J. Indian Inst. Sci., Mar.–Apr. 1996, **76**, 249–255.

Studies on dependence of OPC–SBS efficiency on different time scales in molecular gases

B. RAGHAVENDRA PRASAD, S. RAGHUVEER, P. S. NARAYANAN* AND C. K. SUBRAMANIAN
Department of Physics, Indian Institute of Science, Bangalore 560 012, India.

Received on October 18, 1994.

Abstract

The dependence of phase conjugate efficiency and fidelity on interaction, coherence and acoustic lengths has been investigated in detail in SF_6 and CF_2Cl_2. Two distinct regimes of time scales, broad and narrow bands, have been evolved from the combination of these length scales. It is found that the phase conjugate efficiency and fidelity improve dramatically in the narrow band regime.

Keywords: Phase conjugation, stimulated Brillouin scattering, interaction length, coherence length, acoustic length, fidelity.

1. Introduction

Stimulated Brillouin scattering (SBS) has been recognised as a highly efficient method for optical phase conjugation (OPC). Many applications of OPC–SBS involve the use of multimode pump lasers. For example, high-energy lasers must often be operated in multilongitudinal mode in order to extract all the energy stored in an inhomogeneously broadened gain medium[1]. The extent to which the efficiency of the OPC–SBS process is degraded both in terms of gain and phase conjugate fidelity has to be clearly known. Several aspects of SBS may change when a multilongitudinal mode pump is used. The threshold intensity and hence the effective gain might change. The saturation value or the peak OPC reflectivity and the relative magnitudes of competing nonlinear effects such as self-focussing, SRS (stimulated Raman scattering), etc., may change. In this paper, we make a detailed investigation on all the temporal parameters involved in the process to evolve an optimum condition for gain and phase conjugate fidelity as this is very important for any useful device application of OPC–SBS[2–4].

There are three time/length scales involved in OPC–SBS. They are the effective interaction time or length (L_i/c or L_i), the coherence time or length (Δt or $L_c = c\Delta t$), and the Brillouin linewidth or the acoustic phonon lifetime ($\Gamma_{ph} = \tau_{ph}^{-1}$) which is also known as the acoustic length ($c\tau_{ph}$), *i.e.*, the distance travelled by the scattered photon during the lifetime of the acoustic phonon. The understanding of these time/length scales is of utmost importance for gaining a complete insight into the process and to get the maximum gain under given experimental conditions for a given nonlinear medium.

* Deceased.

Interaction length is the effective length of the medium in which the pump intensity is high enough to give rise to SBS, *i.e.*, the region in which threshold conditions for SBS are met. Longer interaction length implies more scattering centres for the process. From the *magic exponential* $e^{(gIL)} = e^{30}$, for SBS process, it is evident that even if the pump intensity is low, one can still reach the threshold condition by increasing the interaction length. This implies that the longer the interaction length, lower is the threshold pump intensity. For a focused beam geometry, the effective interaction length is set equal to the Rayleigh range or the confocal parameter of the focused Gaussian beam. The Rayleigh range is the measure of the length of the waist region of the focused Gaussian beam and alternately it is the minimum distance from the focused spot where the Gaussian beam intensity drops to half its original value. The confocal parameter which is generally used for experiments is exactly twice the Rayleigh range and is given by $L_t = (2\pi\omega_0^2 n)/\lambda$, where ω_0 is the spot size and is related to the focusing optics by $(2\lambda f)/(\pi D)$, where f is the focal length of the lens and D, the beam diameter[5].

The second parameter, the pump bandwidth $\Delta\nu$ determines the coherence length of the laser, and it is the length over which the frequency of the laser stays constant and is defined as $L_c = c/\Delta\nu$. The narrower the linewidth of the pump beam, the acoustic gratings generated in the media have better phase relationship and their scattering efficiency increases.

Brillouin linewidth (Γ_{ph}) which is a material-dependent parameter determines the build up of acoustic wave amplitude and thus is directly related to the Brillouin gain of the media. The inverse of the Brillouin linewidth is the decay time τ_{ph} of the acoustic wave. The larger the decay time, *i.e.*, the smaller the Brillouin linewidth, greater is the scattering of the pump beam into Stokes signal. The Brillouin linewidth is expressible in the spatial domain by $c\tau_{ph}$, which is the length travelled by a photon during the lifetime of an acoustic wave. The light scattered off a single acoustic wave maintains a constant phase over the length $c\tau_{ph}$ while the light scattered off a different acoustic wave would have different relative phases. The time domain analogue of this is that, for efficient SBS to occur, temporal fluctuations of the pump must be slow compared to the phonon lifetime, *i.e.*, $(\Delta\nu)^{-1} > \tau_{ph}$, otherwise, acoustic waves do not have time to build up before the pump intensity falls suddenly.

