Time-Resolved Measurement of Dynamic Frequency Chirp Due to Electrostriction Mechanism in Optical Fibers

D. Le Quang, Y. Jaouën, M. Zimmerli, P. Gallion, *Senior Member, IEEE*, and J. B. Thomine

***Abstract*—The electrostrictional excitation of acoustic waves by light pulses in optical fibers results in a timing jitter in soliton transmissions which, in turn, imposes a limitation on the transmission rate in long-distance communication systems. In this letter, we report for the first time an experimental investigation of this electrostriction effect by time-domain resolution dynamic frequency shift measurement in a copropagating probe and pulse signal arrangement. The experimental results show a very good agreement with the theoretical model reported by Dianov.**

I. Introduction

ONE of the main limitations of the bit rate and transmission distance in soliton communication lines is the long-range phase-independent interaction of solitons [1]. Dianov has proposed the electrostrictional excitation of acoustic waves by the light pulses and its back influence on the soliton temporal position as a mechanism of this interaction [2]. According to this theory, an optical pulse excites, through electrostriction, an acoustic wave which propagates in a direction transverse to the fiber axis. This leads to a temporal perturbation of the fiber's effective refractive index. Then, the following optical pulses are phase modulated and change their carrier frequency. This results in an additional temporal shift of solitons.

In a recent paper, Mollenauer *et al.* have measured the jitter in pulse arrival times after a recirculating fiber loop [3]. However, the most important contribution to this timing jitter is due to the Gordon–Haus effect. The jitter arising from the electrostrictional excitation of acoustic waves becomes then a weak perturbation. In order to investigate the acoustic effect only, we propose to measure directly the refractive index changes instead of the timing jitter by using a continuous probe optical wave which copropagates with the optical pulses in a dispersion-shifted fiber.

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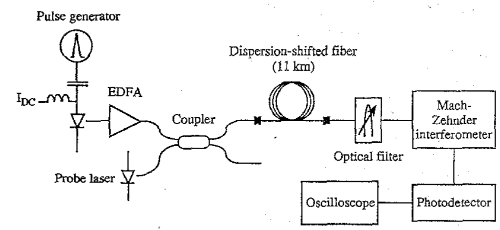

Fig. 1. Experimental setup.

II. Experimental Setup

The experimental setup is presented in Fig. 1. A 100 ps optical pulse train is generated from a gain-switched laser diode ($\lambda_s = 1547$ nm) which is then amplified up to a peak power of several watts by an EDFA amplifier. The fiber used is a 11 km dispersion-shifted single-mode fiber ($\lambda_o = 1557$ nm). The refractive index change due to the acoustic waves excited by high power optical pulses is analyzed by an optical copropagating probe source ($\lambda_p = 1555$ nm). It is mandatory to use a dispersion-shifted fiber in order to have the same group velocity for the two optical sources so that the acoustic interaction is accumulated across the fiber length. The repetition frequency of the optical pulses must be small enough such that no interference occurs between the weak acoustic response of one pulse and the strong third-order nonlinear dependences corresponding to the following pulses.

At the fiber output, an 0.5-nm-bandwidth optical Fabry-Perot filter selects only the probe signal. The 8-nm wavelength difference between λ_s and λ_p corresponds to more than a 50-dB power rejection for the pulse wavelength. The time-domain resolved frequency chirp due to the refractive index variation is analyzed with an all-fiber Mach–Zehnder interferometer [4]. A piezoelectric translator adjusts the relative phase between the two arms of the interferometer. The received optical power is detected by a 20-GHz-bandwidth PIN photodiode and sampled with a digital oscilloscope synchronized to the pulse generator. Assuming a quadrature tuning of the interferometer (i.e., $\omega_o\tau = 2\pi N \pm \pi/2$), the photocurrent $I_D(t)$ can be expressed as

$$I_D(t) = S\{P(t) + P(t-\tau) + 2\vec{X}_1\vec{X}_2 \cdot \sqrt{P(t)P(t-\tau)}\sin[\Delta\phi(t,\tau)]\}, \quad (1)$$

where S is the photodiode's sensitivity, $P(t)$ is the optical power, $\Delta\phi(t,\tau)$ the phase difference due to the differential delay time τ through the interferometer [5]. The two polarization vectors $\vec{X}_1, \vec{X}_2$ can be adjusted by polarization controllers. For a small phase difference $\Delta\phi(t,\tau)$ (i.e., $\sin\Delta\phi \approx \Delta\phi$), the dynamic frequency chirp $\Delta\nu(t)$ is given as

$$\Delta\nu(t) = \frac{1}{2\pi}\frac{\partial\phi}{\partial t} \approx \frac{I_D(t)/S - [P(t) + P(t-\tau)]}{4\pi\tau\vec{X}_1\vec{X}_2\sqrt{P(t)P(t-\tau)}}. \quad (2)$$

This experimental setup allows us to measure two types of nonlinear effects in optical fibers: Electrostriction interaction and Kerr effect.

