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Control of the phase characteristics of Stokes waves in a Michelson interferometer with SBS mirrors

A.A. Gordeev, V.F. Efimkov, I.G. Zubarev, S.I. Mikhailov

Abstract. **It is found that, when using stimulated Brillouin scattering (SBS) mirrors (mounted in a ring Michelson interferometer) with counterfocusing, under pumping by pulses with steep (2–3 ns) leading edges and applying Freon FC-75 as an active medium, the phase difference of the Stokes waves on the semitransparent interferometer mirror obeys the dependence $\Delta\varphi = 2\Delta k\Delta l$ (Δk is the difference in the magnitudes of the pump and Stokes component wave vectors and Δl is the difference in the optical arm lengths).**

Keywords: *SBS mirrors with counterfocusing, ring Michelson interferometer, pump pulses with steep leading edges.*

This work is a continuation of the studies published about a year ago [1], where it was shown that phasing of independent laser channels occurs in a ring Michelson interferometer upon shock excitation of stimulated Brillouin scattering (SBS) in Freon FC-75 by pulses with a short leading edge ($\tau \leqslant 2-3$ ns). The interferometer was tuned to zero difference in arm lengths, in view of which phase-matched Stokes beams were reflected exactly backward into the pump channel. To use this scheme in practice, the phase difference of the Stokes beams must be set equal to π. We investigated [2] a Michelson interferometer scheme in which pump beams after a semitransparent mirror were reflected from a common SBS mirror. The phase difference of the Stokes components on the semitransparent mirror was found to obey the relation

$$\Delta\varphi = \Delta k\Delta l, \quad (1)$$

where Δk is the difference in the magnitudes of pump wave vectors $k_{\rm p}$ and Stokes component $k_{\rm S}$. We assumed relation (1) to be satisfied by using a ring Michelson interferometer with two SBS mirrors. However, even the first experiments showed that another relation is implemented in this case. The purpose of this work was to determine the correct value of the difference in the arm lengths for this interferometer in order to form the phase difference of Stokes beams equal to π.

A schematic of the experimental setup is shown in Fig. 1. A single-mode single-frequency passively Q-switched Nd:glass laser is used as an input pump radiation source. Pump radiation $I_{\rm p}$ with a wavelength $\lambda = 1.06$ μm passes through polariser (*1*) and Faraday isolator (*2*). Glass plate (*3*) reflects some part of radiation to calorimeter (*4*) to measure the pump energy and to photodiode (*5*) to measure the pump pulse shape. Semitransparent mirror (*6*) [glass wedge with an angle of 2° having a dielectric coating (reflectance $R \approx 0.5$) on one of its surfaces and an antireflection coating on the other surface] splits the beam into two parts with practically equal energies. The transmitted (arm 1) and reflected (arm 2) beams are directed by six glass prisms to cell (*7*) with an active SBS medium (Freon FC-75). The beams emerging from the cell are intersected on mirror (*8*) and reflected to be focused one into other in exactly backward directions. Thus, we used the scheme of counterfocusing [3] with dependent SBS mirrors [1]. The focal length of concave mirror (*8*) was 25 cm, and it was spaced from the cell by about 8 cm. The optical path lengths from the semitransparent mirror to the focus of mirror (*8*) (interferometer arm lengths) were $l_{1,2}$ = 208 cm ± 4 mm ($\Delta l \leqslant 0.8$ cm). Experiments were performed at pulse energies of 6–14 mJ, and the pump pulse shape was determined by the parameters of the electro-optic shutter and high-voltage discharger with laser ignition [1]. These elements were used to cut a pulse with a steep leading edge from the master oscillator pulse (which had a shape similar to Gaussian and an FWHM of ~45 ns). The total width of the cut pulse did not exceed 40 ns, and its leading edge was 2–3 ns wide [1].

