STIMULATED BRILLOUIN SCATTERING IN THE OFF-AXIS RESONATOR

(CS_2; possible application laser spectroscopy; E/T)

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It has been shown recently that stimulated Raman radiation can be built up in the off-axis direction using a resonator the axis of which is rotated from the axis of the ruby laser resonator.[2,3]

The stimulated Brillouin scattering which has been found by Chiao, Townes, and Stoicheff[4] shows a characteristic which is different from that of the stimulated Raman scatterings: the stimulated Brillouin scattering was observed even in the direction perpendicular to the incident laser beam when the active medium was placed outside the ruby laser resonator.

Thus it is interesting to investigate the possibility of building up the stimulated Brillouin radiation in the off-axis resonator.

The spectrum of the output of the off-axis resonator was studied with the experimental arrangement shown in Fig. 1. The lens, iris, and Fabry-Perot interferometer were removed in order to investigate the far field pattern of each component. Benzene and carbon disulfide were chosen as typical and exceptional liquid samples, respectively.

The results are shown in Fig. 2. When the carbon disulfide cell was inserted in the off-axis resonator, the coherent radiation at approximately the same wave length as the incident laser beam was found to be built up at an exciting power slightly higher than the threshold exciting power of the first stimulated Raman Stokes line. The angular divergence was measured to be a few milliradians, which was the same as that of the first Stokes line at the same exciting power.

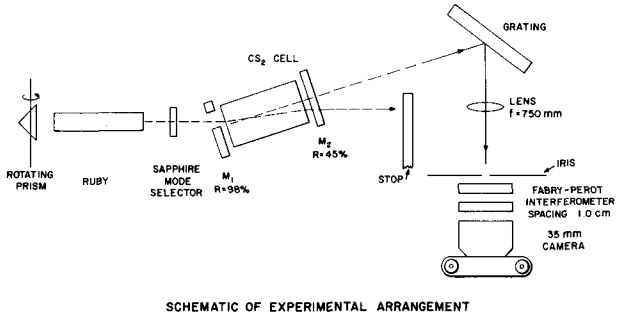

Fig. 1. Schematic diagram of the experimental arrangement.

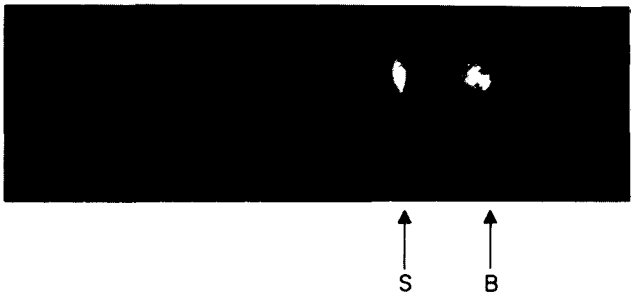

Fig. 2. Spectroscopic far field pattern of the output of the off-axis resonator, when the CS_2 cell was inserted in it. *B*, the stimulated Brillouin radiation; *S*, the first stimulated Stokes radiation.

On the other hand, when the benzene cell was inserted in the off-axis resonator, no stimulated scattering was observed around the ruby laser wave length even under our maximum exciting power (50 MW/cm^2), at which even the third Stokes line was observed in the off-axis direction.

The observation described above indicates that stimulated Brillouin radiation was built up only in the carbon disulfide cell. This is in agreement with the exceptionally low threshold exciting power for stimulated Brillouin scattering in carbon disulfide found by Garmire and Townes.[5]

A Fabry-Perot interferometer with 10-mm spacing was used to examine the spectrum of the output with the carbon disulfide cell in the off-axis resonator. An iris was placed at the focal plane of the 75-cm lens to pick up only the coherent component around the ruby laser wave length, as shown in Fig. 1. The spectrum of the ruby laser output had been examined using the same interferometer and found to be a single frequency as shown in Fig. 3*a*.

The result is shown in Fig. 3*b*, in which two sets of concentric rings are observed: the more intense one (*F*-component) and the weaker one (*B*-component). Both these components have the same angular distribution, and very distinct thresholds.

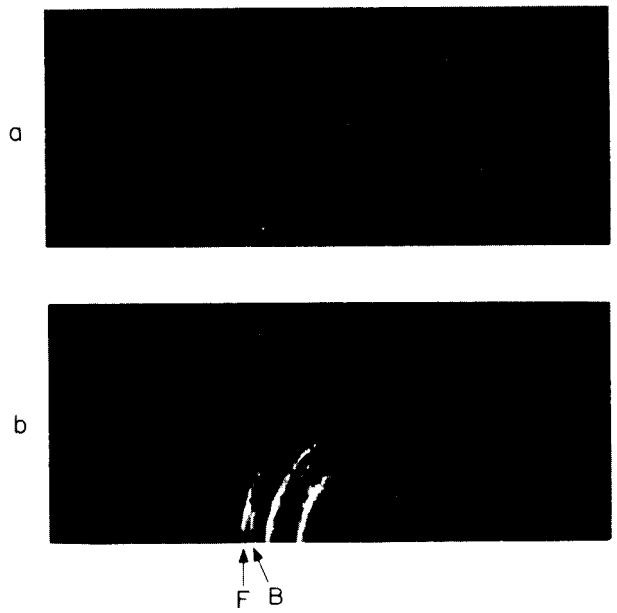

Fig. 3. Fabry-Perot fringes (*a*) of the *Q*-switched ruby laser radiation showing its single-frequency character and (*b*) of the off-axis Brillouin radiation showing *F*, the forward, and *B*, the backward component. In each interferogram the interorder spacing is 0.50 cm^{-1}.

