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Chromatic Dispersion in Ge-doped SiO_2-based Single Mode Fibres due to Temperature Dependence of the Ultraviolet Absorption: Numerical and Experimental Results

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Abstract: The main information transmission limitation in optical communications employing SiO_2 optical fibres is imposed by the optical pulses temporal broadening, resulting from the dispersive properties of the transmission medium (chromatic dispersion). Usually, this dispersion is modelled assuming a -0.4 meV/ºC dependence of the 11 eV gap energy. We have monitored the 4.3 eV absorption band, with temperature and obtained a thermal dependence of -0.026 meV/ºC. With this value we can predict the first and second order chromatic dispersion for a wavelength of 1550 nm.

Introduction

In the last years, the growing number of multimedia and internet applications constantly pushes the transmission requirements of the telecommunications networks. Typically, in order to support this increasing traffic, the networks have progress to an optical solution supported by single mode GeO_2-doped optical fibres (SMF). Even for this solution the transmission capacity has been upgraded to high bitrates. For these high transmission bitrate one of the limiting factors is the fibre chromatic dispersion, which is responsible for a temporal spreading of the optical impulses as consequence of the nonzero spectral width of the optical sources (semiconductor Laser diodes). There are several methods for chromatic dispersion compensation [1,2], however for these high debit systems the tolerances are tight, requiring a perfect management between the dispersion of the fibres and the value of the dispersion compensation devices.

The value of the chromatic dispersion is temperature dependent [3], even for buried optical cable they are subject to seasonal temperature variations higher than 340 ºC [4], which combined with the long link extensions, are responsible for a degrading of the signal quality. The dominant contributions for the chromatic dispersion dependence on the temperature are electronic effects, in particular temperature variations of the electronic absorption ascribed to the material energy band gap (E_g). The temperature dependence of the SiO_2 energy gap around 11 eV has been previously study, and the results accounts well for the chromatic dispersion prediction [5]. However, such higher energetic ultraviolet energy gap is difficult to monitor with standard experimental conditions. The aim of this work is to investigate the temperature dependence of the optical chromatic dispersion in a SiO_2-based GeO_2-doped SMF fibre, through the study of the lower energy gap at

4.2 eV ascribed to Si-Si bonds. Based on such spectroscopic measurements the first and second order chromatic dispersion for a wavelength of 1550 nm is predicted.

Chromatic Dispersion Model

Nowadays, the SMF optical fibres are responsible for the transport of more than 90 % of the optical traffic. An SMF is made of a 125 μm diameter SiO_2 cylinder, with an internal concentric region (the core) with 10 μm in diameter. To assure the waveguide propagation, the fibre core should have a higher refractive index than that of the cladding. This index rising is obtain by doping the SiO_2 with GeO_2, (typically 3 % mol). The optical fibre is a dispersive medium, thus a dependence of the refractive index on the wavelength, so called material chromatic dispersion (D_m), is expected. The classical Lorentz oscillator model is able to account for the electronic transitions and lattice vibrations, from which the SiO_2 Sellmeier equation can be derived, enabling the description of the material chromatic dispersion. Usually, it is enough to consider the two-term Sellmeier formalism, where all electronic oscillators were lumped into one effective term, and all lattice vibrational oscillators into another one. The total chromatic dispersion consideres the material chromatic dispersion and a small term, that accounts for the waveguide dispersion, which is temperature independent and therefore was neglected in this analysis. The material chromatic dispersion is manifested through the wavelength dependence of the core refractive index, (n_n), by the following relation [6]:

$$D_m(\lambda) = -\frac{\lambda}{c} \cdot \frac{\partial^2 n_n(\lambda)}{\partial \lambda} \tag{1}$$

where c is the speed of light in the vacuum.

The temperature dependence of D_m is due to an enhancement in lattice vibrations with increasing temperature [7]. The refractive index variation with respect to temperature is described by the thermo-optic coefficient, ($\partial n/\partial T$), which includes the electronic and optical phonons contribution. The electronic effects, in particular the temperature variations of the electronic absorption ascribed to the material energy band gap (E_g) have the dominant contribution. Therefore, the thermo-optic coefficient can be described in terms of the linear expansion coefficient α and of the temperature variation of the energy gap ($\partial E_g/\partial T$),

$$2 \cdot n \cdot \left(\frac{\partial n}{\partial T}\right) = \left(-3 \cdot \alpha \cdot \left(n_1^{\,2} - 1\right)\right) \cdot \left(\frac{\lambda^2}{\lambda^2 - \lambda_g^{\,2}}\right) + \left(-\frac{2}{E_g} \cdot \frac{\partial E_g}{\partial T} \cdot \left(n_1^{\,2} - 1\right)\right) \cdot \left(\frac{\lambda^2}{\lambda^2 - \lambda_g^{\,2}}\right)^2 \tag{2}$$

where λ_g the wavelength correspondent to the E_g and n_1 is the less dispersive refractive index value.

