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Optical amplification and laser spectroscopy of neodymium-doped fluoride glass channel waveguides

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Abstract

We report on the first observation of optical signal amplification at 1.047 μm in neodymium-doped fluoride glass channel waveguides. Up to 2.7 dB cm^{-1} signal amplification (internal gain) at 1.047 μm has been obtained with absorbed power of 7 mW at 795 nm. This result demonstrates the ability of rare earth (RE) doped heavy-metal fluoride glasses to serve as active waveguides for integrated optics. © 1998 Published by Elsevier Science S.A.

Keywords: Optical amplification; Rare earth-doped waveguides; Fluoride glasses; Nd^{3+} spectroscopy

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1. Introduction

The development of integrated optical amplifiers or lasers opens a wide range of applications for telecommunications: Wavelength Division Multiplexing (WDM) or fiber to home connections, including multimedia operations. The potential advantage of such devices is the compactness, the possible integration of several functions as well as the low cost due to mass production and packaging.

The elaboration of erbium-doped high optical quality thin films with adequate photolithography techniques has allowed demonstration of the capacity to amplify small signal at 1.5 μm with net gain up to 3.3 dB cm^{-1} in silica based materials [1] or in phosphates [2]. However, for integrated optics, short devices of a few centimeters for compactness are required which, in turns, limits gain or multiplies the devices. Unfortunately, increasing concentration in silica-based channel waveguides does not result in an increase in gain because of quenching effects interpreted by clustering or aggregates of erbium ions.

Among other possible materials for channel waveguides, heavy metal fluoride glasses are very attractive because of their high transparency in the near infrared and a subsequent low phonon energy which favor a large number of radiative transitions for rare earth (R.E.) ions including the second (at 1.3 μm with praseodymium) and third (at 1.55 μm with erbium) telecommunication windows [3]. Moreover, some chemical compositions may incorporate quite high R.E. concentration with weak fluorescence quenching only. New chemical composition with low phonon energy has considerably lengthened the $^1G_4$ praseodymium lifetime and subsequently improved the performances of the 1.3 μm optical amplifier [4]. As regards the erbium doped fluoride fibers, quite good gain flatness over more than 30 nm in the 1.55 μm range has allowed performance of WDM transmission with very high bit rates [5]. Finally, evanescent-field amplification in Nd^{3+}-doped fluoride planar waveguide has been recently reported but 0.45 dB cm^{-1} signal amplification has only been obtained [6].

In this report, we present optical, spectroscopy and gain measurements on two chemical compositions of fluoride channel waveguides doped with neodymium ions. The first

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part will deal with material elaboration and optical and spectroscopic techniques. Experimental results are presented in the second section and the discussion includes a theoretical approach.

2. Materials and techniques

Two types of techniques were used to prepare planar waveguides.

- Thin films of RE-doped PZG (PbF_2–ZnF_2–GaF_3) glasses were elaborated by Physical Vapour Deposition (PVD) on fluoride glass (ZBLAN) or CaF_2 substrates, thanks to the similar vapour pressure of the constituents. Films are few microns thick exhibiting a quasi step index profile with a Δn of more than 0.2 determined by m-line spectroscopy. Propagation losses were estimated in this waveguide around 6 dB cm^{-1} by analysing the diffuse light intensity along the planar propagation. Waveguide Raman spectroscopy technique has been applied to check the chemical composition of the guide with respect to bulk composition [7]. Strip waveguides were prepared by carrying out photolithography to create masked regions. ZBLAN substrates were firstly attacked through the mask to create ridge on which RE-doped PZG composition is deposited.
- Fluorine→chlorine (or OD^-) anionic exchange was achieved at the surface of neodymium doped ZBLA (ZrF_4–BaF_2–LaF_3–AlF_3) glass following a diffusion process. For this composition, strip waveguides are prepared by first carrying out photolithography to create masked regions of silica on to bulk glass. The next step is the ion-exchange process itself followed by removing the SiO_2 mask using RIE (Reactive Ion Etching) technique. Near field measurements were performed at several wavelengths to determine mode profile. Then, single mode propagation was obtained in the near infrared at 830 nm and 1.015 μm for a 3 μm-wide waveguide [8].

