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ScienceDirect
Journal of Non-Crystalline Solids 353 (2007) 339–343
JOURNAL OF NON-CRYSTALLINE SOLIDS
www.elsevier.com/locate/jnoncrysol

Waveguide produced by fiber on glass method using Er^{3+}-doped tellurite glass

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Received 6 March 2006; received in revised form 30 November 2006
Available online 30 January 2007

Abstract

We report the fabrication of waveguides using the fiber on glass (FOG) method. Taking advantage of a Thermal Mechanical Analyzer (Shimadzu TMA-50), we were able to produce a new type of waveguide by coupling an erbium doped fiber core onto a planar glass substrate. Both optical fiber core and substrate were fabricated from tellurite glass. Important thermal characteristics of the substrate and fiber like the transition temperature T_g, the temperature for the crystallization onset T_x and the maximum crystallization temperature T_c were determined by Differential Thermal Analysis (DTA). The thermal expansion coefficient of the tellurite glass was determined by Thermal Mechanical Analysis (TMA).

PACS: 42.81.Qb; 51.20.+d; 42.82.Et; 42.70.Ce; 78.66.Jg; 71.20.Eh

Keywords: Optical fibers; Planar waveguides; Glass transition; Scanning electron microscopy; Optical properties; Absorption; Tellurites; Rare-earths in glasses; Glass transition; Thermodynamics; Viscosity

1. Introduction

The integrated optics is a new branch in the field of optoelectronics, which has been progressing rapidly. Optical waveguides are one of the main components in circuits for optical communications. Several methods have been developed to produce optical waveguides in glasses. Among them ion exchange has been recognized as a valuable technique for the fabrication of active devices allowing high optical gain per length unit [1,2]. This technique enables the realization of both passive and active integrated optical devices including the fabrication of waveguides in glass substrates [3–7]. The many benefits of ion exchange include low production and materials cost, low birefringence and propagation losses, and compatibility with single-mode fibers. However, the increasing complexity of functional devices usually requires waveguides of varying widths, often in close proximity to each other.

Glass integrated optics can offer excellent flexibility to accommodate more functions and it is suitable to cost effective mass production. Integrated optical lasers and amplifiers have been obtained using rare earth-doped glasses exploiting different technologies [8].

Moreover, the tellurite glasses have gained a wide attention because of their potential as hosts of rare-earth elements for the development of fiber and integrated optic amplifiers and lasers covering all the main telecommunication bands. In fact, Tm^{3+}, Er^{3+} and Tm^{3+}–Ho^{3+} doped glasses can be used for amplification in the S, C and L bands between 1.46 and 1.61 μm [9–11]. Tellurite glasses exhibit the lowest phonon energy (around 780 cm^{-1}) when compared with the silicate or phosphate glasses and they also offer good stability and chemical durability. Furthermore, they exhibit high refractive index, a wide transmis-

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0022-3093/$ - see front matter © 2006 Published by Elsevier B.V.
doi:10.1016/j.jnoncrysol.2006.12.003

sion range (0.35–5 μm), low process temperature and significant non-linear properties [12–14].

In this work, the fabrication and characterization of waveguides using the fiber on glass (FOG) concept proposed by Benson et al. [15] are reported. This method correlates the principal characteristics of fiber and substrate with the transition temperature T_g, the temperature for the crystallization onset T_x and the maximum crystallization temperature T_c. The fabricated waveguide device was obtained by thermally welding an optical fiber core onto an Er^{3+}-doped glass. Both fiber core and glass substrate were produced from tellurite glasses, which enables the device to operate in the 1.5 μm telecommunications window.

2. Experimental

The glass samples were prepared by the conventional technique of melting and quenching. A platinum crucible containing the glass constituents was placed in a quartz tube, and heated in a resistance furnace from ambient temperature up to 750 °C, where it remained for 2 h. In order to drag vapor from the glass sample, a low oxygen flow was introduced during the melting. After melting, the glass is quenched and cooled to ambient temperature. Finally, to reduce internal stresses caused by the thermal shock, the glass samples underwent annealing at 300 °C during 5 h.

