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Real time measurement of the attenuation coefficient of water in open ocean based on stimulated Brillouin scattering

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ABSTRACT A new method for measuring the attenuation coefficient of seawater in real time is suggested based on stimulated Brillouin scattering. The measurement can be achieved through detecting the intensity of back scattered stimulated Brillouin scattering and the intensity of the laser beam.

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1 Introduction

The attenuation coefficient of seawater is an important factor to the lidar system for remote sensing of the ocean. Generally, the attenuation of light in water includes two parts: absorption and scattering. It can be expressed as $\alpha = a + b$, where a is absorption, b is scattering. This is a linear relationship. However, when the laser used is powerful enough, stimulated scattering may happen, which will cause nonlinearity of the attenuation [1, 2]. For expressing this complicated relation, $\alpha = a + b$ can be rewritten as $\gamma = \alpha + \beta$, where α represents the linear part and β represents the nonlinear part of the total attenuation respectively. Since stimulated Rayleigh-wing scattering [3, 4] and stimulated thermal scattering [4] can be excluded due to their special properties, and since the threshold value of the stimulated Raman scattering is much higher than that of the stimulated Brillouin scattering (SBS) [2, 5], the scattering happened in water could only be SBS when the pulse energy of the laser is controlled in certain range.

The nonlinear attenuation is not independent of the linear attenuation, they are closely related. Scientists are mostly concerned with linear attenuation [6–11], because it is related directly to the turbidity of the seawater. Several kinds of instruments were designed to measure the parameters of the seawater including the attenuation coefficient. These instruments cannot make real time measurements while they are all working with direct contact to the water. If a method or an instrument can be developed that does not touch the water, it would be very helpful for the use of lidar systems for remote sensing of the ocean.

Recently, a preliminary work on the relationship between the nonlinear and linear attenuations was carried out in our laboratory. It shows that through measuring the intensity of SBS [12–14] in backward direction, the linear attenuation coefficient can be obtained easily. It is simple and practical, and is reported as follows.

2 Theoretical considerations

For steady state SBS in materials with absorption, the coupled wave equations are [15]

$$\frac{\partial}{\partial z} I_{\mathrm{P}} = -g_{\mathrm{B}} I_{\mathrm{P}} I_{\mathrm{s}} - \alpha I_{\mathrm{P}} \tag{1}$$

$$\frac{\partial}{\partial z} I_{\mathrm{s}} = -g_{\mathrm{B}} I_{\mathrm{P}} I_{\mathrm{s}} + \alpha I_{\mathrm{s}} , \tag{2}$$

where I_{P} and I_{s} are the intensities of the laser beam and SBS respectively, g_{B} is the gain of SBS. If the intensity of the pump beam is not very strong, (1) can be simplified as

$$\frac{\mathrm{d} I_{\mathrm{P}}}{\mathrm{d} z} = -\alpha I_{\mathrm{P}} . \tag{3}$$

Solving (2) and (3), we have

$$I_{\mathrm{s}}(z) = I_{\mathrm{s}}(l) \exp\left[g_{\mathrm{B}} I_{\mathrm{P}}(0)(\mathrm{e}^{-\alpha z} - \mathrm{e}^{-\alpha l})/\alpha - \alpha(l - z)\right] , \quad (z < l) , \tag{4}$$

where $I_{\mathrm{P}}(0)$ is the intensity when the laser beam just enters the water, $I_{\mathrm{s}}(l)$ is the initial intensity of SBS at depth l where SBS just happens in water, and $I_{\mathrm{s}}(z)$ is the intensity of SBS at an arbitrary depth. From (4), the linear attenuation coefficient α can be determined by measuring $I_{\mathrm{P}}(0)$ and $I_{\mathrm{s}}(0)$, here, $I_{\mathrm{s}}(0)$ is the backward scattered intensity of SBS when it just leaves the water. The physical mechanism is that the threshold value and the gain of the water are closely related to the linear attenuation of the water.

