO2 laser pulses*, Electronics. Letters , 34, 302-305, 1998.

[5] T. Dimmick, G. Kakarantzas, T. Birks, and P. Russell, *Carbon Dioxide Laser Fabrication of Fused-Fiber Couplers and Tapers,* Applied Optics 38, 6845-6848, 1999.

[6] S. W. James and R. P. Tatam, *Optical fibre long-period grating sensors: characteristics and applications*. Measurement Science and Technology, 14, R49-R61, 2002.

[7] C. Baker and M. Rochette, "A generalized heat-brush approach for precise control of the waist profile in fiber tapers," *Optical Materials Express*, 1, 1065–1076, 2011.

[8] A. S. Paterno, R. Kremer, D. S. Matos, R. Zolet, A. Felipe and H. J. Kalinowski, *Asymmetric fiber tapers fabricated with a pulsed CO2 laser*. Proc. SPIE 8794, Fifth European Workshop on Optical Fibre Sensors, 879422, 2013.

[9] H. Latifi, M. Zibaii, S. Hosseini, P. Jorge, *Nonadiabatic tapered optical fiber for biosensor applications*, Photonic Sensors, 2, 340-356, 2012.

[10] Leung, A., Rijal, K., Shankar, P.M. & , Mutharasan, R., *Model protein detection using antibody-immobilized tapered fiber optic biosensors (TFOBS) in a flow cell at 1310 nm and 1550 nm*, Sensors and Actuators B Chemical, 129, 716-725, 2008.

[11] K., Rijal, A. Leung, P.M. Shankar, R Mutharasan, *Detection of pathogen Escherichia coli O157:H7 AT 70 cells/mL using antibody-immobilized biconical tapered fiber sensors*, Biosensors and Bioelectronics, 21, 871–880, 2005.