To analyse the luminescent properties of the channel waveguides, end-pump configuration was used to inject the excitation laser beam into the ridge with a microscope objective. Either a cw Ti sapphire solid state laser or a pulsed pumped dye Nd:YAG laser provide a tunable source in the near infrared range which allows resonant exitation of the $^4F_{5/2}$ and $^4F_{3/2}$ levels of the neodymium ions. Fluorescence was spectrally and temporally analysed at the output or by the side of the waveguide to determine emission cross sections and lifetimes required for evaluating the potential performance of the optical amplifier. Occasionally, low temperature measurements were performed with the waveguides using an appropriate experimental set-up described elsewhere [9]. Furthermore, we have developed an adequate set-up for absorption measurements using a double pass of the light (here the tunable Ti-sapphire beam), OEC (Optimum End-fire Coupling method) as proposed by Haruna et al. [10]. The first pass serves as a mode filter, then the output light is returned to the waveguide by a mirror and the absorption is measured through the second pass.

3. Experimental results

3.1. Absorption and emission

In Fig. 1 the absorption spectrum of a bulk Nd^{3+}:ZBLA glass is shown which indicates the high absorption peak at 795 nm is well suited to pump the system with a laser diode. Infrared fluorescence spectra of bulk and waveguide are presented in Fig. 2 where the reabsorption associated with the confinement affects the high energy side (sharp peak) of the resonant transition to the ground level in the waveguide with respect to the bulk. Low temperature measurements allow identification of the zero-phonon line associated with each electronic transition including the crystal field splitting of each multiplet of the ground term ^4I. The maximum of the main transition occurs at 1.051 nm as normally expected for heavy metal fluoride materials. The cross sections are about one order of magnitude smaller than in crystal, Nd:$LiYF_4$ for instance.

3.2. Fluorescence decay measurements

To test the potential use of these waveguides, fluorescence decay curves have been recorded for all the chemical compositions to obtain a quantitative indication of the radiative probability of Nd^{3+} ions. Special attention was paid to the control of the peak power of the pulsed laser to keep it as low as possible (less than kW) to avoid non linear process or damage of the guide. For the PZG composition, a slight shortening with concentration occurs for the 1 mol.% neodymium fluoride doping with a lifetime value in the long time range of 370 μs which is roughly what is expected in a bulk material with the same concentration [7]. On the other hand, the anionic exchange in ZBLA doped material drastically changes the lifetime for $F^- \rightarrow OD^-$ exchanged waveguide (280 μs) and to a lesser extent for $F^- \rightarrow Cl^-$ sample (390 μs) as compare to bulk material (480 μs) as shown in Fig. 3. We note the quasi exponential behaviour of the decay curve for both bulk and chlorine exchange samples. However, if the former reduction is understood as a result of efficient multiphonon relaxation processes due to the high phonon energy of the OD groups, the behaviour with chlorine anionic exchange is more puzzling. A similar dependence has been reported in the studies of chlorine exchange process of transition metal doped ZBLAN glass [11]. Together with the observation of the increase in size due to the big chlorine ions, these considerations could well

