Measurement of the frequency response of the electrostrictive nonlinearity in optical fibers

Eric L. Buckland and Robert W. Boyd

The Institute of Optics, University of Rochester, Rochester, New York 14627

Received January 2, 1997

The electrostrictive contribution to the nonlinear refractive index is investigated by use of frequency-dependent cross-phase modulation with a weak unpolarized cw probe wave and a harmonically modulated pump copropagating in optical fibers. Self-delayed homodyne detection is used to measure the amplitude of the sidebands imposed upon the probe wave as a function of pump intensity for pump modulation frequencies from 10 MHz to 1 GHz. The ratio of the electrostrictive nonlinear coefficient to the cross-phase-modulation Kerr coefficient for unpolarized light is measured to be 1.58:1 for a standard step-index single-mode fiber and 0.41:1 for dispersion-shifted fibers, indicating a larger electrostrictive response in silica fibers than previously expected.

Electrostriction in optical fibers initiates a broad range of acousto-optic interactions, the most well known of which is stimulated Brillouin scattering.[1] A different class of interactions involving the interaction of light with acoustic modes of the fiber, first observed as guided-acoustic-wave Brillouin scattering,[2] has become more important in recent years. A long-range soliton interaction mediated by acoustic waves was observed by Smith and Mollenauer,[3] and the theory of this interaction was presented by Dianov *et al*.[4] In these studies pulses were separated by times as long as 100 ns, and the interactions involved refractive-index changes associated with acoustic reflections off the fiber cladding. Recently, Townsend *et al*.[5] performed a direct measurement of the magnitude of this electrostriction-initiated response by measuring the phase shift imparted upon 50-ps pulses interacting in a Sagnac-loop interferometer. These interactions were observed at low frequencies (less than 100 MHz). A follow-up experiment examined an acoustic resonance at 465 MHz and demonstrated damping of the acoustic wave at the interface between the fiber cladding and the surrounding polymer jacket.[6] In a separate set of experiments, Kato *et al*.[7] measured the nonlinear refractive index in optical fibers, using cross-phase modulation with a harmonically modulated pump (7 MHz) and a cw probe wave.[7] In these measurements they noticed that the values obtained for n_2 were consistently greater than values obtained in short-pulse self-phase-modulation experiments. We recently suggested that this anomaly was also due to the electrostrictive response in optical fibers, demonstrating that the magnitude of the electrostrictive response is large enough to be observed in the presence of the Kerr nonlinearity, and that this contribution will be significant only if the time scale of the interaction is long enough to initiate the acoustic response.[8] Here, we provide direct experimental evidence for the existence of an electrostrictive contribution to the nonlinear refractive index, demonstrating a strong dependence of the nonlinear response on the modulation frequency of the applied intensity. This study is complementary to those of Townsend *et al.* in that we probe the high-frequency response from 10 MHz to 1 GHz. In contrast with the research of Townsend *et al.*, our experiment probes primarily the immediate electrostrictive response local to the fiber core rather than the response associated with acoustic reflections traversing the fiber.

Electrostriction is the process in which the material density increases in response to the intensity of an applied electromagnetic field,[9] creating a proportional change in the refractive index of the material. The response time for the density change can be estimated as the time required for a sound wave to propagate across the fiber core, ~1 ns. The acoustic waves generated by this interaction propagate outward toward the cladding boundary and create echoes with a period of ~21 ns as they reflect back toward the core of the fiber. These waves can be long lived—the damping time of an acoustic wave in optical fibers has been shown to be of the order of 100 ns.[3,5] The electrostrictive frequency-response function $H(f)$ includes an intrinsic contribution from the density variations that are driven locally by the optical intensity propagating in the fiber, and it includes a contribution from the acoustic echoes. The intrinsic frequency-response function[8] and the response function including damped acoustic reflections[10] are shown in Fig. 1. In principle, the acoustic reflections can be arbitrarily reduced by structural variations in the cladding diameter or by increased acoustic coupling of the fiber to the external environment (i.e., as is accomplished by the fiber's polymer coating); the intrinsic response, however, is fundamental and cannot be eliminated.

