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Investigations on coherence of stimulated Brillouin scattering excited by a single-mode-pulsed laser

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Abstract We experimentally studied the temporal coherence of stimulated Brillouin scattering (SBS) excited by a single-longitude-mode laser. We found that the temporal coherence of SBS is variable but not fixed. In a certain range above the threshold pump energy in which the pulse of the Stokes component is Fourier limited, the coherence length is considerably long, although the temporal coherence decreases with increasing pulse compression rate. If the Fourier transform condition is not satisfied for the pulse of the Stokes component, the temporal coherence decreases rapidly, and the coherence length is much shorter.

1 Introduction

Stimulated Brillouin scattering (SBS) has been widely studied [1–3]. Among its characteristics studied in detail are phase conjugation [4–6], pulse width compression [7], amplification [8, 9] and slow-light effect induced by SBS [10, 11]. Recently, the line width compression of SBS has been studied experimentally [12]. SBS coherence is an important and fundamental property in optics. Some measurement of the SBS coherence length in fiber has been done using a CW laser [13], in which the coherence length was considered to be constant. However, SBS excited by a CW laser is obviously different from that excited by a pulsed laser. On the other hand, SBS temporal coherence has not yet been studied in detail. Bespalov et al. discussed the spatial coherence of SBS, but, they did not give the variable regulation of the coherence of the Stokes component in SBS [14]. Actually, some complex relationship between pulse duration and the temporal coherence should be concerned. In fact, the phenomena of phase conjugation, pulse width compression, amplification and line width compression are all related to SBS coherence. Therefore, revealing the details of coherence will lead to deeper understanding of SBS. In our recent work [12], we found that the coherence of SBS may be complicated but not invariant as constant, which makes studies of coherence more necessary. Our present work reveals that the coherence of SBS is not a constant and is not even Fourier limited. This investigation (result) is significant for the fundamental research in SBS.

2 Experiment

The key factor in determining the temporal coherence is the coherence length. Therefore, we measured the coherence length first. Figure 1 shows schematically the set-up geometry. The material used was distilled water. The laser fired pulses into the water cell to excite SBS after passing through a quarter-wave plate. The backscattered SBS signal passed through the quarter-wave plate again, and was reflected by the polarization beam splitter (PBS). Then, the SBS signal went into a Michelson interferometer (MI) and formed equal-inclination interference. The coherence length of the SBS pulse was measured by translating one arm (mirror 2 in Fig. 1) of the MI. In our experiments, we used an injection-seeded Q-switched pulsed Nd: YAG laser (Contimuum Powerlite Precision II 8000) running at

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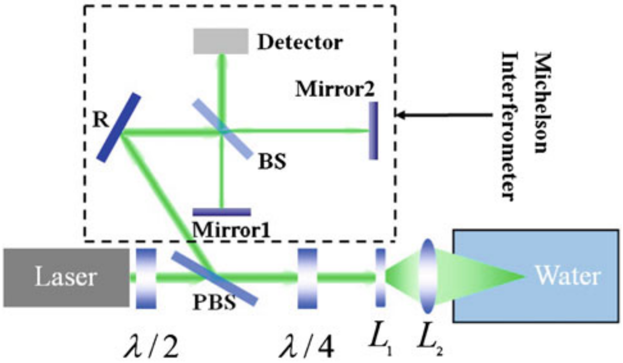


Fig. 1 Schematic of experimental set-up. The PBS is a polarization beam splitter, L is the lens ($f = 300$ mm), ($\lambda/2$) is the half-wave plate and ($\lambda/4$) is the quarter-wave plate. The detectors are an ICCD and a digital camera

532 nm to excite SBS. Its working conditions were a line width of 110 MHz, pulse duration of 8 ns, pulse energy of 1–3 mJ and repetition rate of 10 Hz.

3 Experimental results and discussions

It has been reported that the compression of the pulse duration of Stokes component and the compression of the line width are related [12], and that the pulse will be Fourier limited, i.e., they satisfy Fourier transform (FT) with each other if the temporal profile of the Stokes component of SBS is not distorted. Figure 2 shows the temporal profile of the pulse of the laser used, and the temporal profile of the compressed Stokes component, when the pumping power is controlled in the range in which the temporal of the Stokes component remains undistorted. Figure 3 shows the FT of the envelope of the laser pulse and stokes component of SBS as shown in Fig. 2a and b respectively. The FT was carried out by FFT using the data recorded by the oscilloscope. The zero frequency at the center of (a) and (b) corresponds to the central frequency of the laser and the Stokes component, respectively. The oscilloscope used was an Agilent model DSO 7104A with a bandwidth of 1 GHz. The detector used was an Electro-Optics Technology model ET 2000 with a rising time of 200 ps.

