Development of soft-glasses photonic crystal fiber made by stacking-and-draw technique

E. F. Chillcce, C. M. B. Cordeiro, R. S. Ramos, B. C. Z. Honório, E. Rodriguez, G.J. Jacob, C. H. Brito Cruz, C. L. Cesar and L. C. Barbosa
Departamento de Eletrônica Quântica, Instituto de Física Gleb Wataghin, Universidade Estadual de Campinas - UNICAMP, Campinas, SP, Brazil.

ABSTRACT

We have been able to produce soft glass conventional core-clad and micro-structured fibers using rod-and-tube and stack-and-draw method respectively. The stack-and-draw technique shows several difficulties when used with soft glasses, that we managed to avoid using two different lead and alkaline glasses. Non commercial glasses and fibers were thermo-mechanically and optically characterized.

1. INTRODUCTION

Increasing the number of periods of Micro-Structured, or Photonic Crystal Fibers (PCF), one can obtain better attenuation and stronger light confinement [1] desirable for PCF applications such as optical fiber amplifiers, nonlinear optics devices, gases and biological sensors, among others. On the other hand, the PCF light guiding becomes more sensitive to defects. Therefore, only silica optical fibers, made with high quality silica capillaries, have been used to produce PCFs with more than 4 periods [2, 3]. The main difficulty to produce several periods PCF with soft-glasses is the abrupt viscosity variation with temperature that decreases the accuracy of fiber diameter control. The first idea was to use a tellurite glass core inside a commercial glass structure, such as Pb, Alkaline and borosilicate glasses. However, the PCF is only possible when there is a matching of the thermo-physical characteristics of both glasses. Therefore, we started with the conventional core-clad optical fiber and learn that only Pb/Alkaline glasses have the right properties for optical fibers. We also show that with a careful control of capillaries quality and of the fiber drawing process it is possible to produce soft glass PCF up to five periods with the stack-and-draw technique. The fibers were produced with a Heathway drawing tower with a N_2 flow. Finally, the optical attenuation of these PCFs were measured by the cut-back method and the light confinement on the fiber core observed the by optical microscopy.

2. FIBER DESIGN AND FABRICATION

All fibers, including the PCFs were fabricated in Heathway drawing tower using three main commercially available soft glasses: Alkaline, Lead (Pb) and Borosilicate glasses, and a home-made tellurite glass produced by melting the powder containing $71TeO_2$-$22.5WO_3$-$5.0Na_2O$-1.5

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(+5000ppm) Nb_2O_5 (%mol) composition. Figure 1 show the cross section images of 4 different optical fibers (F1, F2, F3 and F4) produced.