Two distinct regimes of time scales[6], *broad band* and *narrow band*, have been evolved by the combination of the above discussed time scales and their roles in affecting the gains and the phase conjugate fidelity have been investigated. In the broad band regime, the coherence length and the acoustic lengths are smaller than the interaction length and the narrow band conditions prevail when $L_c > c\tau_{ph}$ and $c\tau_{ph} > L_c > L_t$. Experiments were carried out to study the roles of these two regimes of time scales on Brillouin gains and on the phase conjugate fidelity.

2. Experimental results and discussion

A stainless steel gas cell was designed and fabricated for these studies. Experiments were carried out using a pulsed frequency doubled Nd:YAG laser with a pulse duration

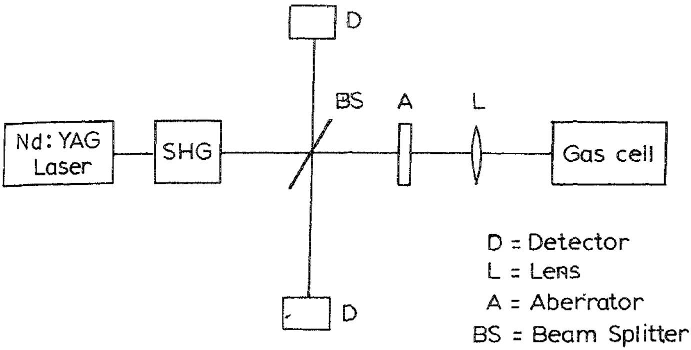


FIG. 1. Experimental layout for OPC–SBS.

of 10 ns. The coherence length of the laser can be varied from 1 to 500 cm using intra cavity etalon and electronic line narrowing facilities. The intensities of the pump and signal beams were measured simultaneously using pyroelectric detectors and an energy meter. Lenses of different focal lengths were used for different interaction lengths (Fig. 1). A phase distorter was used to introduce inhomogenities in the transverse intensity profile of the pump beam. SF_6 and CF_2Cl_2 gases were used as the Brillouin media. CF_2Cl_2 has higher Brillouin gain[6] as compared to SF_6. The advantage of using these gases for these studies is that they have high gain, high transparency and high dissociation energy. The acoustic decay time or the acoustic length can be varied by changing

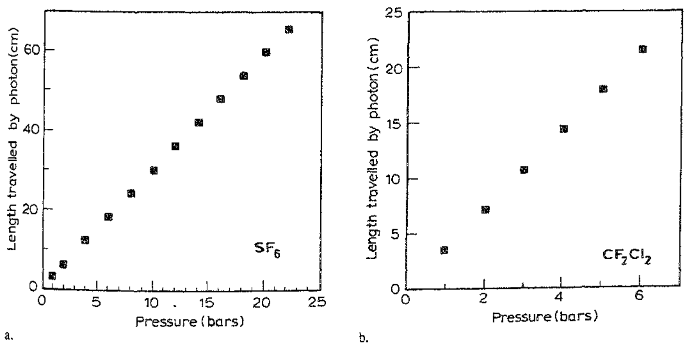


FIG. 2. Distance travelled by a photon during the lifetime of acoustic phonon. (a) SF_6 and (b) CF_2Cl_2.

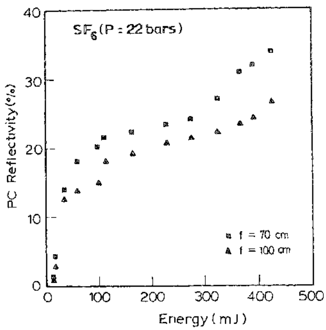


FIG. 3. Dependence of phase conjugate reflectivity on interaction length in broad band regime.

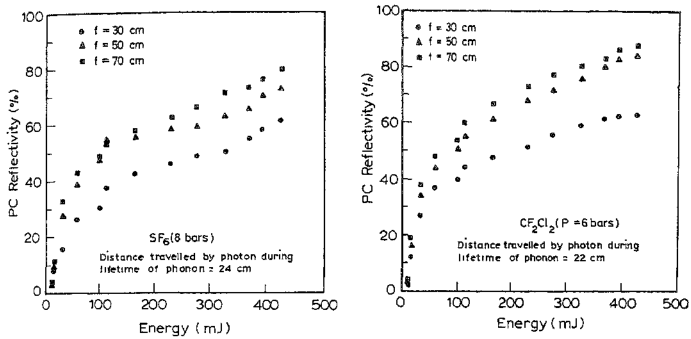
the pressure of the gas. The calculated values of acoustic length as a function of pressure are shown in Fig.2(a,b) for the two gases.