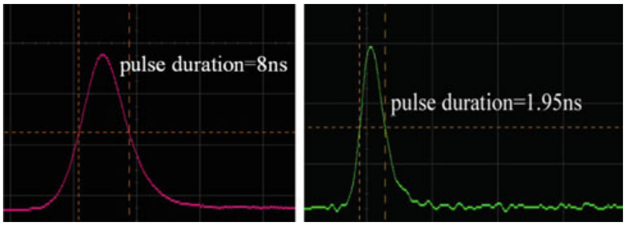


Fig. 2 Measured temporal profile of the laser pulse (*left*) and the compressed Stokes component (*right*)

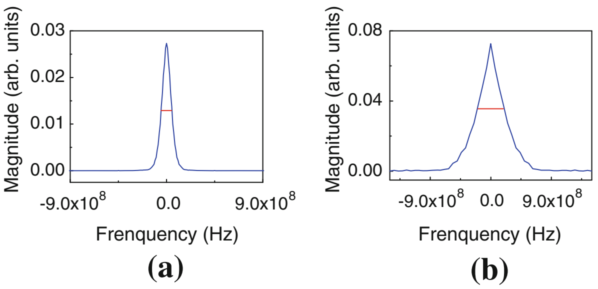


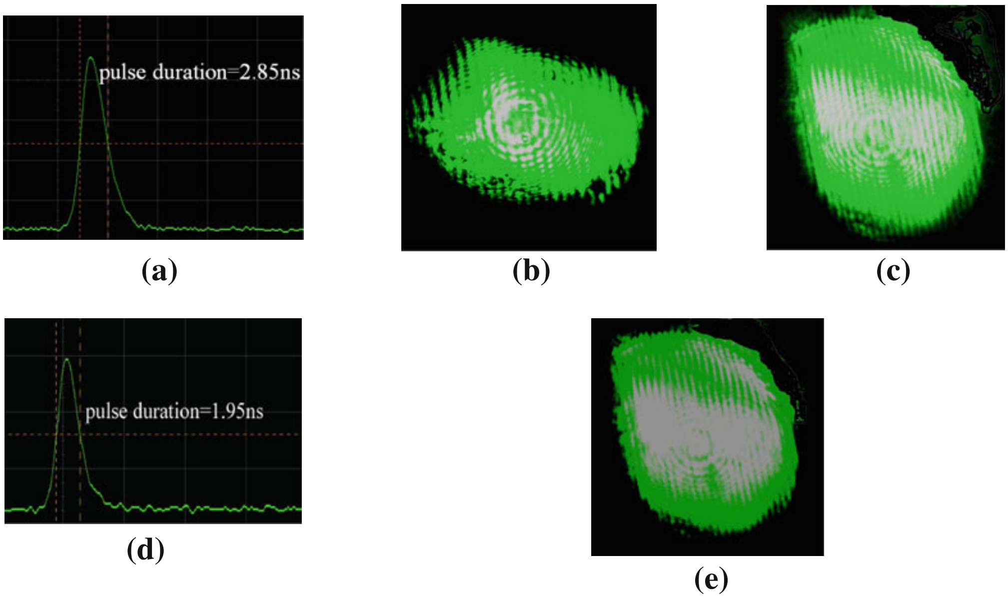
Fig. 3 Fourier transform of the envelopes of laser pulse and stokes component of SBS. **a** Laser pulse of 8 ns. Line width: 110 MHz. **b** Stokes component of 1.95 ns. Line width: 398 MHz

Figure 4 shows the measured interference images under different MI path differences with the Stokes component pulse durations of 2.85 and 1.95 ns. It can be seen that the visibility of the interference fringe under the Stokes component pulse duration of 1.95 ns with a 0.6-m path difference is lower than that of a 0.6-m path difference for a 2.85 ns pulse. During experiments, the image was recorded simultaneously by an intensified CCD (ICCD) for calculating the visibility of the fringes and a digital camera for taking color photos.

The fringe visibility is determined by the maximum and the minimum intensity recorded by the ICCD. In our experiments, the two values are obtained by the average of each whole bright circle and each whole dark circle. Definitely, the visibility has certain error. In our experiments, the error are mainly induced by the pulse energy influence of the laser output and the system noise (including the shot noise of the ICCD used). These are random noise. Although they are uncontrollable, they should not influence the variable regulation of the coherence length.