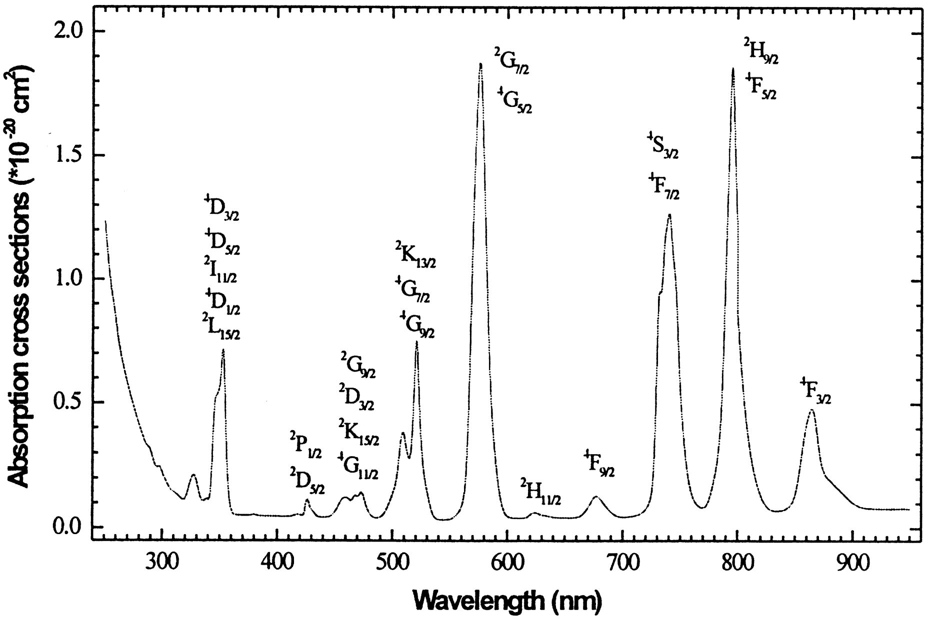

Fig. 1. Absorption spectrum of a 1 mol% neodymium fluoride-doped ZBLA glass.

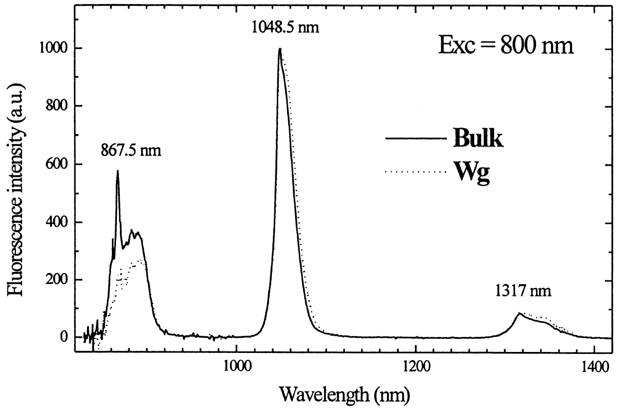

Fig. 2. Comparison of the fluorescence spectra of a 1 mol% neodymium fluoride-doped ZBLA substrate and of the OD$^-$ ion exchange waveguide on top of it.

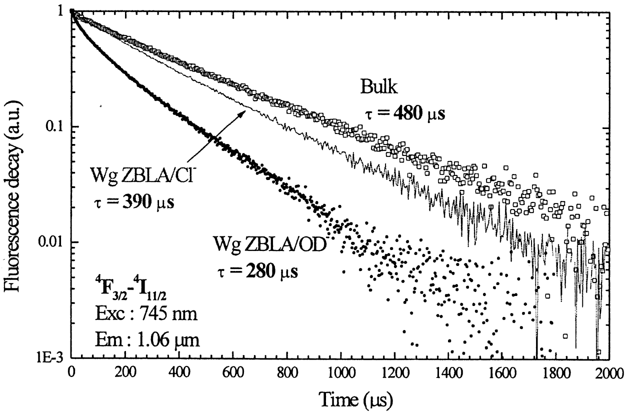

Fig. 3. Fluorescence decay curves of various anionic exchange process and of the corresponding bulk (substrate).

explain the observed increase of the radiative probability. On the other hand, the contamination of hydroxyl ions during the exchange process cannot be completely ruled out at the present.

3.3. Loss measurements

2 dB cm^{-1} propagation losses have been previously reported in a 3 µm-wide undoped Cl$^-$ exchanged waveguide at 830 nm using the cut-back technique [8]. On the other hand, absorption losses have been measured here in neodymium doped waveguides by the OEC method. We observe an increase from 2 dB cm^{-1} to 4.6 dB cm^{-1} but for different waveguides in the two reports, this behaviour is probably due to the different size of the measured waveguides and to both residual rare earth absorption and light diffusion related to inhomogeneities in the doped glass.

3.4. Amplification measurements

Signal gain amplification has been performed at 1.047 µm, using the beam of a diode pumped cw Nd:YLF laser. The pump beam at 795 nm was provided by a Ti-sapphire laser delivering more than a 1 W output power. A simple glass plate was used to combine both pump (transmitted) and signal (reflected) beams to shine on the input end-fire of the channel waveguides. At the output of the waveguide, the amplified signal is sent to a monochromator and/or appropriate filters through a dichroism mirror to remove it from the unabsorbed pump power (and to measure it). Moreover, the signal was modulated and synchronously detected which allows direct determination

