Classification

Physics Abstracts

42.81i — 42.65Ft — 42.55Nw

Spectral Hole-Burning of Nd³⁺ Doped Germanosilicate Fiber

B. Jacquier (^{1,*}), R.M. Macfarlane (¹) and A.M. Jurdyc (²)

(¹) IBM Research Division, Almaden Research Center 650 Harry Road, San Jose, California 95120-6099, U.S.A.

(²) Laboratoire de Physico-Chimie des Matériaux Luminescents, Université Claude Bernard Lyon 1, URA CNRS 442, 43 Bd du 11 Novembre 1918, Bat 205, 69622 Villeurbanne Cedex, France

(Received 28 July 1994, accepted 30 September 1994)

Abstract. — We report the observation of spectral hole-burning in the $^4I_{9/2} \rightarrow ^4F_{3/2}$ transition of Nd³⁺ in a germanosilicate fiber. The temperature dependence of holes was measured in the range of 1.3-3 K and a power law of $T^{1.2+/-0.1}$ was found.

Introduction

Dephasing rates of rare earth luminescent centers in amorphous materials at low temperature are typically two orders of magnitude larger than those measured in crystals [1]. This is because of the large number of low-frequency excitations of the glass which are thermally excited even at low temperatures. Coherent transient phenomena have been reported in a neodymium-doped silica fiber [2, 3] and in an Erbium Doped Fiber Amplifier (EDFA) [4]. These phenomena have potential applications in optical signal processing and storage.

In the frequency domain, spectral hole-burning, as in the case of fluorescence line-narrowing (FLN), requires the excitation of a subset of the inhomogeneous line by a narrow band tunable laser whose linewidth should be small compared to the homogeneous linewidth of the transition excited. In the case of Nd-doped silica fiber [5], measurements using such frequency domain techniques as well as accumulated photon echoes are in good mutual agreement but give significantly larger linewidths than those inferred from two-pulse photon echo decays in the same system. The difference is attributed to spectral diffusion induced by tunneling systems (TLS) in the glass. The time dependence holewidths measured in europium-doped germanosilicate fiber also provides evidence for a spectral diffusion [6].

In this paper, we present some new measurements of persistent hole-burning in a neodymium-doped germanosilicate fiber. We discuss the temperature dependence of the holewidth and its

(*)Permanent address: Laboratoire de Physico-Chimie des Matériaux Luminescents, Université Claude Bernard Lyon 1, URA CNRS 442, 43 Bd du 11 Novembre 1918, Bat 205, 69622 Villeurbanne Cedex, France

relationship to the density of states and dynamics of the low frequency excitation modes of the glass.

Experimental Results

For this study, we chose the well known $^4I_{9/2} \rightarrow ^4F_{3/2}$ transition of the Nd^{3+} ion whose lowest absorption peak is at 885 nm in the germanosilicate fiber. The single-mode optical fiber (cutoff wavelength $\lambda_c = 750$ nm) whose core (diameter = 3 μm) includes 20% of germanium oxide was doped with approximately 100 ppm of neodymium ions. In this case, optical absorption was 1.2 dB/m at 885 nm, as shown in Figure 1. The inhomogeneously broadened $^4F_{3/2}(1)$ state is centered at 885 nm, slightly shifted to the blue compared to pure silica. The shoulder observed at longer wavelength is related to absorption from Boltzman distribution in the first excited Stark component of the ground multiplet, its position being in agreement with low temperature fluorescence data. From absorption and 1.06 μm luminescence excitation spectra, the splitting of the $^4F_{3/2}$ manifold in the germanosilicate fiber studied here was measured to be approximately 340 cm^{-1} , which is less than in pure silica (430 cm^{-1}) but still large compared to the splitting of other Nd^{3+} -doped multicomponent glasses [7].