2.1. *Broad band regime*

This regime is one in which either the $L_c < L_i$ or $L_c < c\tau_{ph}$. Experiments were conducted using lenses of focal lengths 70 and 100 cm with effective interaction lengths of 13.5 and 27.5 mm, respectively. The L_c of the laser was fixed at 1 cm. The gas pressure is chosen in such a way that the condition $c\tau_{ph} > L_c$ is satisfied. The OPC–SBS reflectivities are measured as a function of pump beam intensity for both the lenses as shown in Fig.3. It can be seen that longer the L_i compared to L_c, lower is the overall phase conjugate efficiency. The reason for this is that even though the L_i is larger, the temporal fluctuation in the pump beam is so high that the acoustic waves do not have time to build up before the intensity of the pump drops dramatically, thus reducing the efficiency of the system. Further decrease in the conjugate efficiency with lens of larger confocal parameter is due to the fact that the intensity distribution of the pump beam is over a larger region, thus reducing the overall available intensity to different scattering centres.

2.2. *Narrow band regime*

This can be divided into three cases: one when $L_c > c\tau_{ph} > L_i$, the second when $c\tau_{ph} > L_c > L_i$, and the third is when $L_c = c\tau_{ph} > L_i$. In this case, the temporal fluctuations in pump beam are small due to longer coherence length so that a well-defined grating is formed and also there is a definite phase relationship among all the acoustic waves thus enhancing their scattering efficiency. In the first case, for a gas pressure of 8 bars (SF_6) and 6 bars (CF_2Cl_2), the calculated values of $c\tau_{ph}$ were found to be 24 and 22 cm, respectively. To satisfy the condition $L_c > c\tau_{ph}$, the L_c of the pump beam was fixed at



a. b.

FIG. 4. Dependence of phase conjugate reflectivity on interaction length in narrow band regime when $L_c > c\tau_{ph}$ ($L_c = 50$ cm). (a) SF_6 and (b) CF_2Cl_2.

50 cm. Phase conjugate reflectivity is measured as a function of pump beam intensity for different gain lengths. From the behavior of the plots in Fig. 4(a,b), it is clear that the efficiency of scattering is high for the condition $L_c > c\tau_{ph}$ and increases with L_i.

In the second case, the phase of the intensity pattern formed by the forward-going pump with the back-scattered signal wave is disrupted within the length $c\tau_{ph}$ by the short

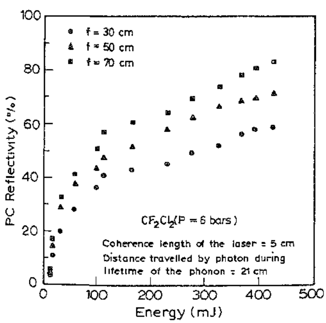


FIG. 5. Dependence of phase conjugate reflectivity on interaction length in narrow band regime when $L_c < c\tau_{ph}$ ($L_c = 5$ cm).

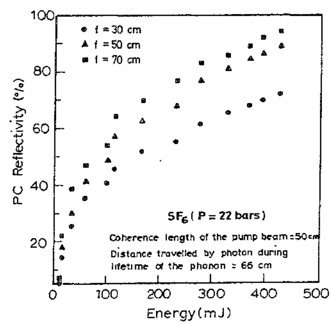


FIG. 6 Dependence of phase conjugate reflectivity on interaction length in narrow band regime when $L_c \simeq c\tau_{ph}$ ($L_c = 50$ cm).

coherence length of the laser. That is, the pump beam loses its coherence over a distance that is short compared to the distance over which light scattered from the acoustic wave maintains its coherence. The calculated value of $c\tau_{ph}$ for SF_6 at a pressure of 22 bars is 66 cm and for CF_2Cl_2, it is 21 cm at a pressure of 6 bars. The L_c of the pump beam was fixed at 5 cm. Figure 5 shows the plot of OPC reflectivity for different L_t as a function of pump intensity. The efficiency of scattering is high for this case. In the third case, where $L_c \cong c\tau_{ph}$, the overall scattering efficiency is high as shown in Fig.6. This is due to the fact that there exists a definite phase relationship between pump and scattered beams. The nonlinear nature or saturation behavior of curves in Figs 3–6 is due to the onset of other nonlinearities.