The glass composition used during the experiences was $75TeO_2$–$2GeO_2$–$(10+x)Na_2O$–$(12-x)ZnO$– $1Er_2O_3$ (mol%), where $x = 0$ applies to the TEGNAZO10 glass and $x = 2$ applies to the TEGNAZO12 glass.

The final samples were cut in square pieces of $10 \times 10 \times 1$ mm and polished until obtaining an adequate transparency for optical characterization. The density of the glass samples was measured by the Archimedes method using distilled water as immersion medium.

Important thermal properties of the glass samples like glass transition temperature T_g, the temperature of crystallization onset T_x, and the maximum crystallization temperature T_c, were measured by DTA using an analyzer Shimadzu DTA-50, which operates in the 30–800 °C temperature region with 10 °C/min heating rates. Thermal expansion coefficients of the glasses were measured through TMA using a Shimadzu TMA-50 analyzer. The measurements were performed at a 40 mg bulk glass sample.

The refractive index of the glass samples was measured at 632.8, 1305 and 1536.4 nm. For these measurements, a prism coupler system (Metricom 2010) with TE polarization and ±0.0001 resolution was used [16–18].

Absorption spectroscopy was performed at room temperature from 500 to 1800 nm with a Perkin–Elmer Lambda 9 spectrophotometer. Photoluminescence spectra were obtained using a lock-in technique with a Ti:sapphire pump laser (790 nm) and a germanium detector.

For the lifetime measurements of the $^4I_{15/2}$ to $^4I_{13/2}$, the sample was irradiated with a 980-nm-laser diode chopped at 50 Hz. The emission signal was collected with a silicon detector and fed into a 100 MHz oscilloscope (Tektronik TDS 1020). The lifetime was finally obtained by fitting a single exponential to the measured decay waveform.

The amplified spontaneous emission (ASE) was measured using an optical spectrum analyzer (OSA Hewlett/Packard 70 000 A). For these measurements, samples were pumped with a 980-nm-laser diode. To minimize reabsorption the samples were polished thinner than 1 mm.

Once the region of temperature ($T_g - T_x$) was determined, the soldering process was started. The soldering was carried out using the same TMA-50 analyzer used for thermal expansion measurements. The flat substrate and the fiber core were sandwiched between two steel plates and placed in the TMA analyzer. The force coil of the equipment was set to exert a constant pressure on the structure while keeping the temperature constant until the welding occurred.

The process was performed in four steps: (i) TEGNAZO10 fabrication, (ii) optical fiber core drawing, (iii) production of the optical cladding substrate (TEGNAZO12 tellurite glass) and (iv) fabrication of the optical waveguide FOG device.

The 100 μm thick rod used as a fiber core was drawn at a Heatway drawing tower (drawing speed of 3.2 m/s).

3. Results

Table 1 presents the basic thermal parameters of the glasses fabricated in the present work. With Na_2O concentrations ranging from 10 to 12 mol%, we succeeded in the fabrication of glasses like TEGNAZO10 and TEGNAZO12 which exhibit similar values of both T_g and T_x. They also exhibit a reasonable $T_g - T_x$ difference (110–120 °C) which favors the welding process. These are the reasons why these glasses were chosen to fabricate the optical fiber core and substrate, respectively.

Based on the T_g results obtained for both glasses, we chose the temperature interval 290–310 °C to perform the soldering between the substrate and the optical fiber.

Table 2 shows results of the optical characterizations conducted at the TEGNAZO10 and TEGNAZO12 glass samples. Refractive index measurements carried out at

Table 1
Important thermal and physical properties of the fabricated glasses

Glass sample	$T_g \pm 2$ (°C)	$T_x \pm 2$ (°C)	$T_f \pm 3$ (°C)	$T_x - T_g \pm 3$ (°C)	Thermal expansion ± 0.03 ($°C^{-1} \times 10^{-6}$)	Density ± 2% (g/cm^3)	Concentrations Er^{3+} ± 3% ($\times 10^{20}$ ions/cm^3)
TEGNAZO10	293	416	445	123	1.35	5.19	4.42
TEGNAZO12	292	403	485	111	1.29	5.12	4.38

