Effect of depolarization on conjugation (inversion) quality in stimulated scattering in optical fibers

B. Ya. Zel'dovich, V. A. Krivoshchekov, A. V. Mamaev, N. A. Mel'nikov,
N. F. Pilipetskiĭ, and V. V. Shkunov
Institute of Problems of Mechanics, Academy of Sciences of the USSR

(Submitted 20 November 1985)
Pis'ma Zh. Eksp. Teor. Fiz. **43**, No. 1, 16–18 (10 January 1986)

In long optical fibers, the primary cause of a low quality of phase conjugation (wave-front inversion) in stimulated scattering is a spatial depolarization of the pump light in the fiber. The condition for suppressing polarization distortion of the inversion is the condition for a high stimulated-scattering gain for the Stokes wave over the pump depolarization length.

Light which is completely polarized as it enters a multimode optical fiber acquires a speckle and a polarization which is nonuniform in a random way over the cross section in the course of its propagation; i.e., it becomes depolarized. The interaction of oppositely directed waves in stimulated Brillouin scattering ("stimulated Mandel'shtam-Brillouin scattering"), which results in phase conjugation ("wave-front inversion"), is extremely sensitive to the spatial structure of the polarization states of the wave.[1-3] In Ref. 2 a depolarization was deliberately caused in the conjugate wave. In the present letter we report a study of the physical consequences of depolarization in a multimode fiber during phase conjugation in stimulated Brillouin scattering. These effects are also of considerable interest for applications, since phase conjugation in fibers has a rather low threshold.[4-7]

0021-3640/86/010017-05$01.00 © 1986 American Institute of Physics

The basic question in phase conjugation problems is the quality of the conjugation. In simulated scattering of spatially depolarized light, there is an independent amplification of the individual polarization components, with a conjugation of the spatial structures but a reproduction of the polarization unit vector. These components are excited from the spontaneous noise independently and thus have random amplitude-phase weights, so that the phase conjugation is only partial, and the relative extent of the conjugation fluctuates markedly.

For the experiments we selected typical multimode fibers with a light-guiding core $\approx 50\ \mu$m in diameter and an aperture angle $\theta \approx 0.2$ rad (in air). If the light beam that enters the fiber fills a significant fraction of the aperture angle, it will acquire a well-developed speckle in just the first few centimeters of the fiber, and by 10–30 cm it is completely depolarized. Since the depolarization length $l_{\rm de}$ is usually much shorter than the length of the fiber, the stimulated scattering occurs in the field of a completely depolarized pump over nearly the entire interaction length, so that the relative extent of the phase conjugation is low and fluctuates from pulse to pulse. Only in a small part of the interaction length, within a distance $l_{\rm de}$ from the entrance end of the fiber, is the depolarization of the pump only partial, and the relative extent of the phase conjugation can increase as a result of a discrimination against the nonconjugate component of the Stokes wave. If this discrimination, which is determined by the total Stokes gain in this region, is strong, the Stokes wave undergoes changes in structure to follow the pump field, so that the reflected light is conjugated and completely depolarized, and the fluctuations in the extent of conjugation are smoothed over. In the opposite case, the Stokes wave retains its spatial depolarization and the random nature of the extent of conjugation.

In an effort to determine the role played by the part of the fiber in which the pump is partially depolarized, we carried out the following experiments. We studied the degree of polarization (P_S) and the relative extent of the conjugation (H) as functions of the reflection coefficient R in multimode optical fibers of various lengths L, in order to study various stimulated-Brillouin-gain lengths $l_g \approx L/30$, and with various depolarization lengths $l_{\rm de}$, arranged by changing the angle (φ) which the pump light makes with the axis of the fiber as it enters the fiber. The pump light is the output from a pulsed single-mode Nd-glass laser with $\lambda = 1.06\ \mu$m and a pulse length $\tau_p \approx 30$ ns.

Figure 1 shows experimental points on H as a function of R in optical fibers of GLSZ glass of various lengths: 2 and 6 m. The depolarization length $l_{\rm de}$ was measured as a function of the entrance angle φ in separate experiments with short lengths of the same fiber. On the basis of the criterion of a degree of polarization $P_L = 0.1$ for a fiber with $L = 2$ m and an entrance angle $\varphi = 6 \times 10^{-2}$ we have $l_{\rm de} \approx 24$ cm, while for a fiber with $L = 6$ m and $\varphi = 8.5 \times 10^{-2}$ we have $l_{\rm de} = 18$ cm. At $L = 2$ m the relative extent of the phase conjugation reaches its maximum value quite rapidly, nearly without fluctuations, and then remains constant, within the experimental errors. In contrast, in the 6-m fiber at low values of R, the value of H is low and fluctuates wildly. Only at $R \approx 50\%$ do we find that the relative extent H reaches its maximum values, and the fluctuations in it are smoothed over.