Experimental

Chromatic dispersion

The first and second order chromatic dispersion for a 25 km SMF reel were measured to a wavelength of 1550 nm with a Agilent Optical Network Analyser 86038A, employing the phase shift method. The fibre was placed in an environmental chamber were the temperature was varied between 233 and 323 K. After temperature stabilization, one hour delay was taken before the measurement made, in order to ensure a stable temperature inside the fibre.

Absorption and luminescence

Prior to the absorption and luminescence measurements a SMF was immersed in acetone to remove the acrylic external protection, and then it was carefully ground until a fine powder was obtained. Absorption measurements were performed on the powdered SMF at room-temperature (RT) on a JASCO V-560 instrument, with a resolution of 0.1 nm. $BaSO_4$ was used as white standard.

Photoluminescence spectra were detected between 14 K and RT on a modular double grating excitation spectrofluorimeter with a TRIAX 320 emission monochromator (Fluorolog-3, Jobin Yvon-Spex) coupled to a R928 Hamamatsu photomultiplier, in the front face acquisition mode. All the photoluminescence spectra were corrected for optics and detection spectral response.

Results and Discussion

Experimental results

Fig. 1 shows the RT absorption for the SMF in the ultraviolet/visible spectral ranges. The spectrum consists of a large broad absorption band at *c.a.* 3.1-5.2 eV (238-400 nm). The absorption edge around 4.2 eV (296 nm) is ascribed to the energy gap (E_g) relating to the Si-Si bonds [8,9].

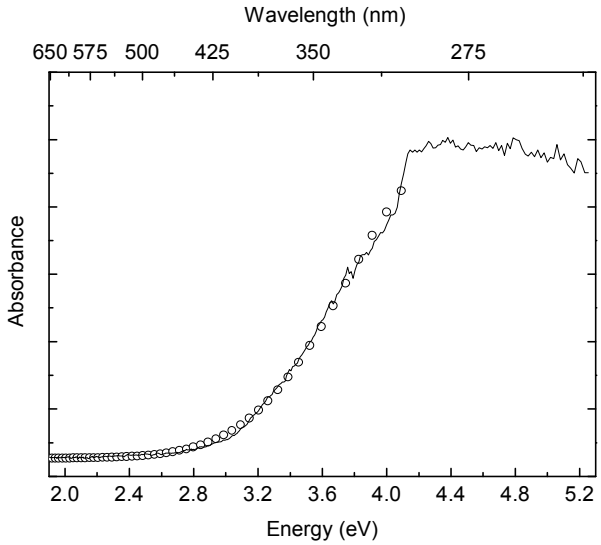

Fig. 1: RT absorption spectrum of the GeO_2-doped fibre. The circles represent the fit to equation 3 ($R^2 > 0.99$).

The absorption spectrum can be approximately expressed as a Gaussian shape for energies bellow the absorption edge, according to:

$$\sigma(E,T) = \sigma_0 \exp\left(-\frac{A(E_{\max} - E)^2}{k_B T}\right) \tag{3}$$

where $E_{\max}$ is the energy gap related to the Si-Si bonds, A is the constant ascribed to the electron-lattice interaction, and σ_0 stands for the maximum absorption constant. Equation 3 was used to fit the absorption spectrum (Fig. 1) and values of 4.2 eV, and 0.33 were obtained for the $E_{\max}$=E_g and A, respectively. The fit errors are less than 3 %.