We are able to map directly the frequency response of the total nonlinear refractive index in optical fiber through cross-phase modulation measurements with a harmonically modulated pump wave. The nonlinear phase accumulated by a probe wave at wavelength λ has a time-varying component given by[8]

$$\Delta\phi^{\mathrm{NL}}(t) = \frac{2\pi}{\lambda}\frac{n_{2\mathrm{eff}}}{A_{\mathrm{eff}}} m\bar{P}L_{\mathrm{eff}}\cos(2\pi f t), \quad (1)$$

$$n_{2\mathrm{eff}} = 2\kappa_{\mathrm{eff}} n_2(\mathrm{fast}) + n_2(\mathrm{str})H_R(f), \quad (2)$$

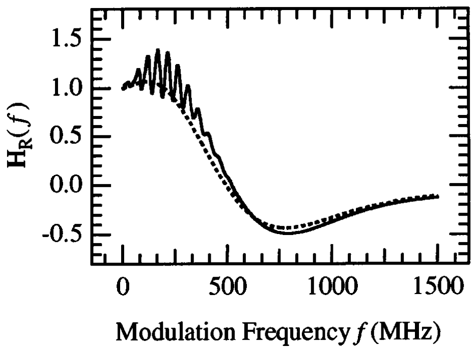

Fig. 1. Theoretical predictions of the electrostrictive frequency response for a fiber with a mode (intensity) radius of 3 μm. The solid curve includes the influence of acoustic reflections structurally damped by variations in the outer cladding diameter. The dashed curve is the intrinsic fiber response, equivalent to 100% damping of acoustic reflections.

where $\overline{P}$ is the average power in the pump, m is the modulation depth of the pump, A_{eff} is the effective area of the nonlinear interaction, L_{eff} is the effective length of the interaction region, f is the modulation frequency of the pump wave, and $H_R(f)$ is the real part of the electrostrictive response function. A numerical factor κ_{eff} is introduced to account for the appropriate tensor properties of the nonlinear interaction; κ_{eff} is equal to 2/3 when either the pump or the probe wave is unpolarized.[8] We distinguish between the Kerr nonlinearity n_2(fast) that originates from the third-order nonresonant electronic susceptibility and the Raman susceptibility, and the sluggish response n_2(str) that is due to electrostriction.

Our experimental configuration for measuring the frequency-dependent nonlinear phase accumulation is shown in Fig. 2. The pump is derived from a single-longitudinal-mode diode laser with a nominal 100–150-kHz linewidth at 1555 nm. The laser drive current is directly modulated with a radio frequency (RF) signal at a modulation frequency selected to be between 10 MHz and 1 GHz. A 50-kHz frequency modulation is also applied to the drive current to eliminate a parasitic amplitude modulation of the detected signal that arises in the homodyne detection process. The modulated pump wave is amplified by an erbium-doped fiber amplifier, and the power launched into the test fiber is varied by a precision optical attenuator; the power is kept below the threshold for stimulated Brillouin scattering in all measurements. The probe wave is derived from a similar single-longitudinal-mode diode laser operated cw at 1537 nm. This signal is split into two parts and recombined after being passed through a depolarizing delay line; with this technique the degree of polarization (DOP) of the probe is maintained below 5%. The depolarized probe wave is combined with the modulated pump wave in a wavelength-division multiplexer and launched into the test fiber.

At the output of the test fiber, the probe wave is separated from the pump by a wavelength demultiplexer, and the nonlinearity-induced sidebands of the probe wave are analyzed by use of self-delayed homodyne detection.[11,12] The 7.3-km delay in the self-delayed mixer is significantly greater than the coherence length of the probe wave. The optical carrier frequency and the sidebands mix at a fast photodiode, and the harmonics associated with this beat signal are monitored on a RF signal analyzer. For a small nonlinear phase accumulation, $\Delta\phi^{\mathrm{NL}} < 0.2$ rad, the measured power of the beat note at the pump modulation frequency f is linearly proportional to $\Delta\phi^{\mathrm{NL}}$. The response at each modulation frequency is measured as a function of the input pump power, and the effective nonlinear coefficient $\gamma(f) = 2\pi n_{2\mathrm{eff}}(f)/(\lambda A_{\mathrm{eff}})$ is calculated as the slope of $\Delta\phi^{\mathrm{NL}}$ versus the ordinate $(m\bar{P}L_{\mathrm{eff}})$. The system is fully calibrated; the modulation depth of the pump was measured as a function of frequency by a dc-coupled oscilloscope, and the detection responsivity was measured by amplitude-modulated light at the probe wavelength.