At low temperature ($T = 4.4\text{ K}$), under broadband excitation the fluorescence spectrum of the $^4F_{3/2} \rightarrow ^4I_{11/2}$ transition (Fig. 2) exhibits a well defined structure leading to a splitting of the $^4I_{11/2}$ manifold of 380 cm^{-1} which is again larger than in other Nd^{3+} -doped multicomponent glasses. Finally, the fluorescence lifetime of the $^4F_{3/2}$ multiplet was found to be 470 μs at 300 K, in agreement with other Nd^{3+} -doped silicate glasses indicating no fluorescence

Fig. 1. — Room temperature absorption of the neodymium-doped germanosilicate fiber.

Fig. 2. — Low temperature fluorescence spectrum of the neodymium-doped germanosilicate fiber in the region of the ${}^4\text{F}_{3/2} \rightarrow {}^4\text{I}_{11/2}$ transition.

quenching effect.

A 2 meter long fiber was spliced to standard single-mode pigtailed on both ends for launching the laser beam and collecting the fluorescence signal at longer wavelength than $1.07 \mu\text{m}$ with an interferential filter. The fiber was held in a cryostat surrounded by cold helium gas and the temperatures measured with a calibrated silicon diode. Measurements were made using an amplitude stabilized cw Ti:sapphire laser with a spectral bandwidth of about 1 MHz. Power densities used for hole-burning were 0.3 W/cm^2 and burning times ranged from seconds to hundreds of seconds. The holes were probed in fluorescence excitation with about 1% of the burning intensity.

Figure 3 shows examples of persistent holes burnt in the inhomogeneous line at two temperatures. Holes were burnt with the laser wavelength on the low energy side of the absorption band and the hole depth was about 2%. Under our experimental conditions (fixed length of the doped fiber, same fluence over the temperature dependence, limited collecting fluorescence intensity) it was not possible to record holes with sufficient confidence above 3 K. In the case of the Nd-doped pure silica fiber, Brocklesby *et al.* [5] found this limit to be 4.2 K. In contrast, holes could be measured to much higher temperatures in Nd-doped bulk fluoride glasses [8] or in Nd-doped silica-based ED-2 bulk glass especially [9]. We note that the holewidth was almost twice as broad in 0.1% neodymium-doped ED-2 glass.

The variation of the half holewidth with temperature is shown in Figure 4, the straight line indicates a $T^{1.2+/-0.1}$ dependence. By extrapolating the temperature dependence to the half

Fig. 3. — Persistent spectral holes burnt in the inhomogeneous line at two different temperatures.

holewidth at 4.2 K, we find roughly the same value of 100 MHz determined by hole-burning [5] or by accumulated photon echoes [3] in a neodymium-doped pure silica fiber.

Discussion

In the absence of spectral diffusion, the half holewidth measures the homogeneous linewidth which, here, is attributed to phonon induced interconfigurational changes in the TLS. Long time scale changes, i.e. in the range of several seconds of burning time and of probing time in the present investigation, can lead to spectral diffusion as it has been observed in the case of Nd-doped silica fiber [5] and, more recently, in Eu-doped germanosilicate fiber (including 2% P_2O_5) [6]. In the absence of two-pulse or accumulated photon echo measurements on our germanosilicate fiber, we cannot separate out the contributions to the width from short time and long time fluctuations of the TLS configurations.

The temperature dependence of the holes could only be measured over a limited range but this was enough to establish the dependence of $T^{1.2 \pm 0.1}$ between 1.3 and 3 K. This result is different from the $T^{1.5}$ dependence found in the Nd-doped silica fiber [5] and from our earlier results in Nd-doped bulk glasses of different composition where a sublinear dependence was found below 4 K [9].

The temperature dependence expected from TLS induced dephasing follows a power of $T^{1+\mu}$ where μ is the exponent of the energy dependence of the TLS density of states determined from the low temperature heat capacity. This has been confirmed for two silicate glasses of different composition by Schmidt *et al.* [10]. For temperatures below 1 K, μ in pure silica has the value of 0.3 [11]. A similar result seems to hold for our germanosilicate fiber, in absence of effects due to rare earth concentration or to the nature of the rare earth ion. Then, the difference observed with our bulk measurements implies a major role of the glass composition in the density of

Fig. 4. — Temperature dependence of the half holewidth measured in the Nd-doped germanosilicate fiber.

states of the TLS. On the other hand, the sublinear dependence found for the neodymium-doped ED-2 bulk glass below 4 K differs from the result of the praseodymium-doped ED-2 glass reported in reference [12]. Finally, it is necessary to point out that the density of TLS drops down drastically above 2 K [11], then other contributions than TLS to heat capacity and therefore to linebroadening must be taking into account.