III. Theoretical Model for the Acoustically Induced Frequency Variation

Acoustic modes can be excited by optical pulses and are described by the eigenfunctions of radial acoustic waves $f_n(r)$ [2]. An expression of acoustically induced frequency variation has been given by Dianov *et al.* [6]:

$$\Delta n(t) = -\left(\frac{\partial\varepsilon}{\partial\rho}\right)^2 \frac{\rho_o}{n^2 c}\frac{E_p}{A_{\text{eff}}^2}\sum_{n=1}^{\infty}\frac{B_n C_n}{\Omega_n} \cdot \frac{e^{-\Gamma_n t}\sin(\Omega_n t)}{1 - 2e^{-\Gamma_n T}\cos(\Omega_n T) + e^{-2\Gamma_n T}}, \quad (3)$$

where ρ_o is the nonperturbated material density, ε is the dielectric permittivity, E_p is the energy of the optical pulse, A_{eff} is the effective cross section, T is the delay time between two consecutive optical pulses, the factors $B_n = \int_0^R\int_0^{2\pi} f_n(r)\Delta_\perp(F^2(r))r\,dr\,d\varphi$ and $C_n = \int_0^R\int_0^{2\pi} f_n(r)F^2(r)r\,dr\,d\varphi$. The parameters $1/\Gamma_n$ and Ω_n are respectively the decay time and the angular frequency of the n^{th} acoustic mode. In coated fibers, the decay of the acoustic waves is due mainly to partial reflections of sound on the boundary between the fiber cladding and the surrounding polymeric medium. The eigenfrequencies Ω_n depend on the sound velocity v and the fiber cladding radius R. The function $F(r)$ describes the transverse field distribution of the optical fiber mode. With the Gaussian approximation, $F(r) = \exp(-r^2/2w^2)$ and $A_{\text{eff}} = \pi w^2$ where w corresponds to the half-width of $1/e$ intensity spot size.

The refractive index variation $\Delta n(t)$ introduces a phase shift $\Delta\Phi(t)$ for the probe wave as $\Delta\Phi(t) = (2\pi/\lambda_p)\Delta n(t)L_{\text{eff}}$, where L_{eff} is the effective length of the fiber. The accumulated frequency shift for the probe signal after the propagation in the fiber is given by

$$\Delta\nu(t) = \frac{L_{\text{eff}}}{\lambda_p}\frac{\partial\Delta n(t)}{\partial t}. \quad (4)$$

Fig. 2 represents the temporal evolution of the frequency shift with $n = 1.46, \rho_0 = 2.2$ g/cm^3, $(\rho_0\partial\varepsilon/\partial\rho) = 1.2$, $A_{\text{eff}} = 50\ \mu$m^2, $R = 62.5\ \mu$m, $T = 10\ \mu$s, $L_{\text{eff}} = 8.18$ km and $\lambda_p = 1555$ nm. In the case of Gaussian pulses, $E_p = \sqrt{\pi}P_0T_0$ where P_0 is the peak power and T_0 represents the half-width at $1/e$ intensity point (here, $P_0 = 2.9$ W and $T_0 = 50$ ps). For coated fused silica fibers, $v = 5.99 \times 10^5$ cm/s and $\Gamma_n = 3 \times 10^7$ s^{-1} [7].

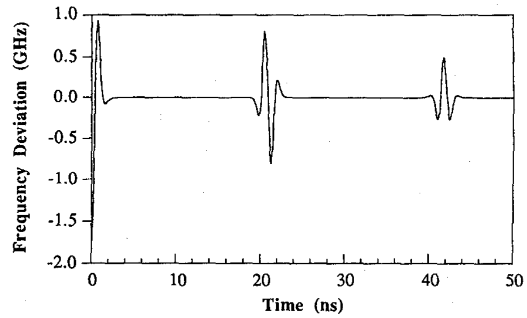

Fig. 2. Acoustically induced frequency shift according to Dianov's theoretical model.