3 Experiments

3.1 *Optical layout*

Figure 1 shows schematically the set-up geometry for measuring the linear attenuation coefficient of water. The laser system used is an injection seeded pulsed Nd:YAG

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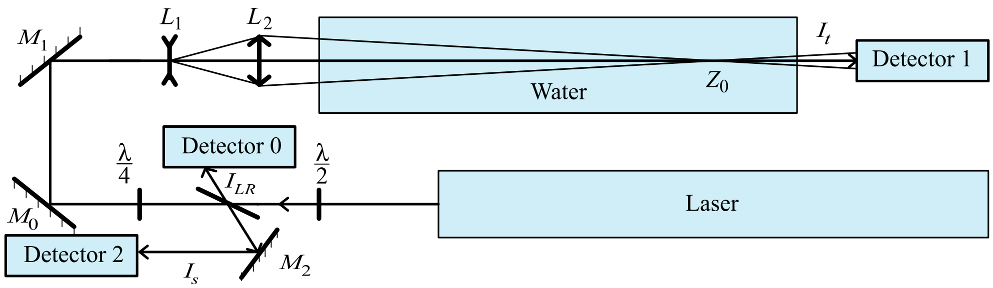

FIGURE 1 Optical layout of experiments for measuring the linear attenuation coefficient of water. BS is a polarizing coupler, M is a mirror, L_1 and L_2 are lenses

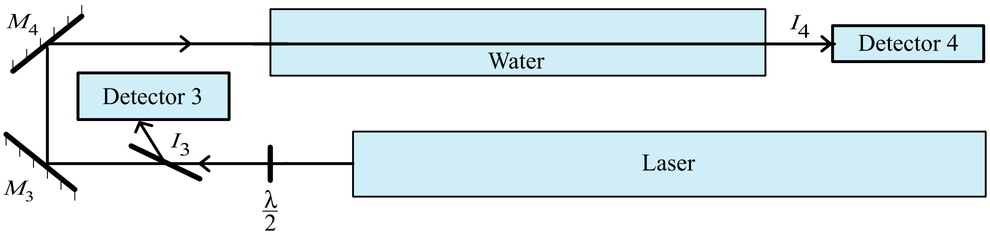

FIGURE 2 Optical layout of experiments for calibrating the linear attenuation coefficient of water. BS is a polarizing coupler, M is a mirror

laser (Continuum Powerlite Precision Plus) with line width of 90 MHz and 30 GHz when the seeder is switched on and off, respectively, its pulse width is 8 ns and its repetition rate is 10 Hz. The wavelength used was 532 nm after frequency doubling. The maximum output energy is 1.6 J per pulse. In the experiments, measurements were made under different pulse energies. In order to keep the output characteristics of the laser unchanged, the pulse energy of the laser was adjusted through changing the time delay between the oscillator and the amplifier, and the time delay was controlled by a DG 535 digital delay/pulse generator. The detectors used were power meters (Coherent FIELDMATE, MOLECTRON PM500A and Newport 1835-C, respectively). The length of the water cell used was 2 m.

A narrow line width laser was used in Fig. 1. The polarization of the output laser beam is vertical, after the beam passes through the half wave plate it becomes horizontal. Most of the energy of the laser beam with horizontal polarization can transmit the polarizing coupler BS. The remaining small part of the energy of the laser beam is reflected by the BS and detected by detector 0 as I_{LR}. The transmitted intensity I_P of the BS can be determined by calibrating the input energy from the laser pulse with the reflected energy I_{LR} by the BS. The transmitted beam with horizontal polarization becomes circularly polarized after passing through the quarter wave plate, and then is reflected by M_0. This reflected beam is reflected again by M_1, and passes through lenses L_1 and L_2, it is then focused to a certain depth in the water cell. In our work, the depth is 1.7 m from the front surface of the water so that steady state SBS will occur. The backward scattered light of SBS (the Stokes component) will become vertically polarized after passing through the quarter wave plate, then it will be mostly reflected by the BS, and can be detected by detector 2 as I_s. The light beam penetrating the water cell is detected by detector 1 as I_t.

3.2 *Measurement of linear attenuation coefficient*

Using the layout shown in Fig. 1, the SBS intensity I_s can be obtained. Since the relationship between I_s and α should be known for determining the linear attenuation coefficient α, calibrations for water with different values of α should be done in advance. For this purpose, set-up geometry using a wide line width laser shown Fig. 2 was used [16]. The polarization of the output laser beam is vertical, after the beam passes through the half wave plate it becomes horizontal. Most of the energy of the laser beam with horizontal polarization can be transmitted through the polarizing coupler BS. A small percentage of the energy of the laser beam will be reflected by BS and detected by detector 3 as I_3. The beam reflected by M_3 is reflected by M_4 and goes into the water cell, the light beam penetrating the water cell is detected by detector 4 as I_4. First, the laser beam passes through the cell without any water. The transmission of the BS is k_0, the attenuation of the mirrors M_3 and M_4 is k_1, the attenuation caused by the front and rear glasses of the water cell is k_2, in the case of normal incidence, the transmission through the interfaces between the air and the glass (and the glass and the air) is T_1. Then the transmitted intensity of the empty cell can be expressed as