When the exciting power was decreased, the *B*-component disappeared first, and the *F*-component next. Just below the threshold, a set of diffuse rings with the same diameter as *F*-component were observed. The difference in the wave number between the *F* and *B*-components was determined to be 0.19 cm^{-1}, which agrees well with the wave number shift due to the 180° Brillouin scattering.

From these observations, the *F* and *B*-components have been assigned to be the stimulated forward (0.0433 radian to the incident beam) and the backward (3.10 radians) Brillouin scattering, respectively.

The threshold condition for the stimulated Brillouin scattering in the resonator has been given by Chiao, Garmire, and Townes as[6]

$$\frac{E_0^2}{8\pi} \geqq \frac{2\epsilon B}{(\rho d\epsilon/d\rho)^2 k_s L_s k_{-l} L_{-l}},$$

where E_0 is the magnitude of the electric field of the incident laser beam, ϵ is the dielectric constant, B is the bulk modulus, ρ is the density, L_s and L_{-l} are, respectively, the decay lengths of the sound and light waves, and k_s and k_{-l} are the propagation constants of the sound and the light waves, respectively. The lower threshold power for the *F*-component shows us the larger value of $(\rho d\epsilon/d\rho)^2 k_s L_s$ for the very-small-angle forward Brillouin scattering. The Brillouin shifts for the 0.0433-radian and the 3.10-radian scattering are calculated to be 124 and 5800 Mc, respectively. The extrapolation of the experimental results on the frequency characteristics of the loss of the sound wave in carbon disulfide[7] gives us the ratio

$$(k_s L_s)_{124\ \mathrm{Mc}}/(k_s L_s)_{5.8\ \mathrm{Gc}} \sim 9 .$$

Although the above estimation is not very accurate because the measurements have been done only up to a few hundred megacycles, it agrees qualitatively with our experimental result. However, if one assumes a single relaxation process, $k_s L_s$ should have its minimum at roughly 100 Mc,[7] and the threshold exciting power should be less in the backward scattering than in the 0.0433-radian forward scattering. This is in contradiction with our experimental result, and shows that the single relaxation theory is too simple to cover the uhf range.

On the other hand, the single relaxation theory is known to show a very good agreement with the experimental results below 100 Mc.[7] Therefore a very low threshold exciting power is expected for a very-small-angle Brillouin scattering.

A multimode resonator with many overlapping resonant modes is recommended for the Brillouin laser, because the resonator should have a resonant mode at the wave length which satisfies the momentum matching condition. Spherical mirrors are expected to give more efficient and reproducible results.

Another interesting experimental fact found in the present work is the difference in the efficiency of the optical resonator between the stimulated Brillouin and Raman scattering. The ratio of the threshold power densities to build up the stimulated Brillouin and Raman scattering was reported by Garmire and Townes to be 30, when the carbon disulfide cell was placed outside the resonator. On the other hand, the ratio of the same definition was found to be of the order of unity in the present work, in which the carbon disulfide cell was placed inside the optical resonator.

This difference between the Brillouin and the Raman scattering may be explained as follows: Brillouin scattering is due to the phonons, the wave length of which is at least of the same order of magnitude as that of the scattered photon. Therefore, when the frequency of the scattering phonon is defined, uncertainty in the direction of the scattered photon is much smaller than it is in the Raman

scattering, in which the wave length of the scattered photon compared to the dimension of the scattering molecule is extremely large. Once a direction of the scattering is defined by the presence of the off-axis resonator, and the phonons which correspond to the Brillouin scattering in this direction are enhanced, the photons are scattered only in limited solid angle around the axis of the off-axis resonator. This makes a contrast to the Raman scattering, where the light is uniformly scattered into a solid angle of 4π even when the Raman active molecular vibration is enhanced in the scattering medium.

As for the difference between the Garmire and Townes experiment and the present work with respect to the ratio of the threshold exciting power of the stimulated Brillouin scattering to the stimulated Raman scattering, it should be noticed that the effective length is very small when the exciting laser beam is focused in the cell. This is unfavorable to the stimulated Brillouin scattering. A detailed discussion will be published elsewhere with a theory of the stimulated Brillouin scattering.

Besides physical interest, the off-axis Brillouin laser is useful as a tunable source of the coherent radiations around the exciting laser wave length, since the wave length can be changed by changing the off-axis angle. The presence of such a coherent source should be a great help for laser spectroscopy.

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[2] H. Takuma and D. A. Jennings, *Appl. Phys. Letters* **4,** 185, (1964).

[3] J. H. Dennis and P. E. Tannenwald, *Appl. Phys. Letters* **5,** 58, (1964).

[4] R. Y. Chiao, C. H. Townes, and B. P. Stoicheff, *Phys. Rev. Letters* **12,** 592, (1964).

[5] E. Garmire and C. H. Townes, *Appl. Phys. Letters* **5,** 84, (1964).

[6] R. Y. Chiao, E. Garmire, and C. H. Townes, *Proceedings of the Enrico Fermi International School of Physics,* Course XXXI, 1963 (to be published).

[7] D. Sette, "Acoustics I," Volume XI/2, *Encyclopedia of Physics,* Springer-Verlag, 1961.