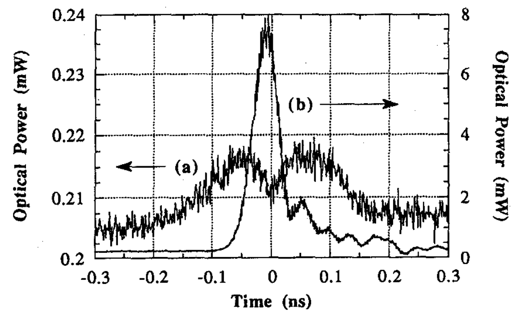

Fig. 3. Amplitude modulation of the probe power in one arm of the Mach–Zehnder interferometer with different values of the peak power P_0: (a) $P_0 = 0.3$ W; (b) $P_0 = 2.9$ W.

IV. Experimental Results and Discussions

In a first experiment, the self-phase modulation (SPM) has been evaluated for a 0.3 W peak power and has shown a very good agreement with an equivalent theoretical gaussian pulse. It is interesting to notice an amplitude variation of the probe power although the optical filter rejects the optical pulses very well. These variations are strongly dependent of the peak power of the optical pulses. A possible origin is the generation of optical pulses using supercontinuum (SC) in optical fibers [8], [9]. SC is explained as a complex nonlinear process due to the combined effects of self-phase modulation, cross-phase modulation, four-wave mixing, and stimulated Raman scattering induced by intense optical pulses. Fig. 3 shows the intensity modulation for two different optical peak powers.

The magnitude of the frequency deviation due to the acoustic interaction is three orders lower compared to the Kerr effect. But usually, it can be detected since its response time (about 1 ns) is greater than the pulse duration. In practice, a peak power of about 2.9 W introduces an SC effect and consequently a time broadening of optical pulses after the propagation. It is for this reason that the measurement of the acoustic interaction is not possible around the pulse position. To avoid this superposition of several effects, the acoustically induced frequency shift is analyzed after a round-trip time of the acoustic pulse from the fiber core to the cladding boundary and back to the core. The measured frequency variations corresponding to the two first acoustic reflections are presented in Fig. 4(a). A good agreement with the theoretical curve (Fig. 2) can be observed. The discrepancy lies in the

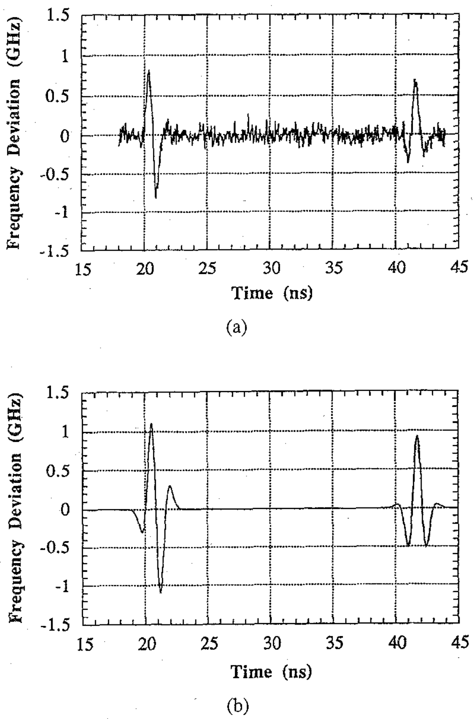

Fig. 4. Acoustically induced frequency deviation corresponding to the two first acoustic reflections: (a) Measurement; (b) Theoretical curve using $\Gamma_n = 1.5 \times 10^7\ s^{-1}$.

ratio between the magnitudes of the two spikes. This can be due to a different value of the acoustic damping coefficient for our fiber. A theoretical curve using $\Gamma_n = 1.5 \times 10^7$ s^{-1} [Fig. 4(b)] shows a quantitatively better agreement with the measurements. These measurements are obtained after an important averaging at the sampling oscilloscope output. The others reflections are not significant.

V. CONCLUSION

We have reported for the first time, to our knowledge, the time-resolved frequency deviation arising from electrostrictional excitation of acoustic waves in optical fibers. This result confirms Dianov's theoretical model and provides an evident explanation of the long-range soliton interaction already observed experimentally. In addition, a better agreement is obtained with an acoustic damping coefficient $\Gamma_n = 1.5 \times 10^7\ s^{-1}$, a value twice smaller than that used by Dianov. Finally, in order to be able to give a more accurate comparison between the theory and the experimental results, more detailed informations about the tested fiber are necessary.

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