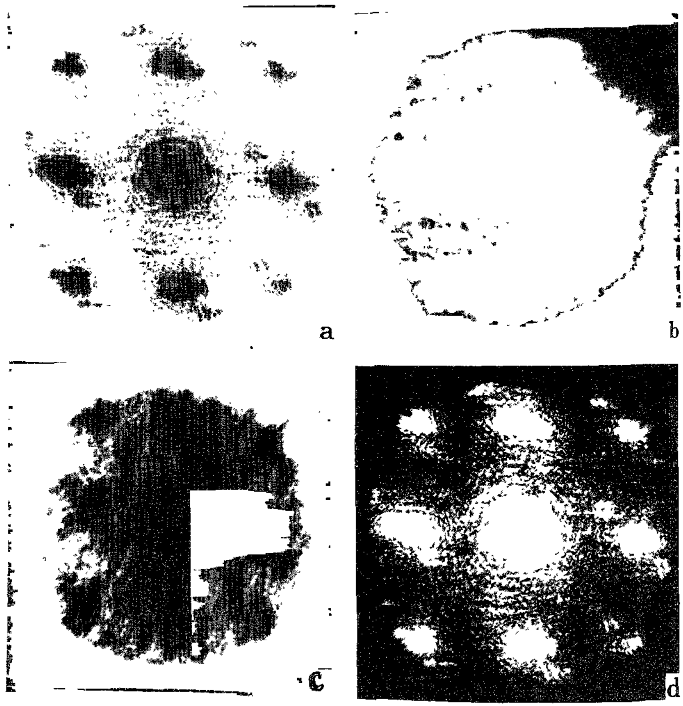


FIG. 7. Distortion correction properties of OPC–SBS. (a) original beam, (b) distorted beam, (c) broad band regime, and (d) narrow band regime.

3. Phase conjugate fidelity

Phase conjugate fidelity is defined as the accuracy of the wavefront reversal process. Experiments were conducted to study the dependence of phase conjugate fidelity on broad and narrow band regimes. A grid was used for creating a definite intensity pattern for the pump beam and a phase distorter was used to distort the transverse intensity profile of the pump thus distorting the image. The intensity distribution of the original pump beam, distorted pump beam and the signal beams was recorded photographically using a Linhof-Technica camera in the far field and is shown in Fig.7(a–d). It can be seen from Fig.7c–d that there is a dramatic change in fidelity from broad to narrow band regions. The reason is that the OPC–SBS process relies on the transformation of phase variations in the focused region, giving rise to phase-conjugated gain maze. If the region of maximum reflectivity is incoherent with the noise from the far field, the SBS will not be a phase conjugate of the input. This is the reason for the improvement in phase conjugate fidelity in narrow band regime.

4. Conclusion

From the above studies it is clear that the efficiency of the process OPC–SBS can be improved by choosing an appropriate time/length scale. It is also found that the fidelity of the process improves remarkably in the narrow band regime. It is possible to have a very high efficiency phase conjugator with very good fidelity even at low working pressure of gases by proper choice of pressure, coherence length of the pump beam and finally the focusing optics.

Acknowledgements

This work was supported by the Defence Research and Development Organisation (DRDO), Ministry of Defence, Government of India, under its Research and Training programme.

References

1. ROCKWELL, D. A. — A review of phase conjugate solid state lasers, *IEEE J*, 1988, **QE-24**, 1124–1140.

2. MULLEN, R. A., LIND, R. C. AND VALLEY, G. C. — Observation of stimulated Brillouin scattering gain with a dual spectral line pump, *Opt. Commun.*, 1987, **63**, 123–128.

3. VALLEY, G. C. — A review of stimulated Brillouin scattering excited with a broad-band pump laser, *IEEE J.*, 1986, **QE-22**, 704–712.

4. NARUM, P., SKELDON, M. D. AND BOYD, R. W. — Effect of laser mode structure on stimulated Brillouin scattering, *IEEE J.*, 1986, **QE-22**, 2161–2167.

5. SEIGMAN, A. E. — *Lasers*, 1986, Oxford University Press.

6 RAGHAVENDRA PRASAD, B. — *Optical phase conjugation studies in molecular gases by stimulated Brillouin scattering and in organic systems by four wave mixing*, Ph.D. Thesis, Department of Physics, Indian Institute of Science, Bangalore 560 012, India, 1993.