Figure 5 gives the visibility of the interference fringes under different path differences for a fixed Stokes component pulse duration of 2.85 ns. We see that the visibility of the interference fringes decreases as the path difference increases. However, the results show that for the SBS excited by a single-mode-pulsed laser, the coherence length is considerably long with a value larger than 1 m. The relationship between the fringe visibility and the path difference of MI for different Stokes pulse durations is similar to Fig. 5.

It should be pointed out that, the above discussions are all in the condition that the FT between the pulse duration and the line width is satisfied. In this case, there is only a single wave train in one pulse envelope. It makes that the measured result of the MI path difference (coherence length) is in consistence with the measured line width through FT. However, if the FT condition is not satisfied, several wave trains may exist in one pulse envelope. It will result in



(a) (b) (c)

(d) (e)

Fig. 4 Measured interference images under different path differences formed by SBS with different pulse durations of 2.85 ns and 1.95 ns. **a** Temporal profile of the compressed SBS pulse with 2.85 ns. **b** Interference images under 0.6 m path difference. **c** Interference images under 1 m path difference. **d** Temporal profile of the compressed SBS pulse with 1.95 ns. **e** Interference images under 0.6 m path difference

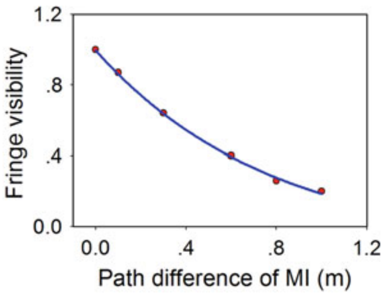


Fig. 5 Visibility of interference fringes under different path differences for a fixed Stokes component pulse duration of 2.85 ns

disagreement between the measured result of the MI path difference and the measured line width through FT.

Figure 6 shows the FT results of distorted temporal profiles of the Stokes component excited by stronger pump beam. It can be seen that the pulse of the Stokes component is highly compressed, and the visibility of interference fringes become worse even under the shorter path difference of MI. It is reasonable because a shorter pulse duration must correspond to a shorter coherence length. However, the line widths of the FT spectra in Fig. 6b and e seem even narrower than that of the laser shown in Fig. 3. It can be understood that the FT condition is not satisfied because there are more than one wave train in a single pulse envelope. In this case, the narrow line width by FT does not reflect the actual coherence length which should only be determined by the path difference of MI.

It should be mentioned that the pulse duration of Stokes component can be controlled by changing the pulse energy, the focal length or the temperature of the material [12]. However, the condition under which the SBS pulse is not Fourier limited can only be achieved by increasing the pump energy.

Figure 7 gives the fringe visibility under different pulse durations of Stokes component for a fixed MI path difference of 0.3 m. It is obvious that the fringe visibility increases with the increase of the Stokes pulse duration no mater the FT condition is satisfied or not.

4 Analysis

The temporal coherence can be analyzed as follows. For a MI, the interference can be expressed by a self-correlation function [15, 16],

$$\Gamma(\tau) = \langle u(t+\tau)u^*(t)\rangle, \tag{1}$$

where, $u(t)$ is the optical field and $\langle\rangle$ represents the operation of self-correlation. The complex degree of coherence can then be defined as

$$\gamma(\tau) = \frac{\Gamma(\tau)}{\Gamma(0)} \tag{2}$$

Further, deduction shows that the visibility of the interference fringe of a MI is

