Electrostrictive nonlinearity in optical fiber deduced from Brillouin gain measurements

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Abstract: Brillouin gain spectrum measurements make possible a quantitative evaluation of the electrostrictive contribution to the optical Kerr effect at frequencies corresponding to picosecond pulses. It turns out that this contribution is much larger than formerly estimated.

Summary

The nonlinear refractive index has drawn considerable attention these past few years, since it may significantly perturbate long-range propagation of lightwaves in optical fibers. Two main origins to this nonlinearity have been identified[1]: non resonant electronic nonlinearity and electrostriction. These contributions differently interact with light, so that it is of prime importance to quantify the relative importance of each contribution. Some recent works demonstrated that electrostriction may contribute more significantly than formerly expected[2] and a tentative quantification was even reported[3].

On the other hand the electrostriction is the main driving mechanism of stimulated Brillouin scattering that is today quantatively very well described, since very accurate measurements of the Brillouin linear gain g_B have been recently obtained[4]. This paper shows that the electrostrictive contribution to the nonlinear refractive index n_2 may indeed be straightforwardly calculated from Brillouin gain measurements.

The Brillouin linear gain g_B is dependent on material properties and in particular on the electrostrictive coefficient $\gamma_e = \rho\, \partial\varepsilon / \partial\rho$, according to the following relation[1]:

$$g_B = \frac{2\pi\, \gamma_e^2}{c_o\, \varepsilon_o^2\, \lambda_o^2\, \rho\, \Delta\nu_B\, c_A\, n}$$

where c_o is the vacuum light velocity, λ_o the vacuum wavelength, ρ the fiber material density, $\Delta\nu_B$ the Brillouin FWHM linewidth, n the refractive index and c_A the fibre acoustic velocity that is directly deduced from the Brillouin Stokes shift $\nu_B = 2\, n\, c_A / \lambda_o$. The three parameters g_B, ν_B and $\Delta\nu_B$ fully characterize the Brillouin gain spectrum and were measured with a high accuracy[4], as shown in Fig. 1. The electrostrictive coefficient γ_e may be easily calculated from the gain spectrum measurements, since the other material coefficients are well known.

The electrostrictive pressure is balanced by the medium compression, resulting in an increased density and thus a modified susceptibility[1]:

$$\Delta\chi = \frac{\Delta\varepsilon}{\varepsilon_o} = \frac{1}{2}\,\frac{C\,\gamma_e^2}{\varepsilon_o}\,\frac{|E|^2}{2}$$

where $C = \rho\,\partial p/\partial\rho$ is the medium compressibility and $|E|^2/2$ results from the time-averaging of the squared optical field E^2. The electrostriction generates a susceptibility change proportional to the optical intensity $I = (n\,\varepsilon_o\,c_o/2)|E|^2$, that modifies the refractive index this way:

$$\Delta n = \frac{\partial n}{\partial\chi}\,\Delta\chi = \frac{\Delta\chi}{2n} = \frac{1}{4}\,\frac{C\,\gamma_e^2}{\varepsilon_o}|E|^2 = \frac{1}{4}\,\frac{C\,\gamma_e^2}{n^2\,\varepsilon_o^2\,c_o}\,I$$

so that the electrostrictive nonlinear refractive index reads:

$$n_2^{elec} = \frac{C\,\gamma_e^2}{4\,n^2\,\varepsilon_o^2\,c_o} = 0.7\times 10^{-20}\,\frac{\mathrm{m}^2}{\mathrm{W}} \qquad \text{for a standard single mode fiber.}$$

Assuming a total nonlinear refractive index $n_2 = 2.96\times 10^{-20}\ \mathrm{m}^2/\mathrm{W}$ the contribution of the electrostriction to the Kerr effect amounts to 23% at a 12-13 GHz frequency, corresponding to pulse width in the 20-30 ps range. This is much more in magnitude and in bandwidth than what was formerly suggested[3], since the maximal calculated value of 16% was expected to rapidly vanish for pulse width narrower than 1 ns.

Fig. 2 shows the electrostrictive contribution to the nonlinear refractive index deduced from Brillouin gain measurements for a wide bunch of fibers having different GeO_2 core doping concentration. The scattering of the results is most probably due to an unknown factor specific to stimulated Brillouin scattering: the overlapping degree between optical and acoustic guided modes. This factor is always smaller than unity, so that the electrostrictive contribution is at most underestimated using Brillouin gain measurements. The actual value should be close to 50% of the total nonlinear index, taking into account an estimation of the overlapping degree.

1 R. W. Boyd, "Nonlinear Optics", Ch. 4, Academic Press, inc., 1992, San Diego, CA, USA

2 E. Dianov, A. Luchnikov, A. Pilipetskii and A. Starodumov, Opt. Lett., **15**, p. 314, (1990)

3\. E. L. Buckland, R.W. Boyd, OFC'96 Technical digest, OSA publications, ThF2, pp. 224-225, (1996)

4 M. Niklès, L. Thévenaz, Ph. Robert, J. Light. Tech., **15**, October 1997, *in press*

Figure captions

Fig 1 High-accuracy Brillouin gain spectrum measurement of a single mode silica fiber performed at a 1319 nm wavelength, with the estimated value of the three characterizing parameters.

Fig. 2 Calculated electrostrictive contribution to the nonlinear refractive index from Brillouin gain spectrum measured in single mode fibers with different core doping.