The shape of the Stokes pulse formed in the focal waist of mirror (*8*) (arm 1) and propagating in the backward direction with respect to its focused pump beam was measured by photodiode (*11*). Similarly, the shape of the Stokes pulse formed in the focal waist of mirror (*8*) (arm 2) and propagating backward with respect to its focused pump beam was measured by photodiode (*10*). Stokes waves E_1 and E_2 interfere on mirror (*6*). The interference result is determined by the phase difference $\Delta\varphi$ between them. If $\Delta\varphi$ is close to zero, the waves are summed and propagate in the direction E_+, opposite to the propagation direction of the input pump $I_{\rm p}$. When radiation passes through the Faraday isolator, the plane of wave polarisation is rotated by 90°, and the radiation is reflected by polariser (*1*) to calorimeter (*12*) and photodiode (*13*). If phase difference $\Delta\varphi$ between the Stokes waves is close to π, the waves are summed and propagate in the direction E_-; this radiation is measured by calorimeter (*14*) and photodiode (*15*).

The in-phase parameter of the Stokes beams, which determines the degree of proximity of $\Delta\varphi$ to zero, is the quantity

$$\eta_+ = |E_+|^2(|E_+|^2 + |E_-|^2)^{-1},$$

A.A. Gordeev, V.F. Efimkov, S.I. Mikhailov P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; e-mail: efimkov@sci.lebedev.ru;
I.G. Zubarev P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; National Research Nuclear University 'MEPhI', Kashirskoe sh. 31, 115409 Moscow, Russia

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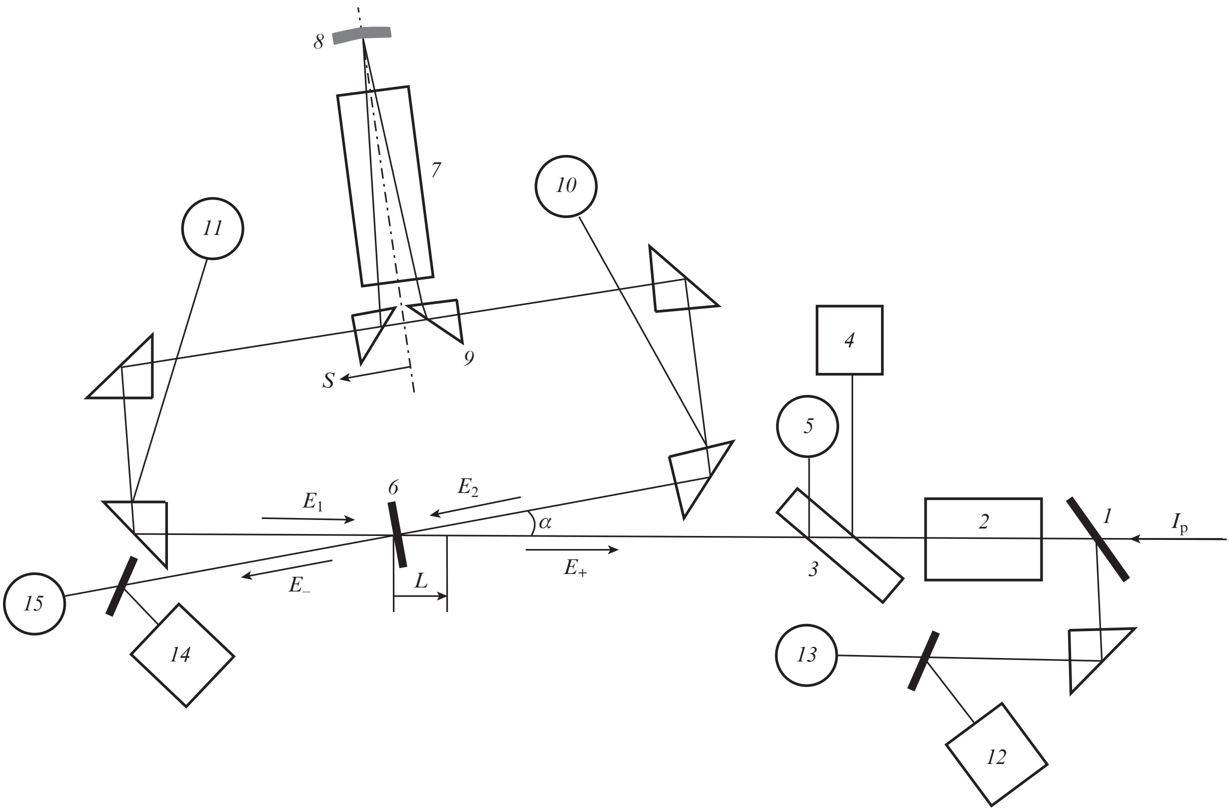