$$I_4 = I_3 k_0 k_1 k_2^2 T_1^4 \,. \tag{5}$$

Then, keeping the set-up geometry unchanged and filling water into the cell, the intensities detected by detectors 3 and 4 are recorded again as I'_3 and I'_4 respectively, let the transmission of the glass to water (and water to glass) interfaces be T_2, L be the length of the cell, the intensity of the light penetrated the cell filled with water can be expressed

$$I'_4 = I'_3 k_0 k_1 k_2^2 T_1^2 T_2^2 \mathrm{e}^{-\alpha L} \,. \tag{6}$$

At normal incidence, the value of T_1 and T_2 can be calculated by the Fresnel equation $T = 4n_1 n_2 (n_1 + n_2)^2$. Let the refractive index of the glass be 1.499 and the refractive index of the water be 1.333 [17], and assuming that the attenuation of light in the air before the beam is incident on the cell is 10^{-3}, the average attenuation coefficient of light in the water can be obtained through (1) and (2), and we have

$$\alpha = -\frac{1}{L}\ln\left(\frac{I_2'/I_1'}{I_2/I_1}\times 0.927388\right). \quad (7)$$

Water with different turbidities should be measured in the laboratory in advance to obtain their linear attenuation coefficients. These values of α can be used as calibrations.

3.3 *Determination of α*

Assuming the total attenuation of the quarter wave plate, M_0, M_1, L_1 and L_2 in Fig. 1 be k_1', the attenuation caused by the front and rear glasses of the water cell is k_2'. And let the laser beam be incident on the surface of the water cell with a tiny angle so that the reflected beam from the cell surface will not propagate in the same direction as the light of the SBS, thus, its influence can be excluded. In this case, the transmission of the air to the glass and the glass to the air interfaces is T_1', and the transmission of the glass to water and water to glass interfaces is T_2' .Therefore, the intensity of the laser beam at a position z in the water cell ($z < l$) will be

$$I_P(z) = I_{LR}k_0k_1'k_2'T_1'T_2'e^{-\alpha z}. \quad (8)$$

The SBS occurs at $l = 1.7$ m where the laser beam is focused to, and its intensity is

$$I_s(l) = I_P(l) - I_t(l)\ldots\text{or}\ldots I_s(l) = \eta I_P(l), \quad (9)$$

where I_t is the residual intensity of the laser beam after exciting SBS (η is efficiency of SBS). From (4), we have

$$I_s(0) = I_s(l)\exp\left[g_B I_P(0)(1-e^{-\alpha l})/\alpha - \alpha l\right]. \quad (10)$$

The intensity I_s detected by detector 2 is

$$I_s = I_s(0)k_0k_1'k_2'T_1'T_2' \quad (11)$$

let $K = k_0k_1'k_2'T_1'T_2'$, which is a constant. Therefore, the relationship between I_P, I_s and α can be obtained by

$$I_s = \eta K I_P(0)\exp(g_B I_P(0)(1-e^{-\alpha l})/\alpha - 2\alpha l). \quad (12)$$

By doing Taylor expansion and keeping only the first two orders, we have

$$\alpha = \frac{g_B I_P(0)}{2l^2} - \frac{1}{2l}\ln\left(\frac{I_s}{\eta K I_P(0)}\right). \quad (13)$$

It can be seen that the linear attenuation coefficient α can be determined by measuring the intensity of the backward scattered SBS and the intensity of the output laser beam.

3.4 *Calibration*

In practical applications, a laser with fixed pulse energy will be used. In order to determine the unknown linear attenuation coefficient α of the open ocean, a database in which a great deal of data reflecting the relationship of (13) should be included. Through lots of experiments by using Figs. 1 and 2, the intensity of SBS in the water with different linear attenuation coefficients can be obtained. In this way, the database will be built and can be used for calibration.

4 Experimental results and discussions

Figure 3 is the scattered spectrum occurring in water when the pulse energy is higher than the laser-intensity threshold value of SBS in water. It can be seen clearly that it is a typical spectrum of SBS. There is only the Stokes line and its intensity is much higher than that of the Rayleigh line. This spectrum was generated by a F-P etalon with a free spectral range of 19.6 GHz, and recorded by a ICCD camera (PI-MAX 2 1003 of Princeton Instruments).