Reducing the DOP of the probe wave rather than of the pump eliminates the polarization dependences of the nonlinear interaction and the polarization dependences of the detection process. With a depolarized probe wave we verified that changing the input polarization state of the pump produces no change in the measured nonlinear phase accumulated by the probe. Depolarizing the pump is not equivalent; when the probe wave remains polarized, amplitude modulation of the probe is detected at the pump modulation frequency. We believe that this is due to nonlinear polarization evolution of the polarized probe, where amplitude modulation arises from the small DOP-dependent loss in the output devices. When the DOP of the probe wave is minimized, no sign of amplitude modulation is observable by direct detection.

We performed measurements on a selection of dispersion-shifted (zero-dispersion wavelength $\lambda_0 \approx$ 1550 nm) fibers (DSF's) and standard ($\lambda_0 \approx 1310$ nm) single-mode fibers. The experimental values of $n_{2\mathrm{eff}}(f)/A_{\mathrm{eff}}$ for one representative fiber of each type are plotted in Fig. 3. The response measured for the DSF (bottom plot of Fig. 3) shows oscillations in the intermediate-frequency region, from 200 to 700 MHz, presumably owing to acoustic echoes. These features appear to be more strongly damped for the standard single-mode fiber. We believe not that this distinction represents a fundamental difference in the electrostrictive responses of the two fiber designs but rather that the acoustic damping rates associated with the outer cladding boundaries are different for these two test fibers.

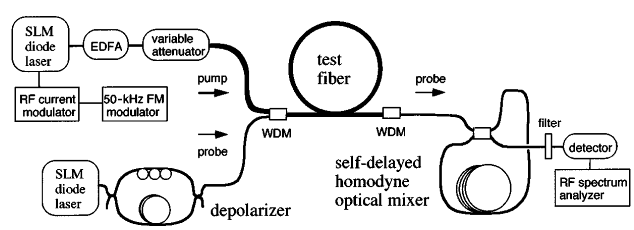

Fig. 2. Experimental configuration. SLM, single-longitudinal-mode laser; EDFA, erbium-doped fiber amplifier; WDM's; wavelength-division multiplexers.

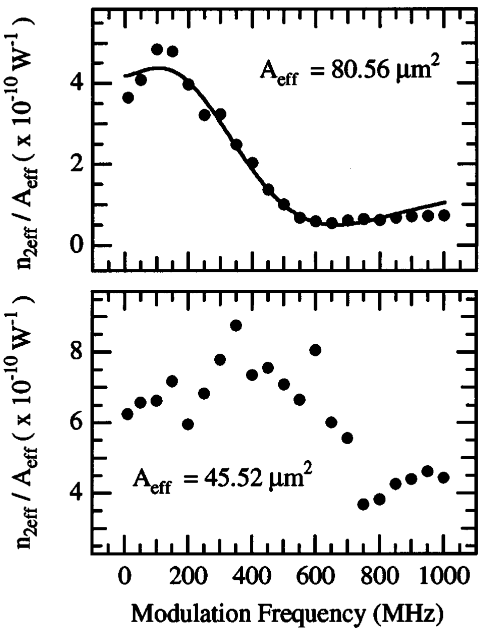

Fig. 3. Measured nonlinear coefficient $n_{2\text{eff}}(f)/A_{\text{eff}}$ versus pump modulation frequency for a standard single-mode fiber (top) and a DSF (bottom). The solid curve in the top plot is a theoretical fit to the data.

The frequency dependence of the nonlinear response indicates a strong electrostrictive contribution to the nonlinearity. For the standard single-mode fiber, the curve fit of the experimental data to a function of the form given by Eq. (2), using the response function of Eq. (4) in Ref. 8, is plotted in Fig. 3. The fit parameters indicate that the relative strength of the electrostrictive nonlinearity in relation to the fast cross-phase-modulation nonlinearity is $\xi = n_2(\text{str})/[2\kappa_{\text{eff}} n_2(\text{fast})] = 1.58$ for this fiber. For the DSF, the quality of the curve fit is insufficient to permit us to extract meaningful values of the nonlinear coefficients. However, an estimate of the relative electrostrictive nonlinearity for the DSF is obtained from the ratio R of the measured values of $n_{2\text{eff}}(f)/A_{\text{eff}}$ at 10 MHz to the values at 1 GHz; the ratio thus obtained is $R = 1.41{:}1$, suggesting a relative electrostrictive strength $\xi = (R - 1) = 0.41$ for this fiber. One obtains the relative electrostrictive contribution to the self-phase-modulation nonlinear response for polarized light propagating in a randomly birefringent fiber by multiplying these values by 3/2.[13] We note that measurements performed on a series of DSF fibers with similar construction but with effective areas spanning a 5:1 ratio all yielded ratios R in the range of 1.38:1 to 1.42:1.