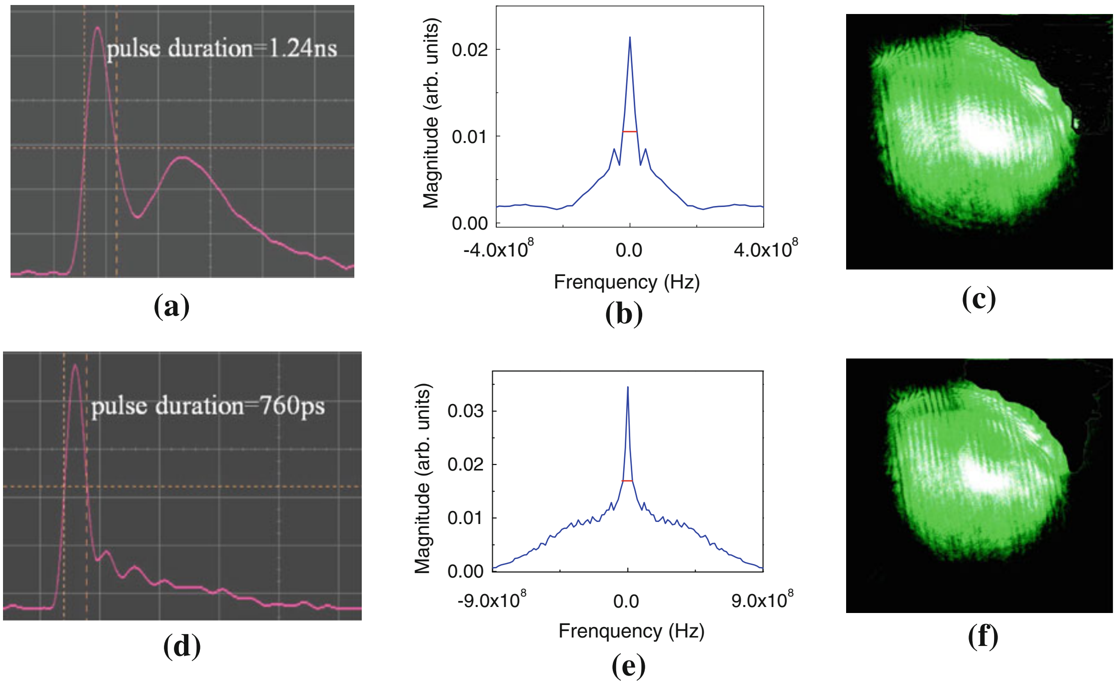


Fig. 6 Measurement for the case in which the SBS pulse is not Fourier limited. **a** Temporal profile of compressed SBS pulse (1.24 ns width). **b** The spectrum by FFT FWHM: 48 MHz. **c** Interference image under path different of 0.3 m. **d** Temporal profile of compressed SBS pulse (760 ps width). **e** The spectrum by FFT FWHM:84 MHz. **f** Interference image under path different of 0.3 m

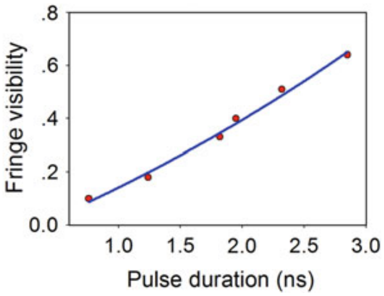


Fig. 7 Visibility of interference fringes under different pulse durations of Stokes component for a fixed MI path difference of 0.3 m

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{2k_1k_2}{k_1^2 + k_2^2}\gamma(\tau = {}^{2h}\!/_{c}), \tag{3}$$

where k_1 and k_2 are the transmission coefficients of the two arms in the MI, and h is the path difference of the two arms. We chose 1:1 as the ratio of the beam splitter of the MI, so we have $k_1 = k_2$. Letting $k_1 = k_2 = k$, Eq. (3) becomes

$$V = \gamma(\tau = {}^{2h}\!/_{c}). \tag{4}$$

Based on the measurements, Table 1 gives the visibility and complex degree of coherence.

From Table 1, we see that the higher the compression ratio of the SBS pulse the lower the complex degree of coherence. The SBS coherence length becomes obviously shorter as the pulse duration decreases after compression. This means that better temporal coherence and higher pulse duration compression cannot be obtained simultaneously. In General, the complex degree of coherence and the power spectral density are a FT pair, in this case, the measurement of coherence can be carried out by measuring the line width through FT of pulse duration of Stokes component. However, for a highly compressed Stokes component, the

Table 1 Complex degree of coherence for different pulse durations of Stokes components

Pulse duration of Stokes component (ns)	Path difference of MI (m)	Fringe visibility of interference	Complex degree of coherence γ
2.85	0	1.0	$\gamma = 1.0$
	0.1	0.87	$\gamma = 0.87$
	0.3	0.64	$\gamma = 0.64$
	0.6	0.4	$\gamma = 0.4$
	0.8	0.26	$\gamma = 0.26$
	1.0	0.2	$\gamma = 0.2$
2.32	0.3	0.51	$\gamma = 0.51$
1.95	0.3	0.4	$\gamma = 0.4$
1.82	0.3	0.33	$\gamma = 0.33$
1.24	0.3	0.18	$\gamma = 0.18$
0.76	0.3	0.1	$\gamma = 0.1$

complex degree of coherence and the power spectral density are no longer related by FT.

5 Conclusion

The temporal coherence of the Stokes component in SBS is not a fixed value, it is dependent on the compression ratio of Stokes component pulse duration. When Fourier transform between the pulse duration and the line width is satisfied, the measured result of the coherence length will be in consistence with the measured line width through FT. However, when the pulse after compression is distorted, Fourier limit will be broken down, the line width by FT does not reflect the actual coherence length which should be determined by the path difference of MI.

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