Optics Communications 281 (2008) 4523–4525

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Threshold reduction of stimulated Brillouin scattering by Stokes seeds via acousto-optic effect

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A R T I C L E I N F O

Article history:
Received 27 February 2008
Received in revised form 13 May 2008
Accepted 13 May 2008

Keywords:
Stimulated Brillouin scattering
Threshold reduction
Stokes seeds
Acousto-optic effect

A B S T R A C T

We present a method of threshold reduction of stimulated Brillouin scattering by importing Stokes seeds, which are generated from the light passing through the Brilloun medium via an acousto-optic medium. To realize the scheme, the acousto-optic medium and the Brillouin medium should be of the same material, and the frequency of the transducer must be identical with the Brillouin shift. Essentially, the transducer and the acousto-optic medium constitute a special acousto-optic shifter. Calculations suggest that it is easy to reduce the SBS threshold by at least one magnitude and enhance the reflectivity remarkably by this scheme.

There is significant interest in phase conjugation mirrors (PCMs) in laser engineering, for they can remove the effect of optical distortion due to aberrations in the gain medium and in other optical components. Compared with the PCMs based on other kinds of nonlinear effects, the stimulated Brillouin scattering (SBS) PCM gets simpler and easier implementation [1–2]. However, there is a high threshold or intensity demand in the SBS process, which hinders lasers with low intensity from using SBS PCMs [3–4]. And besides, when the light intensity is too high, other competitive nonlinear effects, such as optical breakdown, might occur, resulting in SBS phase conjugating fidelity reduction and even destruction of the medium [5].

Importing Stokes seeds is one way to reduce the threshold [6], for it depends on the strength of the Stokes field [7–8]. And the Stokes seeds can also help to make the SBS process more competitive than other nonlinear effects, because the seeds can shorten the SBS establishing time and enhance the SBS reflectivity [9]. Till recently there have been mainly two ways of generating Stokes seeds. One is the self-feedback scheme, in which part of the scattered light is looped to the other side of the medium to act as seeds [10–11]. The degree of threshold reduction this method could undertake is limited because the seeds are still generated via SBS effect. The other is the way of enhancing the Stokes noise initiation [6]. However, the intensity of the seeds is limited.

We report, in this communication, a method of producing Stokes seeds via acousto-optic medium to reduce the SBS threshold and enhance the SBS reflectivity. The seeds intensity can be higher and the threshold can become lower due to the mature technology for acousto-optic applications.

The scheme we design is shown in Fig. 1, in which, besides a regular Brillouin cell, a hollow transducer and acousto-optic medium are used to generate Stokes seeds. An incident pump laser is focused into the Brillouin cell by a convex lens L_1, whose focal plane is close to the window. L_2, confocal with L_1, collimates the emanative light to parallel one, which travels through the hollow transducer into the acousto-optic medium. Traveling acoustic waves are stimulated in the acousto-optic medium by the transducer. At the other side of the acousto-optic medium, there is sound absorption material which prevents from producing standing waves. To make the light that passes through the Brillouin cell be diffracted by the acousto-optic medium and become SBS Stokes seeds, two conditions should be satisfied: the Brillouin medium and the acousto-optic medium should be of the same material and the working frequency of the transducer equates the SBS shift. The analysis is as follows.

Actually, ultrasonic waves in an acousto-optic medium are equivalent to gratings moving with sonic velocity which modulates the properties of the medium. When a light beam passes through the medium, its phase is modulated by the grating in the medium. Diffraction will happen in some direction if the Bragg condition is satisfied [12],

$$2\lambda_a \sin\frac{\theta}{2} = \lambda_L/n \tag{1}$$

where λ_a and λ_L are the wavelengths of the acoustic wave in the medium and the incident light in vacuum, respectively, n is the refractive index of the light in the medium, and θ is the angle

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doi:10.1016/j.optcom.2008.05.013

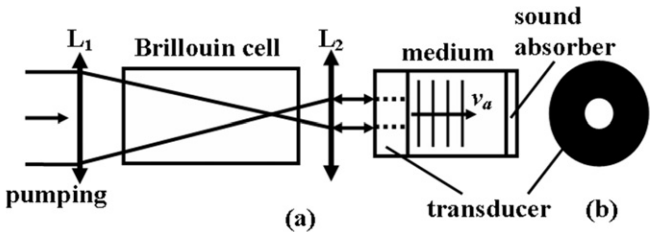

Fig. 1. Schematic of the SBS experiment with the seeds generated via acousto-optic effect. (a) Experimental setup and (b) side view of the hollow transducer and the acousto-optic medium.