Table 2
Results of the optical characterizations conducted at the glass samples TEGNAZO10 and TEGNAZO12

Glass sample	$n_{\lambda=633\ nm} \pm 4\%$	$n_{\lambda=1305\ nm} \pm 3\%$	$n_{\lambda=1536\ nm} \pm 4\%$	Bandwidth ± 2 (nm)	τ_{exp} (ms) ± 0.3
TEGNAZO10	2.0169	1.9705	1.9658	71	5.8
TEGNAZO12	2.0073	1.9608	1.9567	76	6.9

Refractive index measurements were performed at 632, 1305 and 1536 nm. Both bandwidth and lifetime for the $^4I_{15/2}$ to $^4I_{13/2}$ erbium transition were measured at 1550 nm.

three different wavelengths revealed a lower refractive index for the glass used as the substrate (TEGNAZO12). This difference enables the light guiding just by welding the fiber core (TEGNAZO10) onto the glass substrate, which plays the role of cladding for the optical fiber.

Optical and thermal characterization conducted at glass samples with the same fabrications parameters produced at different stages of the experiences revealed similar results, indicating the excellent repeatability obtained during the fabrication process.

The bandwidth (70–76 nm) was obtained through direct measurement of the FWHM of the photoluminescence band around 1550 nm (Fig. 1(b)). The lifetime obtained for the $^4I_{15/2}$ to $^4I_{13/2}$ erbium transition was around 6 ms.

Table 3, the principal parameters that are to be considered during the welding process are presented. Experiences were carried out at different temperatures (290–320 °C), exerting different pressures on the fiber–substrate structure and during different times (2–8 min). After many attempts and tests, 310 °C, 5 min, and 40 mN revealed as the optimal parameters for performing the 'FOG' process.

Fig. 1 shows the absorption and photoluminescence spectra of the fabricated glass samples. Absorption spectra exhibit the typical absorption bands of Er^{3+}-doped glasses. Photoluminescence was measured around 1550 nm and enabled the determination of the bandwidth of the glasses.

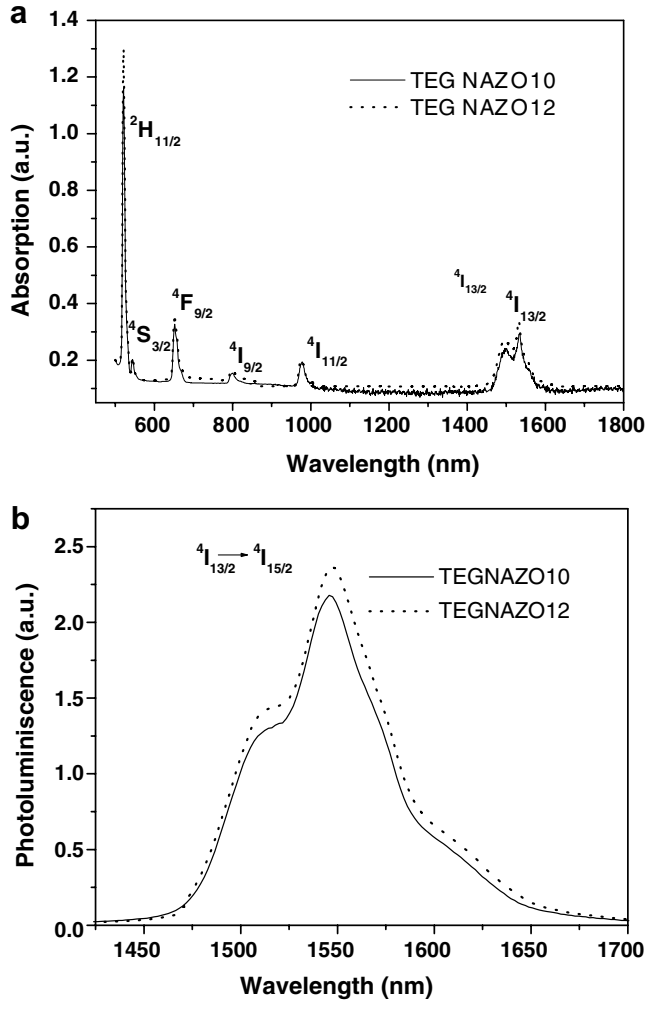

Fig. 1. (a) Absorption spectrum and (b) photoluminescence for the fabricated glass samples. The PL spectrum was obtained using a 790 nm Ti:sapphire pump laser. Straight lines are for TEGNAZO10 and dotted lines for TEGNAZO12 glass.