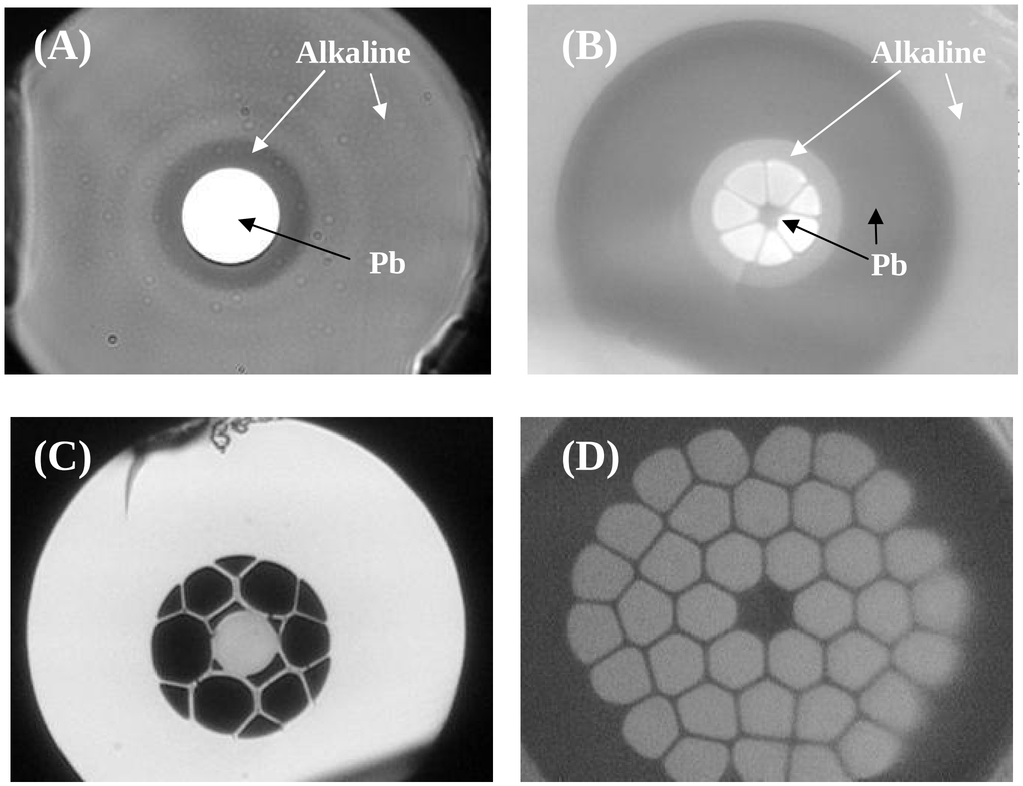


Fig. 1 Cross section images of 4 optical fibers. (A) Fiber F1: conventional Pb-glass core and Alkaline-glass clad. (B) Fiber F2: one period Pb/Alkaline glass PCF. (C) Fiber F3: one period tellurite-glass PCF. (D) Fiber F4: three periods borosilicate glass PCF.

The fact that the refractive index of the Pb glass was higher than the Alkaline glass one, while both drawing temperature are about the same (around 1040°C) made it possible to produce the with 20μm-core Pb glass and 120μm-external diameter alkaline glass clad, conventional core-clad fiber F1 of Figure 1.A. Table 1 show the refractive index measurements for these glasses for different wavelengths obtained with a Metricon Prism Coupler. The pre-form for this fiber was fabricated by the rod-in-tube method and the drawing was performed at 1040°C using 7 l/min N_2 gas flow, 1.8 mm/min pre-form feed speed and 2.8m/min draw speed.

The proximity between drawing temperatures of the alkaline and Pb glasses also allows one to produce PCFs. Figure 1-(B) shows a PCF cross section image of a 6μm core and 160μm external diameter fiber F2, with only one hollow period, made with these two glasses. To do that we used a 1 mm Pb glass for the core surrounded by seven 1.2mm Pb glass capillaries inside a 3.5 mm internal and 6mm external alkaline glass jacket that was drawn to a 1.2 mm pre-form. This pre-form was placed inside a new Pb glass tube a 3.4 mm-Pb glass jacket filling all the space up to a 6mm-external alkaline glass. The final PCF was drawn at 860°C using 7 l/min N_2 gas flow with 2.4 mm/min pre-form feed speed and 1.5m/min draw speed.

Table 1. Refractive index of commercial soft glasses.

Glasses	Wavelength (nm)	Refractive index
Alkaline	632.8	1.5108
	1305.4	1.4997
	1536	1.4957
Pb	632.8	1.5347
	1305.4	1.5210
	1536	1.5187

Figure 1-(C) shows a 20μm core and ~125μm external diameter tellurite glass PCF fiber F3 cross section image with six capillaries around the core, produced by the stack-and drawn technique [4]. The 6mm- jacket tube, 1mm-capillaries and 1mm-rod (core) were obtained from $71TeO_2$-$22.5WO_3$-$5.0Na_2O$-1.5 (+5000ppm) Nb_2O_5 (%mol) glass. The core rod was additionally doped with 7500ppm Er_2O_3. This tellurite glass PCF was drawn at 580°C using 8 l/min N_2 gas flow, with 1.0 mm/min pre-form feed speed and 2.8m/min draw speed.