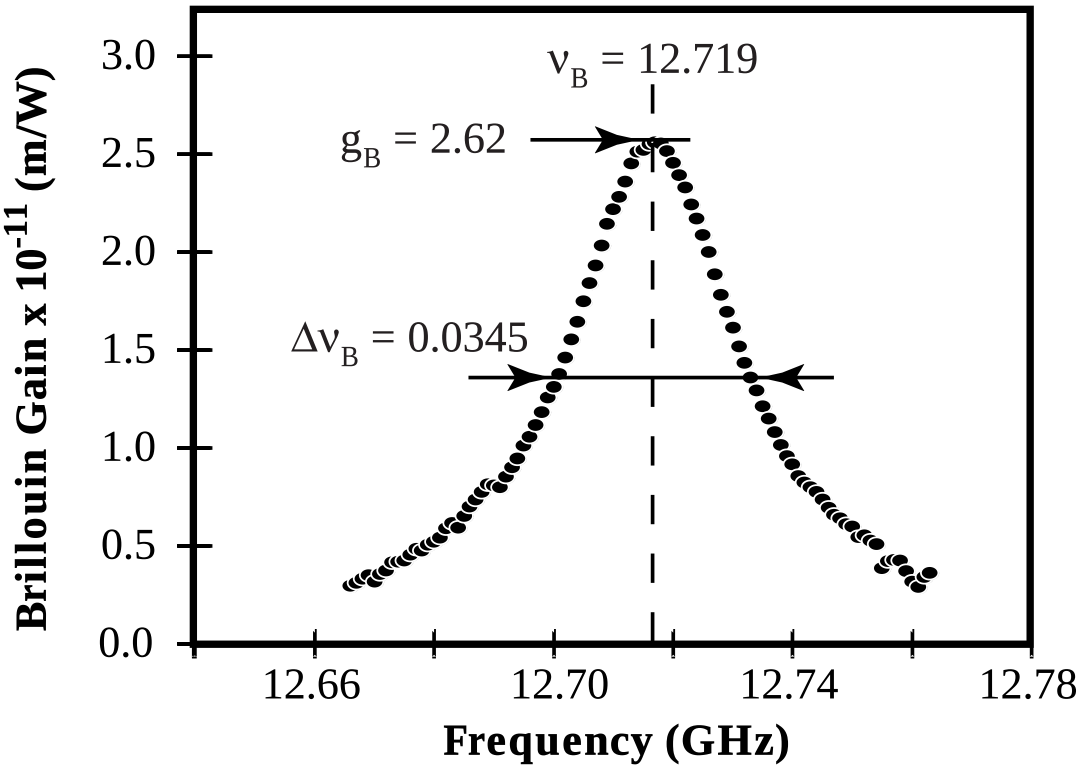

Figure 1

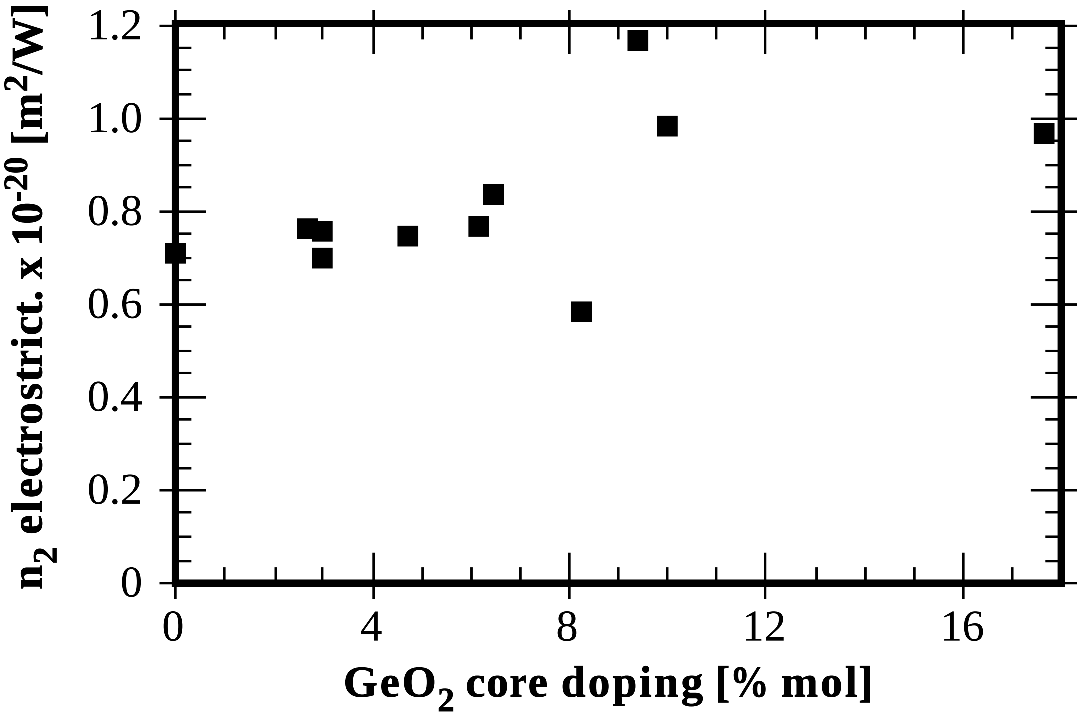

Figure 2