Figure 2 shows experimental points on the degree of depolarization of the Stokes

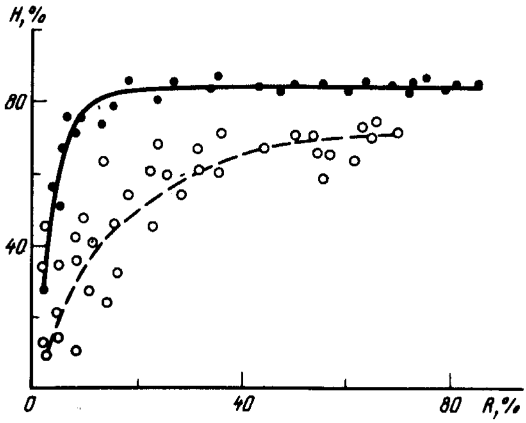

FIG. 1. The relative extent of phase conjugation, H, versus the reflection coefficient R. ●—$L = 2$ m; ○—$L = 6$ m.

wave, $1 - P_S$, as a function of R. For a short fiber, the Stokes wave is almost perfectly polarized at all reasonable values of R, while at $L = 6$ m the polarization P_S increases with increasing R from extremely low values, fluctuating markedly. At the small values of R, these fluctuations are particularly great, while they become smoothed over at high pump saturation levels, $R \sim 1$. Remarkably, we see a linear correlation between H and P_S, which tells us unambiguously that the fluctuations in the conjugation quality are caused by fluctuations in the degree of polarization of the Stokes wave and, ultimately, fluctuations in the amplitude of the seed waves which excite the various polarization components of the Stokes wave (Fig. 3).

We can estimate the degree of polarization $1 - P_S$ theoretically on the basis of the simple model in which the pump is completely polarized at $0 < z < l_{\rm de}$ $[\mathbf{E}_L(z < l_{\rm de}) = \mathbf{e}_1 E_1(\mathbf{r},z)\sqrt{2}]$, while at the point $z = l_{\rm de}$ it becomes completely depolarized: $\mathbf{E}_L(z > l_{\rm de}) = \mathbf{e}_1 E_1(\mathbf{r},z) + \mathbf{e}_2 E_2(\mathbf{r},z)$, $\langle |E_1|^2 \rangle = \langle |E_2|^2 \rangle = I_L/2$, $\langle E_1 E_2^* \rangle = 0$. At the

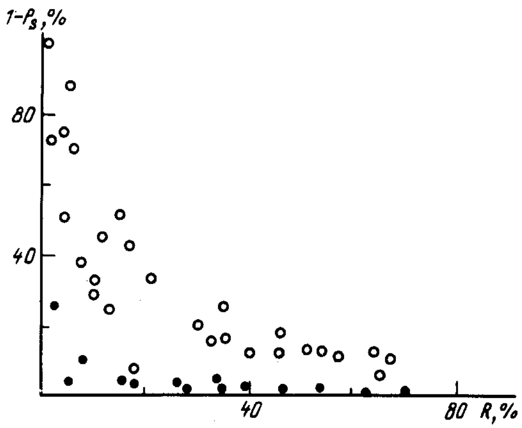

FIG. 2. The degree of depolarization of the Stokes wave, $1 - P_S$, versus the reflection coefficient R. ●—$L = 2$ m; ○—$L = 6$ m.

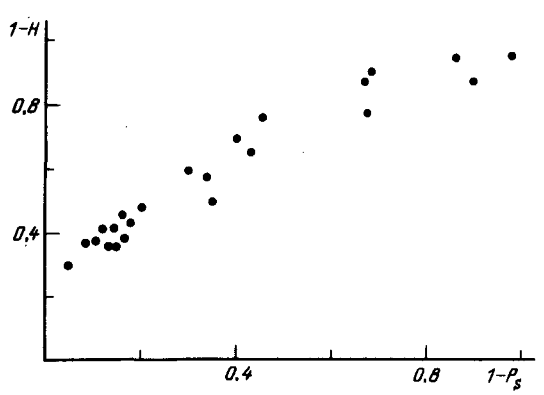

FIG. 3. Relative extent of the nonconjugation, $1-H$, versus the depolarization of the Stokes wave, $1-P_S$.