Figure 1-(D) shows a 12μm core and ~125μm external diameter borosilicate PCF fiber F4 cross section image with thirty six capillaries around the core. The 1.35mm-capillaries and the 1.35mm-rod (core) were stacked inside a 14mm- jacket tube to form the periodic structure. This borosilicate fiber was drawn at 1000°C using 7 l/min N_2 gas flow with 0.4 mm/min pre-form feed speed and 4.3m/min draw speed.

Figure 2 A shows the light confined at the core of the fiber F4 while Figure 2.B shows the light confined at the core of a 5 period PCF fiber F5. Fiber F5 was produced exclusively with borosilicate glass by stacking 96 0.98 mm capillaries around a .98 mm core inside a 10.5 mm internal and 14 mm external diameter jacket. Rods with .8 mm on the edge were used to fill the space to provide mechanical stability for the fiber. This structure was drawn at 1000°C using 8 l/min N_2 flow with 0.4 mm/min pre-form feed speed and 4.5 m/min draw speed. Figure 2 B is a clear demonstration that stack-and-draw technique can be used with soft glass to produce structures with 5 periods.

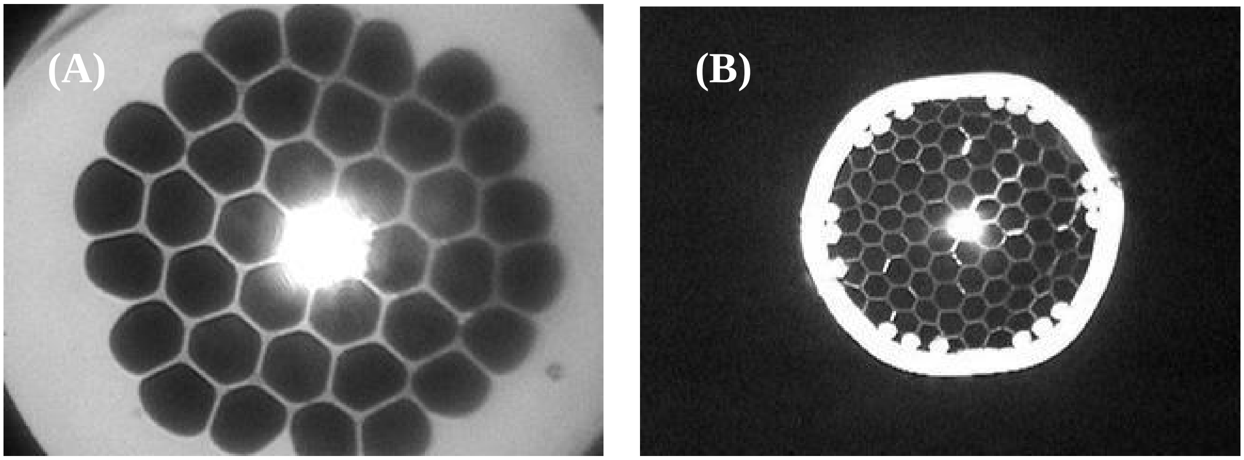


Fig. 2. (A) Light confinement at the core of the fiber F4. (B) Light confinement at the core of a five periods borosilicate PCF fiber F5.