Figure 1. Schematic of the experimental setup: (*1*) polariser; (*2*) Faraday isolator with a quartz 45° plate; (*3*) glass plate; (*4*, *12*, *14*) calorimeters; (*5*, *10*, *11*, *13*, *15*) photodiodes; (*6*) semitransparent mirror; (*7*) cell with an active SBS medium; (*8*) highly reflecting concave mirror with a focal length of 250 mm; (*9*) rotary prisms.

where $|E_+|^2$ and $|E_-|^2$ are energies of the radiations measured by calorimeters (*12*) and (*14*), respectively. Here, we should note the following. To sum the radiations in two Stokes channels, one must provide the condition $\Delta\varphi = 0$ or π, depending on the summation scheme. If $\Delta\varphi = 0$, $|E_-|^2 = 0$ and $\eta_+ = 1$. If $\Delta\varphi = \pi$, $|E_+|^2 = 0$ and $\eta_+ = 0$. In the absence of phasing in channels, the division of the Stokes-wave energy on mirror (*6*) randomly changes from pulse to pulse.

Lee et al. [3] used a scheme based on independent SBS mirrors with counterfocusing and pumping by short (8–9 ns) pulses to obtain a stable phase difference between the Stokes components. The initial (i.e., after assembling the experimental scheme) phase difference was random, and the necessary $\Delta\varphi$ value was provided by microdisplacements (by several tenths of wavelength) of a concave mirror in one of the interferometer arms using piezoelectric devices. We thoroughly investigated the scheme of an interferometer with independent SBS mirrors in [1] and reliably established the existence of pulse-to-pulse instability of the phase difference between the Stokes beams interfering on a semitransparent mirror, in particular, upon shock excitation by a pump pulse with a short leading edge (about 2–3 ns). The spread of the phase difference in our experiments is due to the instability of interferometer arm lengths, which is caused by microdisplacements of interferometer elements installed on several optical benches, as well as the temperature drift, air motion, and mechanical effect of flash lamps in laser amplifiers (we used a laser Nd : glass scheme with a response rate of one pulse per several minutes).

A scheme with coupled mirrors was proposed to compensate for the instability of interferometer arm lengths (see Fig. 6 in [1]), where each pump beam was focused into the other. This scheme can be considered either as a well-known Sagnac interferometer or as an antiresonance ring [4, 5] with inserted SBS mirrors. We refer to it as a ring Michelson interferometer with SBS mirrors operating under counterfocusing conditions. The spread of the phase difference could be eliminated using only pump pulses with a short (2–3 ns) leading edge. The in-phase parameter η_+ turned out to be 0.93 ± 0.02, a value corresponding to $\Delta\varphi \approx 0$; i.e., the energies of the Stokes components E_1 and E_2 were summed along the E_+ direction. The arm optical lengths $l_{1,2}$, measured from the semitransparent mirror to the corresponding beam foci, were found to be 208 cm ± 4 mm ($\Delta l \leqslant 0.8$ cm).

Some practical applications call for the summation of the energy of Stokes components E_1 and E_2 along the E_- direction (see Fig. 1). To this end, one must set $\Delta\varphi = \pi$. In addition, the dependence of $\Delta\varphi$ on $\Delta l = l_1 - l_2$ is of great importance for this interferometric scheme. To gain this information, one must change the Δl value. This was done by changing the length of one of the interferometer arms in [2]. Under our experimental conditions, a simpler way was to shift semitransparent mirror (*6*) (see Fig. 1). In view of the smallness of the reflection angle ($\alpha \approx 4.3°$), one can assume that the length of arm 1 increases and the length of arm 2 decreases by the same value. Shifting the semitransparent mirror by a distance L from the point where $l_1 \approx l_2$, a relation corresponding to a close-to-zero phase difference [2], we arrive at