These values suggest that the magnitude of the electrostrictive nonlinear coefficient $n_2(\text{str})$ is greater than that of the Kerr coefficient in Ge-doped silica optical fibers; this result is not expected based on the physical parameters that contribute to $n_2(\text{str})$.[4,8] This apparent anomaly in the strength of the electrostrictive nonlinearity may suggest that the accepted values of the physical parameters are incorrect (e.g., the value of the electrostrictive coefficient would need to be three times greater than previously[4,8] reported). However, it must be noted that the strength of the high-frequency nonlinear response measured by this cross-phase-modulation technique is unusually low. The nonlinear coefficient of the DSF fiber was previously measured by self-phase modulation of polarized light to be $n_2(\text{fast})/A_{\text{eff}} = 5.21 \times 10^{-10}\ \text{W}^{-1}$.[14] Based on this measurement, an asymptotic high-frequency value of $7.82 \times 10^{-10}\ \text{W}^{-1}$ is expected in the current cross-phase-modulation experiment,[13] compared with the value of $6.24 \times 10^{-10}\ \text{W}^{-1}$ measured here. The origin of the discrepancy between the expected strength of the electrostrictive response and the magnitude of the response measured in this experiment requires further investigation.

We thank V. Da Silva and D. Hall of Corning Incorporated for providing access to their facilities, for providing the test fibers, and for their helpful comments. E. L. Buckland (ELB) thanks A. Pilipetskii and E. Golovenchko for providing their computer code for calculating the time-dependent refractive-index change originating from the acoustic eigenmodes. ELB acknowledges support through a National Defense Science and Engineering Graduate Fellowship. This research was supported by Corning Incorporated, the sponsors of the Center for Electronic Imaging Systems of the University of Rochester, by the National Science Foundation, and by the U.S. Army Research Office.

References

1. G. P. Agrawal, *Nonlinear Fiber Optics*, 2nd ed. (Academic, Boston, Mass., 1995).
2. R. M. Shelby, M. D. Levenson, and P. W. Bayer, Phys. Rev. B **314,** 5244 (1985).
3. K. Smith and L. F. Mollenauer, Opt. Lett. **14,** 1284 (1989).
4. E. M. Dianov, A. V. Luchnikov, A. N. Pilipetskii, and A. M. Prokhorov, Appl. Phys. B **54,** 175 (1992).
5. P. D. Townsend, A. J. Alistair, P. J. Hardman, and K. J. Blow, Opt. Lett. **21,** 333 (1996).
6. P. J. Hardman, P. D. Townsend, A. J. Poustie, and K. J. Blow, Opt. Lett. **21,** 393 (1996).
7. T. Kato, Y. Suetsugu, M. Takagi, E. Sasaoka, and M. Nishimura, Opt. Lett. **20,** 988 (1995).
8. E. L. Buckland and R. W. Boyd, Opt. Lett. **21,** 1117 (1996).
9. R. W. Boyd, *Nonlinear Optics* (Academic, Boston, Mass., 1992).
10. A. N. Pilipetskii, A. V. Luchnikov, and A. M. Prokhorov, Sov. Lightwave Commun. **3,** 29 (1993).
11. T. Okoshi, K. Kikuchi, and A. Nakayama, Electron. Lett. **16,** 630 (1980).
12. M. Nazarathy, W. V. Sorin, D. M. Baney, and S. A. Newton, J. Lightwave Technol. **7,** 1083 (1989).
13. In the absence of electrostriction, one must multiply the values of n_2 obtained in this experiment by $(1/2 \times 3/2 \times 8/9 = 2/3)$ to compare to self-phase-modulation values obtained by polarized light in randomly birefringent fibers.[8]
14. A. Boskovic, S. V. Chernikov, J. R. Taylor, I. Gruner-Nielsen, and O. A. Levring, in *Conference on Lasers and Electro-Optics*, Vol. 9 of 1996 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1996), paper CMA7.