Conclusion

We have measured spectral hole-burning in a second example of Nd-doped fiber, the first being Nd-doped pure silica [5]. Over the restricted temperature range accessible, we found a $T^{1.2 \pm 0.1}$ dependence of the width on temperature. This would include both short-time homogeneous broadening and longer time (secs) spectral diffusion effects. From the discussion, it is clear that further measurements are needed both as a function of temperature and as a function of glass composition.

Acknowledgments

The authors wish to thanks Alcatel Alsthom Recherche (AAR) for providing the neodymium-doped germanosilicate fiber. This work was supported by an IBM-CNRS joint study agreement #0531.

References

- [1] Seltzer P. M., Huber D. L., Hamilton D. S., Yen W. M. and Weber M. J., Anomalous fluorescence linewidth behavior in Eu^{3+} -doped silicate glass, *Phys. Rev. Lett.* **36** (1976) 813 and Macfarlane R. M., Shelby R.M., Homogeneous line broadening of optical transitions of ions and molecules in glasses, *J. Luminescence* **36** (1987) 179.
- [2] Hegarty J., Broer M. M., Golging B., Simpson J. R. and MacCesney J. B., Photon echoes below 1K in a Nd-doped glass fiber, *Phys. Rev. Lett.* **51** (1983) 2033 and Broer M. M., Golding B., Haemmerle W. H., Simpson J. R. and Huber D. L., Low-temperature optical dephasing of rare earth ions in inorganic glasses, *Phys. Rev.* **B33** (1986) 4160.
- [3] Uesugi N., Shimizu M. and Mitsunaga M., Picosecond accumulated photon echo in Nd-doped optical fiber, Technical Digest of QELS'92, paper QFA5.
- [4] da Silva V. L., Silberberg Y., Heritage J. P., Chase E. W., Saifi M. A., Adrejco M. J. and YiYan A., Photon echoes in Er-doped fibers, Technical Digest of QELS'92, paper QMC3.
- [5] Brocklesby W. S., Golding B. and Simpson J. R., *Phys. Rev. Lett.* **63** (1989).
- [6] Wannemacher R., Koedijk J. M. A. and Völker S., Dynamics of spectral holes in rare- earth-doped glass fibers, *J. Luminescence* **60&61** (1994) 437.
- [7] Pellegrino J. M., Yen W. M. and Weber M. J., Composition dependence of Nd^{3+} homogeneous linewidths in glasses, *J. Appl. Phys.* **51** (1980) 6332.
- [8] Macfarlane R.M. and Jacquier B., Spectral hole-burning of Nd^{3+} -doped heavy metal fluorides, *J. Non-Cryst. Solids* **161** (1993) 254
- [9] Jacquier B. and Macfarlane R.M., "Spectral hole-burning in fluoride and silicate glasses doped with Nd^{3+} ", (paper TuB32-2) Technical Digest Vol 22 of Spectral Hole-burning and Luminescence Line Narrowing, Ascona, Switzerland, sept. 1992.
- [10] Schmidt Th., Baak J., van de Straat D. A., Brom H. and Völker S., Temperature dependence of optical linewidths and specific heat of rare earth-doped silicate glasses, *Phys. Rev. Lett.* **71** (1993) 3031.
- [11] Lasjaunias J. C., Ravex A., Vandorpe M. and Hunklingern S., The density of low energy states in vitreous silica: specific heat and thermal conductivity down to 25 mK, *Solid State Commun.* **17** (1975) 1045.
- [12] Schmidt Th., Baak J., van de Straat D. A., Brom H. and Völker S., Temperature dependence of optical linewidths and specific heat of rare earth-doped silicate glasses, *J. Luminescence* **58** (1994) 180.