Figure 4 gives the relationship between the pulse energy of SBS and the pulse energy of the output laser beam for two water samples of $\alpha = 0.237$ and $\alpha = 0.316$. The pulse energy of SBS was detected by detector 2, and the pulse energy of the output laser beam was monitored by detector 0. Each piece of data in the figure is the average of six measured data (with error bars). It shows that the linear attenuation coefficient of water can only be determined by this relation. Figure 5 gives the relationship between the pulse energy of SBS and the pulse energy of the output laser beam for water samples with eight different attenuation coefficients. Every curve is the fitted result of six groups of measured data. These curves are actually the calibration results in terms of the measurements with the layout shown in Fig. 1. These eight attenuation coefficients cover most actual cases of the seawater in the open ocean. It can be seen that the slope of the curve will increase with the decrease of the attenuation coefficient. The reason is

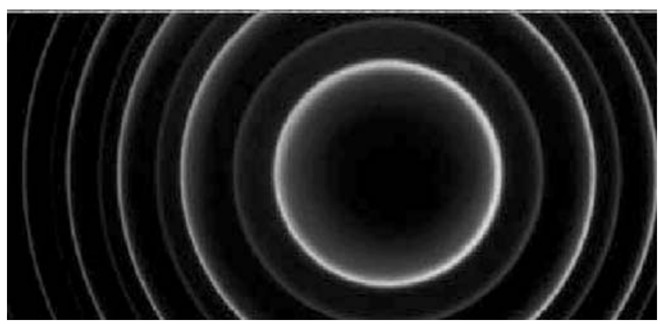

FIGURE 3 Spectrum of stimulated Brillouin scattering when the pulse energy of the laser beam is higher than the threshold value

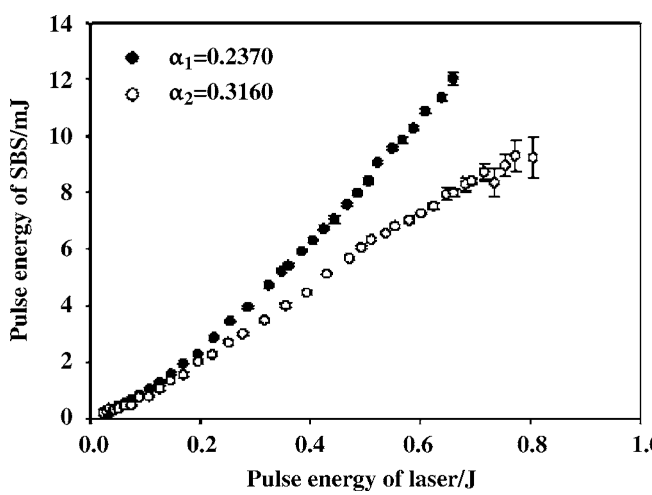

FIGURE 4 Relationship of the pulse energy of SBS vs. the pulse energy of the output laser beam

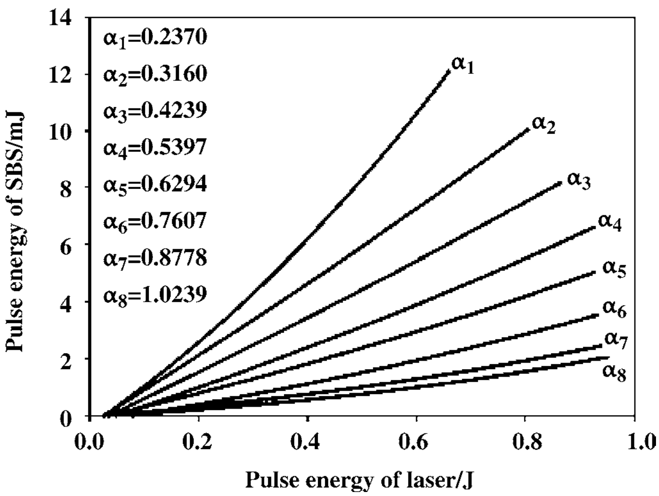

FIGURE 5 Experimental relations between the pulse energy of SBS and the pulse energy of the output laser beam for eight different attenuation coefficients of water