between the incident light and the diffracted light. In our scheme as shown in Fig. 1, θ is 180°, then Eq. (1) becomes

$$2\lambda_a = \lambda_L/n \quad (2)$$

Since $\lambda_a = 2\pi v_a/\omega_a$ and $\lambda_L = 2\pi c/\omega_L$, where v_a and c are the velocity of the sound in the medium and the light in vacuum, respectively, ω_a and ω_L are the circular frequencies of the ultrasonic wave and the light, Eq. (2) is equivalent to:

$$\omega_a = 2\omega_L n v_a/c \quad (3)$$

Besides, since the ultrasonic waves travel at a speed of v_a, the diffracted light is shifted due to the Doppler effect. The shift $\Delta\omega$ is identical with the frequency of the ultrasound [12], that is, the frequency of the diffracted light, $\omega_{\rm diff}$, should be

$$\omega_{\rm diff} = \omega_L - \omega_a = \omega_L(1 - 2nv_a/c) \quad (4)$$

where the subtraction sign means the diffracted light is down-shifted compared with the incident one, corresponding to cases where the light and the sound wave travel in the same direction, as shown in Fig. 1. When the directions are opposite, the sign should be changed into plus one.

On the other hand, the frequency of the Stokes seeds for the SBS process, $\omega_{\rm Stokes}$ is [3]:

$$\omega_{\rm Stokes} = \omega_L(1 - 2n'v'_a/c) \quad (5)$$

where n' and v'_a are the refractive index and sonic velocity in the Brillouin medium, respectively. To make the diffracted light act as the Stokes seeds, $\omega_{\rm diff}$ should equate to $\omega_{\rm Stokes}$. Comparing Eq. (4) with Eq. (5), we get

$$nv_a = n'v'_a \quad (6)$$

Then, combining Eq. (3) with Eq. (6), we have

$$\omega_a = 2\omega_L n'v'_a/c = \Delta\omega_{\rm SBS} \quad (7)$$

where $\Delta\omega_{\rm SBS}$ is the Brillouin shift [3]. Eq. (7) implies that the frequency of the transducer or the ultrasonic waves should be identical with the Brillouin shift. And besides, to satisfy Eq. (6), we shall choose the acousto-optic medium made of the same material as that of the Brillouin medium. Thus, we get the sufficient and necessary conditions for producing the Stokes seeds by the acousto-optic medium: the two media are made of the same material, and the frequency of the transducer is identical with the Brillouin shift. We can deduce that the two conditions are the results of the two necessary conditions of the scheme: the diffraction could happen, and the shift equates that of the SBS process. In a word, the key point of the scheme is that the transducer stimulates the same acoustic waves in the acousto-optic medium as that generated in the SBS process.

Based on the deductions above, we can conclude that the transducer and the acousto-optic medium essentially constitute a special acousto-optic shifter. The scheme can be considered as a Brillouin amplifier, in which the transducer and the acousto-optic medium act as a Brillouin generator. The scheme differs from ordinary Brillouin amplifier in two ways: mechanism of producing Stokes seeds and experiment setup (generally, in the latter, light is only focused in generators).

Besides, we can also find the similarity between the acousto-optic effect and the SBS process, that is, an incident light is "diffracted" or "scattered" due to the same mechanism, and the light is shifted due to the Doppler effect. The difference between them is the way in which the ultrasounds are stimulated: one by the transducer, and the other by the lights.

Next, to evaluate the scheme, we take carbon disulfide (CS_2) as the media and calculate the steady state SBS reflectivity R as a function of Stokes seeds and incident laser power. A continuous Gaussian laser with a wavelength of 1.06 μm is assumed. Parameters used in calculations are as following: the Gaussian waist, assumed at the position of laser window, is Φ1 cm, Brillouin medium is 20 cm long, focus of L_1 is 30 cm, the distance between L_1 and incident window is 11 cm, and the distance between laser window and L_1 is 10 cm. The parameters of the media are as follows: density 1265 kg/m^3, refractive index 1.6, sonic velocity 1158 m/s, and phonon life 1.73 ns. The intensity of the Stokes seeds is regarded as boundary condition for the scattering light with a time delay of τ, i.e. $I_{\rm scatt}(l, t) = I_{\rm diff}(l, t) = rI_L(l, t-\tau)$, where r is the intensity reflectivity of the diffracting light by the acousto-optic medium, l refers to position at the window, $I_{\rm scatt}$, $I_{\rm diff}$ and I_L are intensities of the stimulated scattering light, the seeds and the pump, respectively. The time delay, τ, is taken as 1 ns in the calculations. The model of noise-generation, in which SBS is initiated by