3. RESULTS AND DISCUSSIONS.

3.1 Thermo-physical Properties

We performed the thermo-physical characterization of the tellurite glass to see if it matches the properties of other commercial glasses. Figure 3 shows the Differential Thermal Analyzer (DTA), Thermo-mechanical Analysis (TMA) and Viscosity (η) curves as a function of temperature for the tellurite glass. The viscosity measurement was obtained with a Brookfield viscometer HBDV-II+PRO model from 570°C to 405°C with rotation torque control between 1.7% and 88%. The soft point temperature (T_s) around 364°C was obtained from the TMA curve, while the glass transition (T_g) around 350°C, the crystallization onset (T_x) at 500°C and the melting temperature (T_m) at 588°C were obtained from the DTA curve. The thermal stability range (T_x-T_g = 150°C), with a Hruby number of H_R = 1.7 [5], is large enough to allow fiber drawing without crystallization problems. The fiber drawing temperature is defined as the temperature for which $\log [\eta(T_{Drawing})] = 5$ and represents the minimum temperature for which the draw process is possible. For lower temperatures the glass tend to not flow and the fiber break is eminent. On the other hand the crystallization onset, T_x, temperature defines the maximum temperature for the drawing process before crystallization happens. In our case this range [$T_{Drawing}$, T_x] was [430°C, 500°C]. The tellurite glass PCF was drawn at (435±5)°C, in the low extreme to avoid the collapse of the whole structure.

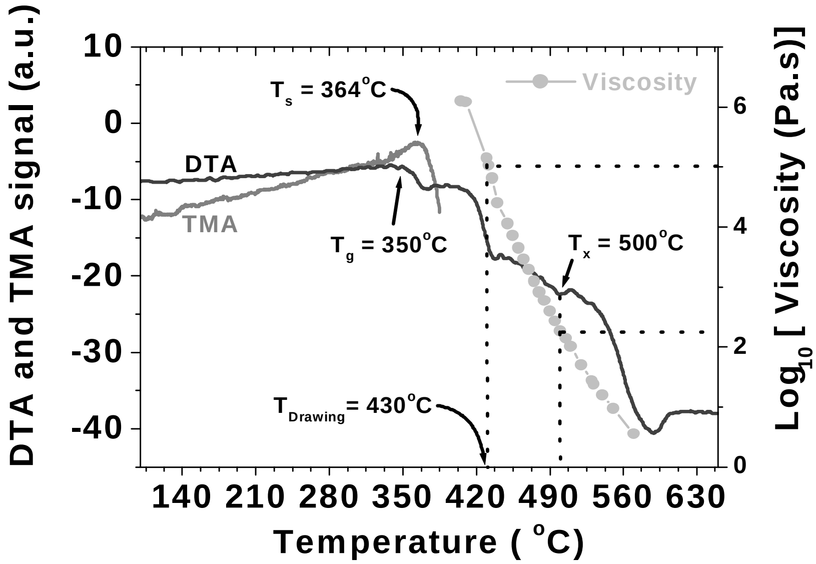
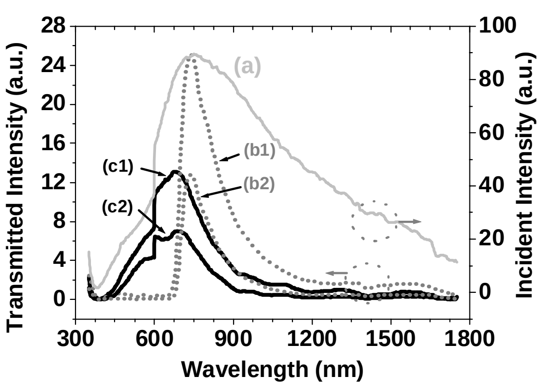


Fig. 3 The DTA, TMA and viscosity curves for $71TeO_2$-$22.5WO_3$-$5Na_2O$-1.5

3.2 Optical Properties

The optical fiber attenuation measurements were performed by the cut-back method. For this purpose a Tungsten-Halogen lamp (Oriel) white light was coupled at one fiber end with a 0.35-NA objective lens, collected at the other end with a multimode (50 µm core) silica fiber coupled to an Optical Spectrum Analyzer (OSA).