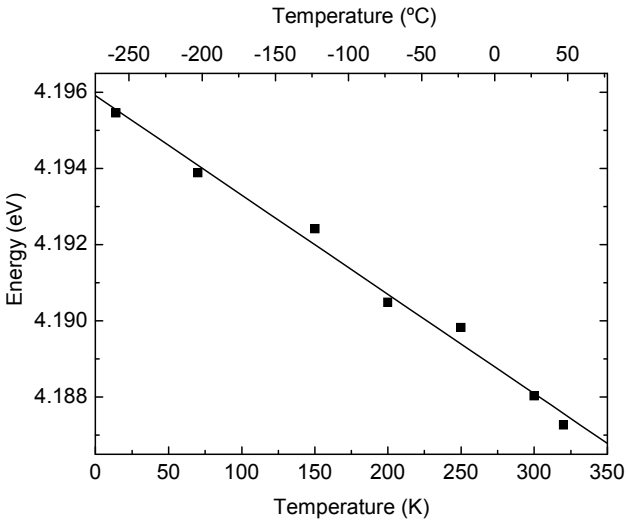

Fig. 2: Energy gap relating to the Si-Si bonds as function of the temperature. The solid line corresponds to the data linear fit ($R^2 > 0.99$).

Exciting the fibre around 296 nm a large broad band peaking at *c.a.* 310 nm is observed (not shown). In order to investigate the dependence of the energy gap relating to the Si-Si bonds, the excitation spectra was monitored around 310 nm in the temperature interval between 14 and 330 K. Fig. 2 shows the energy gap absorption peak as function of the temperature, revealing a linear behaviour with a slope E_g/temperature of (-0.026 ±0.001) meVK^{-1}.

The chromatic dispersion was measured for several temperatures. As shown in Fig. 3, for the first and second order chromatic dispersion values, it is observed a temperature dependence of (-1.46 ±0.07) ×10^{-3} ± ps nm^{-1} km^{-1} K^{-1} and (2.03 ±0.32) ×10^{-6} ps nm^{-2} km^{-1} K^{-1}, respectively.

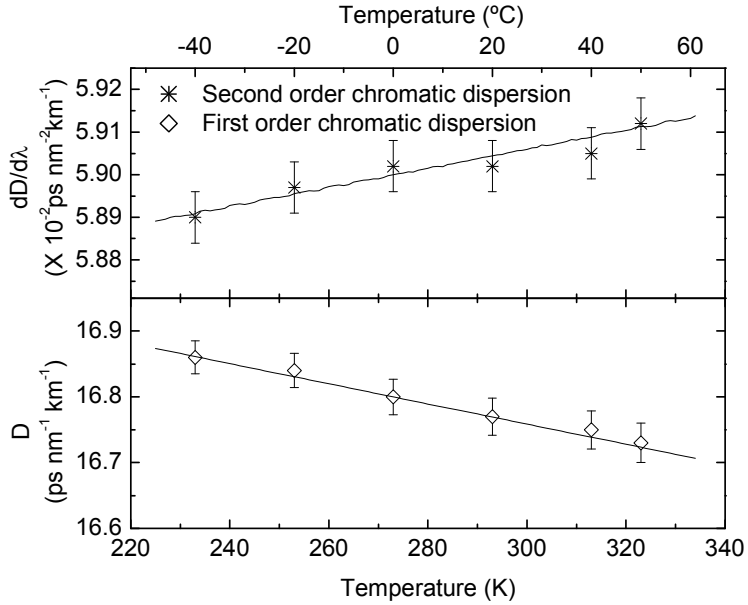

Fig. 3: First and second order chromatic dispersion, and respective error bars. The lines represent the fit using equations 1 and 2.

Numerical results

We have numerically calculate the chromatic dispersion at 1550 nm, recurring to a two term Sellmeier equation [7] and to equation 1, with the typical parameters values for the SiO_2 [7]. Then, the refractive index dependence with temperature was modelled through expression 2, using a less dispersive wavelength of 1309 nm. The input values of the energy gap and its temperature

dependence were those obtained from the previous section (E_g = 4.3 eV and $\partial E_g/\partial T$ = -0.026 meVK^{-1}).
The numerical simulation values for the first and second order chromatic dispersion are also plotted in Fig. 3, showing that our model accounts well for the prediction of the experimental results.

Conclusions

We have modelled the first and second order chromatic dispersion of single mode optical fibres, taking into account temperature effects, in particular the energy gap ascribed to the Si-Si bonds dependence on the temperature. Such energy dependence was experimentally measured, and used as input value for our numerical model. A comparison between the experimental values for the chromatic dispersion with the numerical ones, demonstrate that our model accounts well for the prediction of the experimental results.

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