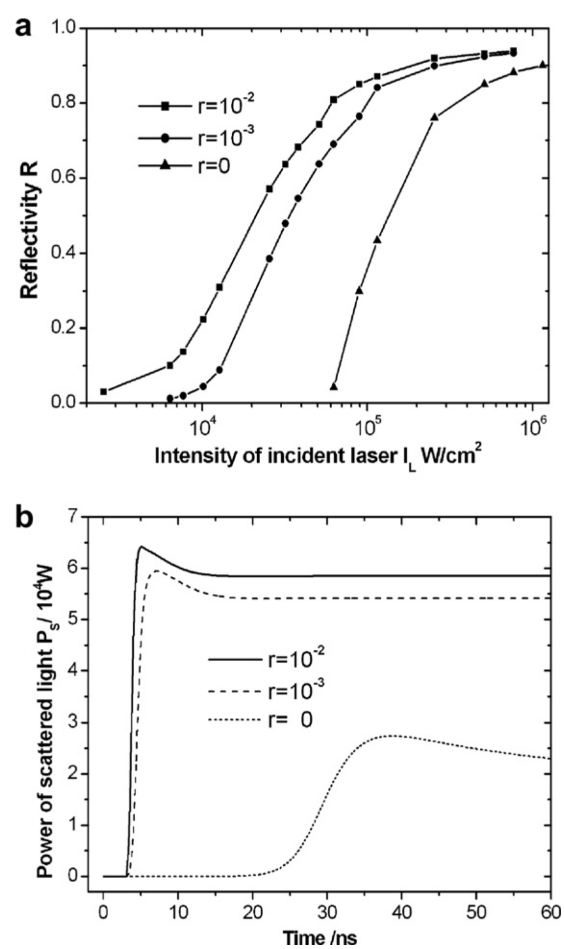

Fig. 2. Calculation results of the SBS scattered light when $r = 10^{-2}$, 10^{-3} and 0. (a) Steady state reflectivity R as a function of laser intensity I_L at the laser window, and (b) power of scattered light as a function of time when $I_L = 9 \times 10^4$ W/cm^2.

spatially distributed thermal fluctuations of the density of the Brillouin medium [7], is adopted in the numerical calculations. And the Stokes component in the reflected pump light by the window of the Brillouin medium is considered, and the intensity ratio between the Stokes component and the pump light is about 10^{-8} [13].

The calculated threshold is about 6×10^4 W/cm^2 when $r = 0$ by the threshold definition of $R = 0.01$, while it is about 5×10^3 W/cm^2 when $r = 10^{-3}$. Fig. 2a shows an acousto-optic medium with $r = 10^{-3}$ can enlarge the scale of applicable laser intensity for SBS, and the scale become larger when $r = 10^{-2}$. With increase of the laser intensity, the difference of the reflectivity with different r becomes smaller. However, the establishing times of SBS process are different with different r, as Fig. 2b shows. The establishing time is about 5 ns when $r = 10^{-3}$ and $r = 10^{-2}$ with a moderate intensity 9×10^4 W/cm^2, while the time is more than 30 ns when $r = 0$. That means, the reflectivity is still lower if a pulse laser is incident when $r = 0$. The results suggest that the scheme of importing Stokes seeds via acousto-optic medium can help to reduce the threshold and enhance the reflectivity. And it can also make the SBS process more competitive than other nonlinear effects due to shorter establishing time.

In the scheme only one pumping light is needed and the experimental setup is simple. And the SBS process is more efficient with the aid of the acousto-optic medium due to two aspects of reasons: one is efficiency of the seeds generating, and the other is that the source of the seeds is the passing through "useless" light. In the method of enhancing noise initiation and that of self-feedback, the threshold was reduced to a level about four times lower [6,10]. In this method, it is easy to reduce the SBS threshold by one magnitude, for it is easy to get a reflectivity r of above 0.1 at present. Besides, if the transducer is put on the other side of the acousto-optic medium, the seeds are anti-Stokes. Thus the scheme can be used to test if stimulated anti-Stokes Brillouin scattering could occur.

In conclusion, we have presented a method of threshold reduction of SBS by Stokes seeds via acousto-optic medium. The acousto-optic medium and the transducer are essentially a special acousto-optic shifter. Calculations show that the scheme can reduce the SBS threshold by at least one magnitude and enhance the reflectivity remarkably.

Acknowledgement

Thanks are due to F.J. Xi for helpful discussion, and to K. Liu for help in amending the manuscript.

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