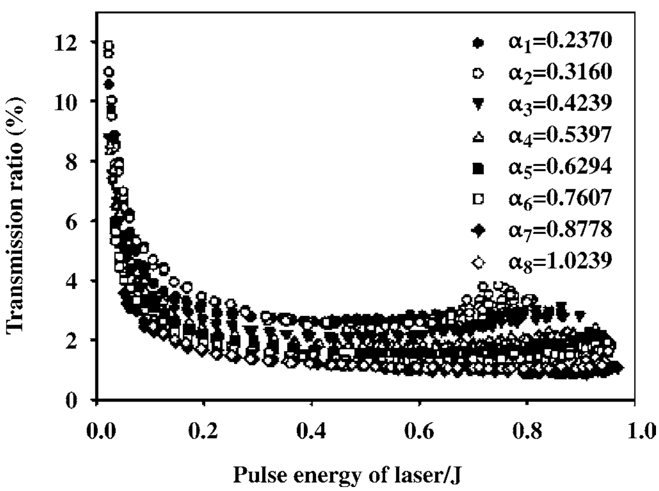

FIGURE 6 Transmission vs. pulse energy of laser at different linear attenuation coefficients of water

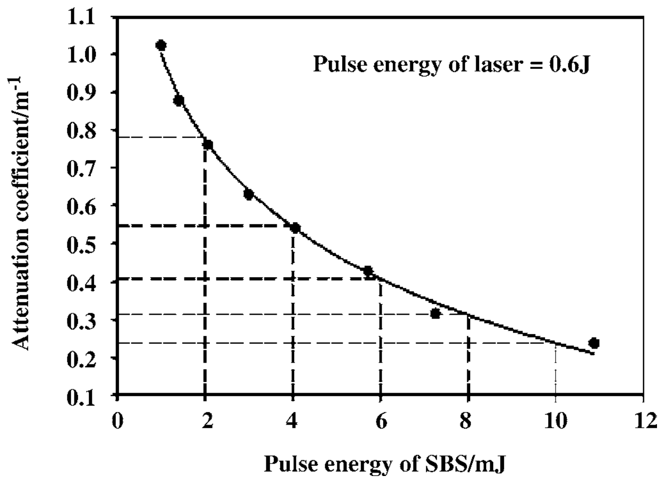

FIGURE 7 The relationship between the attenuation coefficient and the intensity of SBS at a fixed pulse energy of the laser 0.6 J. The *dots* represent the measured results, and the *line* is the fitted curve

that the threshold value of SBS in water will become higher when the value of the attenuation coefficient of water is larger.

Also, the pulse energy I_t penetrating the water cell was detected by detector 1 simultaneously, and the transmission $T = I_t/I_P$ versus the pulse energy of the output laser beam is given in Fig. 6 for different attenuation coefficients. It is obvious that the measured result is stable and reliable when the pulse energy of the output laser beam is in the range of $0.3 \sim 0.7$ J because the stability of the transmission ratio reflects the stability of SBS. The above results were obtained under conditions with a temperature of $25 \sim 28$ °C and a humidity of $50\% \sim 60\%$. The actual variation range of temperature and humidity for the open ocean covers our experimental condition. Thus, more calibration data are needed in practical measurement.

5 Error analysis

According to (12) or (13), the uncertainty of the measured results of α is dependent on the accuracy of measured intensities $I_s$of SBS and the pulse energy $I_P(0)$ of the laser. The accuracy of the pulse energy of the laser is determined by the specifications of the laser used, (it is not analyzed here). From (13), we have

$$\Delta\alpha = \sqrt{\left(\frac{\partial\alpha}{\partial I_s}\right)^2 (\Delta I_s)^2} = \frac{1}{2lI_s}(\Delta I_s)\,. \quad (14)$$

It can be seen that stronger I_s will lead to smaller $\Delta\alpha$. However, from Fig. 6, if the pulse energy of the laser is beyond a certain range, the measured data for SBS will be more unstable. It means that ΔI_s in (14) will increase rapidly. Generally, fixed pulse energy is used in practical applications. According to Fig. 6, the measured intensity of SBS is more stable with laser pulse energy in the range of $0.3 \sim 0.7$ J. Figure 7 gives the relationship between the attenuation coefficient and the intensity of SBS at fixed pulse energy of the laser 0.6 J which is the optimal value in our experiments. The slope of the fitted curve represents the relation of (14). It is clear that in a certain range the experimental results are in good consistency with theoretical analysis.

6 Conclusion

The linear attenuation coefficient of seawater can be measured in real time through measuring the signal intensity of the SBS in sea water. In a certain range of the laser pulse energy this measurement is stable and reliable.

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