exit from the fiber ($z=0$) we then find

$$1-P_S(0)=\frac{2|\alpha_2|^2+|\alpha_3|^2}{|\alpha_2|^2+0{,}5|\alpha_3|^2(1+N_n)+|\alpha_1|^2 N_c}, \tag{1}$$

where α_1, α_2 and $\alpha_3/\sqrt{2}$ are the excitation amplitudes of the independent Stokes components $E_1^*\mathbf{e}_1$, $E_2^*\mathbf{e}_2$ and $E_1^*\mathbf{e}_2+E_2^*\mathbf{e}_1$, respectively[6]; and N_n and N_c are the gain factors for the nonconjugate and conjugate waves of polarization $\mathbf{e}_1$ in the region $0<z<l_{\text{de}}$. In the steady state, we have

$$N=I_S(0)/I_S(l_{\text{de}})=\frac{\exp(gl_{\text{de}})-R}{1-R},$$

where g is the threshold gain for the component. However, a comparison of these results with the experimental results reveals that the discrimination factors increase more rapidly with increasing R than is predicted by the steady-state theory. In a time-varying situation, with $\tau_p \sim \Gamma_{SB}^{-1}$, we have $N_c \cong \exp(15\sqrt{2}l_{\text{de}}/L)$ and $N_n \cong \exp(15 l_{\text{de}}/L)$ at the threshold. For a fiber of length $L=2$ m we find $1-P_S(0)\approx 17\%$ from (1), and for $L=6$ m we find $1-P_S(0)\approx 72\%$, in good agreement with the experimental results for $R \ll 1$. The entrance region of the fiber raises the quality of the phase conjugation of the Stokes wave only in that time interval in which the pump light is propagating through it. Consequently, the effect occurs for sufficiently long pulses, with $\tau_p > L/c$. With $L=6$ m, in our case we have $\tau_p = L/c \cong 30$ ns. Accordingly, phase conjugation of good quality is achieved only well above the threshold, where the stimulated scattering develops at the beginning of the pump pulse.

In summary, in order to achieve high-quality phase conjugation in long multimode optical fibers, one should increase the distance (l_{de}) over which the pump light retains its polarization to $\sim 1/30$ of the length of the fiber or work with a pump level well above the threshold, to provide the required degree of discrimination $g_{\text{eff}}\cdot l_{\text{de}} > 1$. For short pump pulses, with $\tau_p < L/c$, high-quality phase conjugation can be expected only at the beginning of the laser pulse, before the entire pulse has entered the fiber and has become depolarized over the entire interaction length.

[1] B. Ya. Zel'dovich and V. V. Shkunov, Zh. Eksp. Teor. Fiz. **75**, 428 (1978) [Sov. Phys. JETP **48**, 214 (1978)].

[2] V. N. Blashchuk, B. Ya. Zel'dovich, V. N. Krashcheninnikov, N. A. Mel'nikov, N. F. Pilipetskiĭ, V. V. Ragul'skiĭ, and V. V. Shkunov, Dokl. Akad. Nauk SSSR **241**, 1322 (1978) [Sov. Phys. Dokl. **241**, 588 (1978)].

[3] B. Ya. Zel'dovich, N. F. Pilipetskiĭ, and V. V. Shkunov, Obraschchenie volnovogo fronta (Phase Conjugation), Nauka, Moscow, 1985.

[4] T. T. Basiev, E. M. Dianov, A. Ya. Karasik, A. V. Luchnikov, S. B. Mirov, and A. M. Prokhorov, Pis'ma Zh. Eksp. Teor. Fiz. **36**, 85 (1982) [JETP Lett. **36**, 104 (1982)].

[5] M. P. Petrov and E. A. Kuzin, Pis'ma Zh. Tekh. Phys. **8**, 729 (1982) [Sov. Tech. Fiz. Lett **8**, 316 (1982)].

[6] V. V. Grigor'yants and V. I. Smirnov, Kvantovaya Elektron. (Moscow) **10**, 2002 (1983) [Sov. J. Quantum Electron. **13**, 1334 (1983)].

[7] A. A. Chertkov, Pis'ma Zh. Tekh. Fiz. **10**, 1416 (1984) [Sov. Tech. Phys. Lett. **10**, 598 (1984)].

Translated by Dave Parsons