Table 3
Input parameters used for the TMA control program during the FOG device fabrication, and final results obtained with each parameter set

Force ± 1 (mN)	Time (min)	Temperature ± 2 (°C)	Final results
35	2	290	No welding
35	4	290	Apparently soldering
40	5	310	Optimum
45	6	320	Superficial damages
45	8	320	Total damages

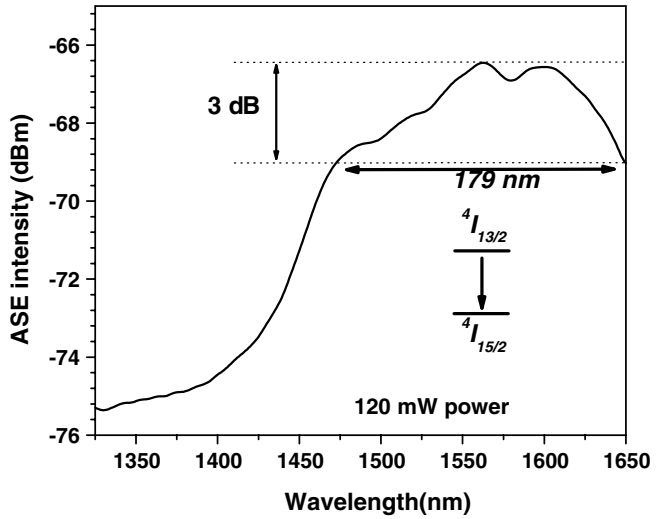

Fig. 2. ASE spectra of the FOG waveguide device. For these measurements, the device was pumped at 980 nm using a 120 mW laser diode. Bandwidth measured at −3 dB from maximum intensity was 179 nm.

Fig. 2 shows the ASE spectrum of the fabricated waveguide device. The spectrum corresponds to the $^4I_{15/2}$ to $^4I_{13/2}$ Er^{3+} transition around 1550 nm. Samples were pumped at 980 nm with a 120 mW laser diode.

The bandwidth is defined as the full width at half maximum power by the relation $P_{\text{peak}-\max}(\text{dB}) = 10\log\left[\frac{P_{\max}/2}{1\text{ mW}}\right]$, resulting in $P_{\text{peak}-\max}(\text{dB}) - 3\text{ dB} = 10\log[P_{\max}]$. The bandwidth for the TEGNAZO10 glass (after welding with the planar substrate) was 179 nm measured at −3 dB.

Fig. 3 presents a plain-view SEM micrograph of the fabricated waveguide device. Arrows in the figure indicate the fiber core and substrate, respectively. Fig. 4 shows a cross-section micro-photograph of the device. The dimensions of the fiber agree with those reported during the drawing process.

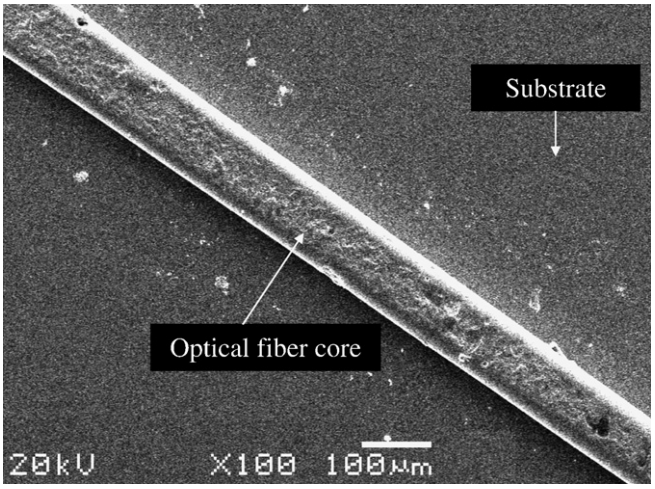

Fig. 3. Plain-view SEM micrograph showing the 'FOG' waveguide. Optical fiber and substrate can be seen after the 'FOG' welding process.