$$\Delta l \approx 2L, \ \Delta\varphi = \Delta k 2L. \tag{2}$$

It follows from (2) that the phase difference $\Delta\varphi = 2\pi$ corresponds to the length $L_{2\pi}$; this length is found from the relation $2\pi = \Delta k 2L_{2\pi} = 2\pi\Delta\nu 2L_{2\pi}$, where $\Delta\nu = 0.045$ cm^{-1} is the Stokes shift for Freon FC-75 at the Nd : glass laser wavelength [1]. Hence, we have

$$L_{2\pi} = (2\Delta\nu)^{-1} \approx 11.1 \text{ cm}. \quad (3)$$

However, the length $L_{2\pi}$ in our experiments turned out to be smaller by half, i.e., equal to 5.6 cm, and the in-phase parameter was $\eta_+ \approx 0.91 \pm 0.04$. With a decrease in the shift by half ($L \approx 2.8$ cm), the phase difference turned out to be close to π, because the in-phase parameter was $\eta_+ \approx 0.1 \pm 0.04$ in this case.

Obviously, to study the dependence of $\Delta\varphi$ on Δl, one must measure $\Delta\varphi$, changing Δl in a certain range (as this was done in [2]). The corresponding measurements were performed with the system presented in Fig. 1. Semitransparent mirror (*6*) was returned to the starting position ($L = 0$), and Δl was changed by shifting an optical rail, on which mirror (*8*), cell (*7*), and two rotational prisms oriented perpendicular to the rail (cell) axis were installed. Figure 2 shows an experimental dependence of the in-phase parameter η_+ on Δl, where squares are measured η_+ values and the solid line is the approximating function

$$f(\Delta l) = 0.51 + 0.48\sin(2\Delta k\Delta l + 1.494), \quad (4)$$

the corresponding parameters of which were calculated using the <sinfit> function of the Mathcad 15 package. The change in the difference in the optical interferometer arm lengths is $\Delta l = 2S$, where S is the displacement of the optical rail on which the SBS mirror is mounted.

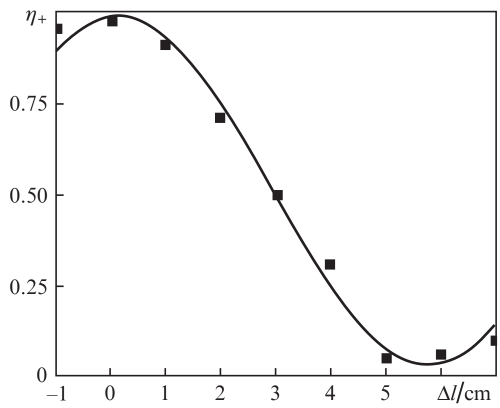

Figure 2. Dependence of the in-phase parameter η_+ on the path difference Δl: (squares) the measured values and (solid line) the approximating sinusoid.

These results are in seeming contradiction with formula (1) reported in [2]. However, there is a fundamental difference between these studies. In [2], the phase conjugation mirror was switched on simultaneously for both pump beams, independent of the Δl value. In the case under consideration, both mirrors are switched on simultaneously only at $\Delta l = 0$. Therefore, the phase difference $\Delta\varphi$ consists of two parts: spatial component $\Delta\varphi_{sp} = \Delta k\Delta l$ and temporal component $\Delta\varphi_t = \Delta\omega\Delta\tau$, where $\Delta\omega$ is the Brillouin frequency shift and $\Delta\tau = \Delta l/c$ is the switch-on delay of one SBS mirror with respect to the other. Then, $\Delta\varphi = \Delta\varphi_{sp} + \Delta\varphi_t = 2\Delta k\Delta l$, in correspondence with our experimental results.

Thus, it was shown that the phase difference of Stokes waves obeys the dependence $\Delta\varphi = 2\Delta k\Delta l$ under our experimental conditions, which include the use of SBS mirrors with counterfocusing, mounted in a ring Michelson interferometer (due to which stable phasing of Stokes waves is provided); pumping by pulses with a steep (2–3 ns) leading edge; and application of Freon FC-75 as an as active medium. Note also that, as was indicated in [6], the mode of absolute instability of counterpropagating pump waves occurred in our experiment. In this case, the Δk value may differ from those for the exact resonance. This question must be considered separately; it will be the subject of our next study.

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