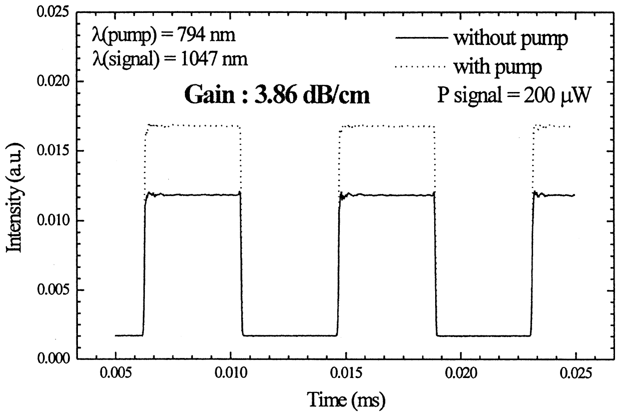

Fig. 4. Oscilloscope traces of gain measurement of the Nd:PZG glass waveguide.

of signal gain with and without pump beam. Such measurement gives rise to internal gain and losses must be subtracted to reach the net gain. In Fig. 4 a typical observation of two oscilloscope traces after averaging the output signals of PZG:Nd waveguide amplifier is shown. Note that the signal power was high, 200 μW. The signal amplification gain is rather high, 3.86 dB cm^{-1} but losses were not measured because the mode profile is far from circular, they are certainly large. For smaller waveguides, typically less than 40 μm, obtained with chlorine anionic exchange process, gain dependence with absorbed pump power is represented in Fig. 5. A 2.7 dB cm^{-1} maximum gain was achieved at 1.047 nm which should give rise to a 3 dB cm^{-1} at the maximum of the stimulated emission cross section of the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition in a neodymium-doped ZBLA glass as shown in Fig. 2. No further optimisation was developed to adjust the mode profiles of the signal and pump beams. Furthermore, we are expecting more gain with properly covered waveguides as far as losses are not increased at the new interface with the upper layer. Again, the gross gain is not high enough to compensate for the 4.6 dB cm^{-1} losses measured by the OEC method. Other similar results have been obtained with smaller signals. Finally, we may indicate that excitation of small size waveguides results, of course, in a better slope efficiency but careful polishing as well as cleaning of the end-face surfaces are strongly recommended for both amplification and loss measurements.

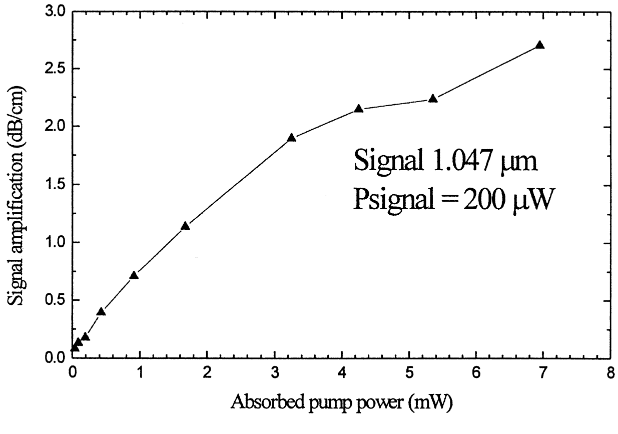

Fig. 5. Signal amplification versus absorbed pump power in the chlorine anionic exchange waveguide. The absorbed pump power is measured by tuning the pump wavelength to a non absorbing region of the neodymium spectrum, namely 835 nm.

Signal amplification calculations using a four-level scheme are being investigated which correctly reproduce the gain curve at low pump power and predict much higher gain above 4 mW of absorbed pump power.

4. Conclusion

We have reported, for the first time, signal amplification in a neodymium-doped fluoride glass channel waveguide with gains of 2.7 dB cm^{-1} in a chlorine anionic exchange device (with a 3 dB cm^{-1} value at the peak emission) and 3.86 dB cm^{-1} in PZG glass deposited by the PVD technique. At the present, propagation losses are still too high to achieve net gain for a further amplifier device. However, optimisation of the different elaboration techniques will soon allow us to reach 1 dB cm^{-1} losses. Furthermore, we should be able to improve the gross gain by optimising the neodymium concentration and end-face surfaces to obtain a positive net gain of more 3 dB cm^{-1} as predicted by the theoretical model. Thus, erbium-doped fluoride glass channel waveguides are presently being investigated for amplification gain at the strategic 1.5 μm wavelength, as well as praseodymium-doped fluoride glass channel waveguides for the 1.3 μm telecommunication window.

Acknowledgements

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