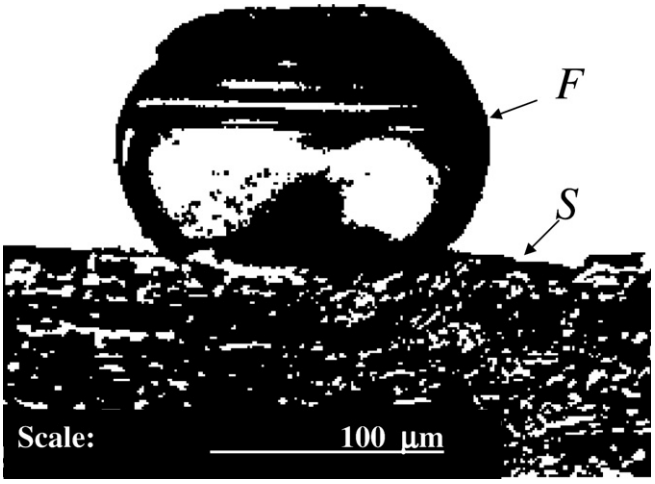

Fig. 4. Cross-section micro-photograph of the waveguide fabricated using the FOG method. F is the optical fiber (TEGNAZO10) and S the planar substrate (TEGNAZO12).

4. Discussion

The $T_x - T_g$ difference was an important criterion to evaluate the glass stability and consequently its glass formation capability. This criterion was used to know if the glass was viscous enough to shape in the FOG concept.

To obtain good results during the welding process, it is desirable that both the fiber core and the glass substrate exhibit similar values for T_g. In order to prevent against possible crystallization, it is also desirable that both the substrate and the fiber core show a large difference between T_g and T_x ($T_g - T_x$). Furthermore, to avoid structural damages it is required that both the planar substrate and the fiber core exhibit values of the thermal expansion coefficient close to each other.

The modifications performed in the Na_2O–ZnO concentrations resulted in variations of both the thermal characteristics (T_g, T_x, T_f, thermal expansion coefficient and density) and the optical characteristics (refractive index, bandwidth, and lifetime) of the glass samples (Tables 1 and 2). Similar results were previously reported by Ebendorff-Heipedriem et al. [19]. With these modifications, it was possible to fabricate glass samples possessing the required characteristics to succeed in the welding of a fiber core onto a glass substrate. The TEGNAZO10 and TEGNAZO12 glass samples exhibit similar T_g, reasonable $T_g - T_x$ temperature region and comparable values for the thermal expansion coefficient.

The large bandwidth around 1550 nm, the lifetime for the erbium transition measured at 1550 nm and the large ASE bandwidth obtained for the fabricated glass samples suggest the possibility of using these glasses for the fabrication of planar optical devices in small dimensions with high amplification efficiency [20,21]. All those characteristics also transform these tellurite glasses (TEGNAZO10 and TEGNAZO12) into excellent candidates for improving the performance of optical devices with high number of channels operating in the window for optical communications.

5. Conclusion

In this work, we have described the fabrication of a new class of active optical devices formed by an optical fiber thermally welded onto a glass substrate. Both the optical fiber and the substrate were fabricated from tellurite glass doped with high Er^{3+}-ions concentrations. The device was produced through the FOG method. This technique is an alternative for the production of active optical devices in the form of channel waveguide differing from the classical waveguide fabrication methods as ion exchange, thin film deposition, sputtering and femtosecond laser writing. Moreover, this technique results attractive and in producing optical devices more work is needed to obtain the optimal parameters for the fabrication of an efficient device.

Acknowledgements

The authors would like to thank the Brazilian agencies CNPq, FAPESP, PRONOE, CEPOF for the financial support.

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