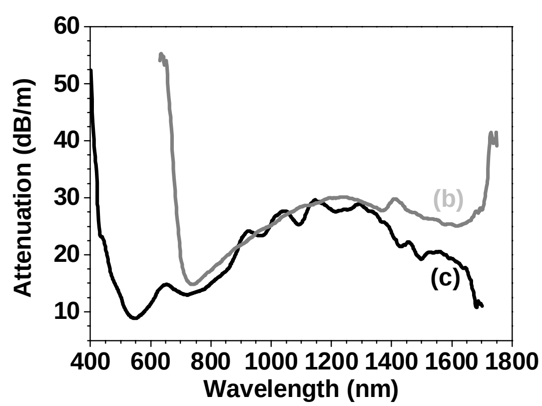


Fig. 4 In left, Tungsten-Halogen lamp spectrum as (a) curve, and transmitted light intensity after passing through F1 and F2 fibers as (c1), (c2) and (b1), (b2) curves respectively. In right, attenuation spectra of F1 and F2 fibers as (c) and (b) curves respectively.

Figure 4 (left) shows (a) the Tungsten-Halogen lamp spectrum collected directly by the multimode silica fiber, (c1) and (c2) after passing through 45cm and 65cm of the F1 fiber, respectively, and (b1) and (b2) after passing through 51.5cm and 71.5cm of the fiber F2, respectively. From these curves the attenuation spectra of F2 (b) and F1 (c) fibers was obtained and showed in Figure 4 (right). The transmission window of the PCF fiber F2 [~700 to ~1750 nm] is smaller than the [~400 to >1800 nm] core/clad fiber F1 window. The attenuation minimum value obtained was 10dB/m for the conventional optical fiber F1 and 15dB/m for the micro-structured optical fiber F2.

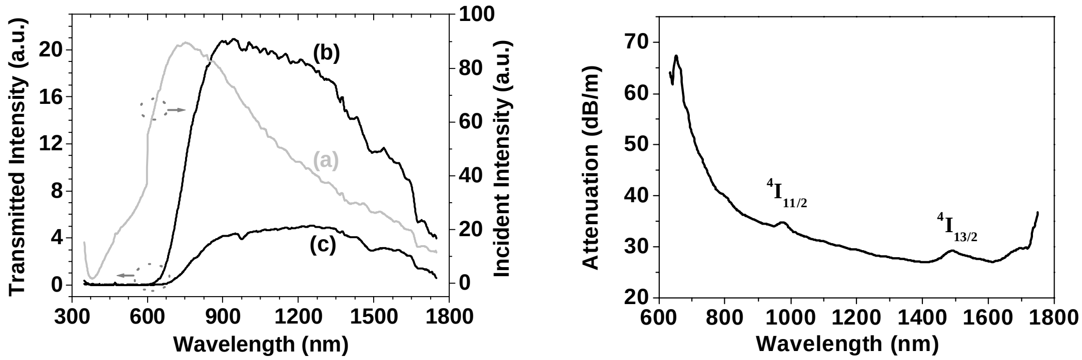


Fig. 5 In left, Tungsten-Halogen lamp spectrum as (a) curve, and transmitted light intensity after passing through F3 fiber as (b) and (c) curves. In right, attenuation spectra of F3 fiber.

The same measurement was performed for the tellurite PCF fiber F3. Figure 5 (left) shows (a) the white light spectrum, (b) and (c) after passing through 47cm and 67cm of the tellurite PCF fiber F3. The attenuation spectrum is shown in Figure 5 (right) with a 30dB/m attenuation minimum value around the 1400 nm. It also shows the Er^{3+}-ions absorption peaks as ridges around 975nm and 1490nm that correspond to ${}^4I_{15/2} \rightarrow {}^4I_{11/2}$ and ${}^4I_{15/2} \rightarrow {}^4I_{13/2}$ transitions respectively.

4. CONCLUSIONS

We demonstrate that the stack-and-draw technique can be used to produce up to five periods soft glass Photonic Crystal, or Micro-structured, Fibers. The fibers were fabricated with a Heathway drawing tower using four different soft glasses, Alkaline, Lead (Pb), Borosilicate and tellurite glasses. The fact that the tellurite glass core of the PCF was doped with Er^{3+} shows the potential of these fibers for optical amplification or other active devices. Optical fibers Attenuation measurements were realized using cut-back method.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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