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SINGLE PHOTON COUNTING IN BRILLOUIN LASER LIGHT SCATTERING EXPERIMENTS

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What follows is a description of the electronics and simple mechanical equipment needed for single photon counting. It is intended as an introduction and guide to assist users in the measurement of Brillouin laser light scattering on acoustic hypersonic waves. Simple method of a numerical filtration of the low-intensity-level optical signal is described in detail.

1. Introduction

Observation of the acoustic wave in the hypersonic range consists in measuring changes of photon energy inelastically scattered in annihilation and creation processes by phonons lying at the beginning of the first Brillouin zone. However the intensity of this optical signal is very low with respect to the intensity of light incident on the investigated sample, so an appropriate registration method must be applied. One of the most sensitive techniques that can perform this task is a single photon counting SPC [1–3], well known from its wide application to different materials such as crystals, thin layers and superlattices structures [4–9].

The main purpose of this paper is to instruct users how to perform such experiments and how to build their own experimental setup, especially for observing acoustic waves in the hypersonic range by the Brillouin laser light scattering.

2. Experimental apparatus

The general scheme of an electronic for the SPC method is presented in Fig. 1. The signal from a fast photomultiplier, for example, a Hamamatsu P-series, is amplified and then formed to a rectangular shape. An amplitude discriminator with upper and lower thresholds is then applied, followed by a counter sensitive for TTL standard signal level connected with a computer. In the case of presented experimental equipment the amplifier, the shaper and the discriminator are stored in a PTI-614 analog-digital module

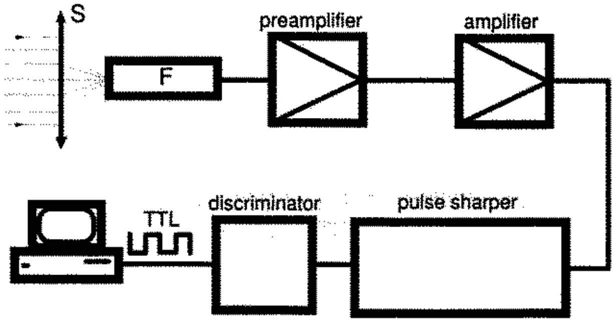

Fig. 1. Block diagram of electronic equipment for the SPC method. S – lens, F – photomultiplier. An optical signal comes through a lens to the photomultiplier. At the output of the electronic equipment the signal is in TTL standard and is registered by the PC computer.

produced by PTI Inc. Table 1 provides the main parameters of this unit. The Hamamatsu R-4220P photomultiplier was placed inside the PTI-614. Table 2 provides its parameters. One of the most important parameters of the PTI-614 module is a pulse pair resolution equal to 250 ns. This means that any photon or a group of photons coming into the photomultiplier in a period of time shorter than 250 ns will not be recognized as a new count. The signal coming to the counter (in our case, a standard counter used for nuclear experiments), possessed a stochastic nature due to the thermal noise of the photomultiplier and the random nature of the low-intensity-level scattered light.

Table 1. Parameters of the 614 PMT analog/digital unit.

Drift of the signal (%/hour)	Maximum count rate (MHz)	Pulse pair resolution (ns)	Raise time of the pulse (ns)	Fall time od the pulse (ns)	Pulse width (ns)
0.03	4	250	20	100	220

Table 2. Parameters of the R4220P photomultiplier.

Photocatode	Amplification	Spectral response (nm)	Raise time of the signal (ns)
Low noise "bialkali" (Na-K-Sb)	$1.2 \cdot 10^7$	185 – 710 (max. 410)	2.2 ns

For these reasons a numerical filtration must be performed, assuming that the noise is conformable to the Poisson distribution (Fig. 2). The signal is also a function of the voltage supply of the photomultiplier (Fig. 3). The main reason for performing filtration is to obtain a smoothed Brillouin spectrum. So a weighted average was used of some neighboring values of counts, creating an "average window". This averaging was achieved as follows:

An error of a single measurement is set equal to

$$\Delta N_i = \sqrt{N_i}. \tag{1}$$

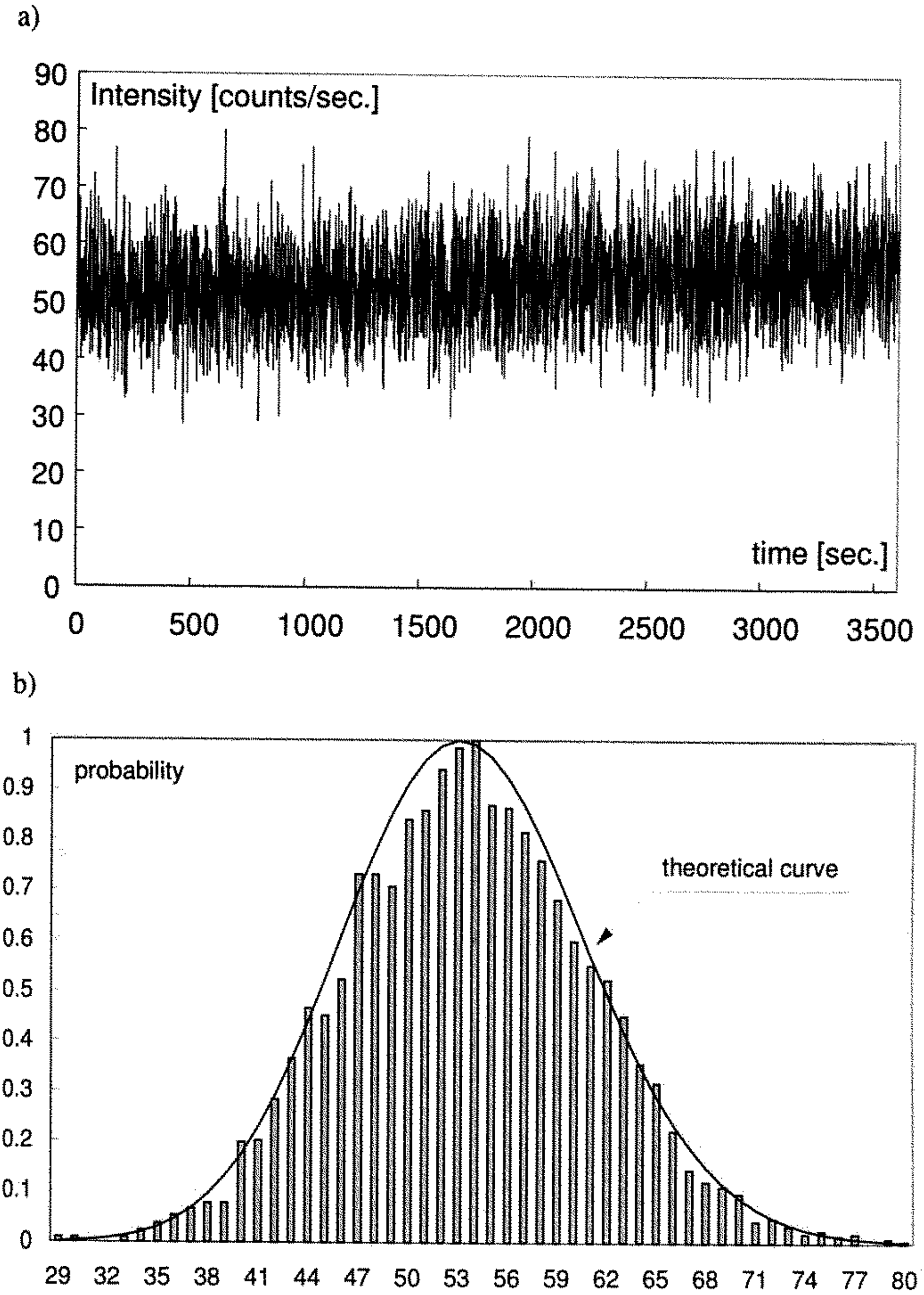

Fig. 2. Noise of the photomultiplier with no optical signal (a) and a histogram of its Poisson distribution (b). Time of measurement was equal to one hour.

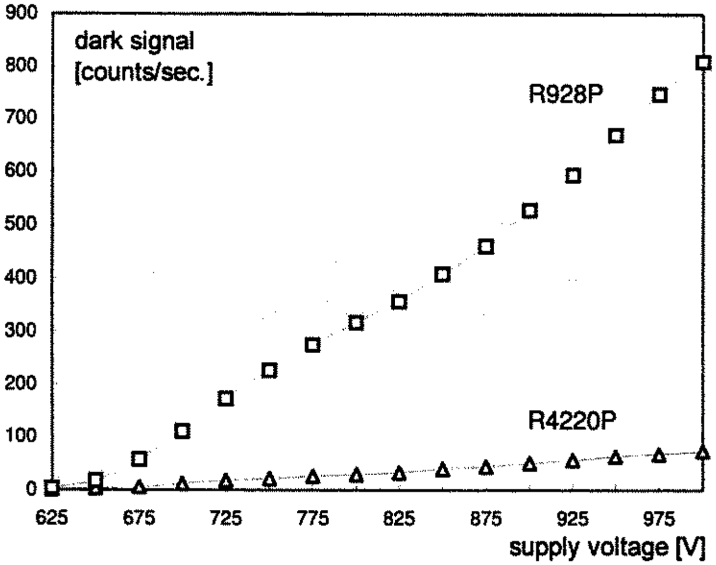

Fig. 3. Comparison of dark signals from two photomultipliers: R928P and R4220P. The second photomultiplier is more useful for low-level optical signal detection.

A relative error of a single measurement is equal to

$$\frac{\Delta N_i}{N_i} = \frac{\sqrt{N_i}}{N_i} . \tag{2}$$

Then, a weighted average value from n single measurements is equal to

$$\overline{N} = \frac{\sum\limits_{i=1}^{i=n} \omega_i N_i}{\sum\limits_{i=1}^{i=n} \omega_i} , \tag{3}$$

where the weight of a single measurement ω_i is equal to the reciprocal of a relative error, of this measurement, raised to the second power. By substituting Eq. (2) into Eq. (3) we obtain

$$\overline{N} = \frac{\sum\limits_{i=1}^{i=n} N_i^2}{\sum\limits_{i=1}^{i=n} N_i} , \tag{4}$$

where $\overline{N}$ is a weighted average value from the "filtration window" of the width equal to n. The above procedure must be performed from the first point of data of initial position to the position equal to $(N_T - n + 1)$, where N_T is the total number of registered points.

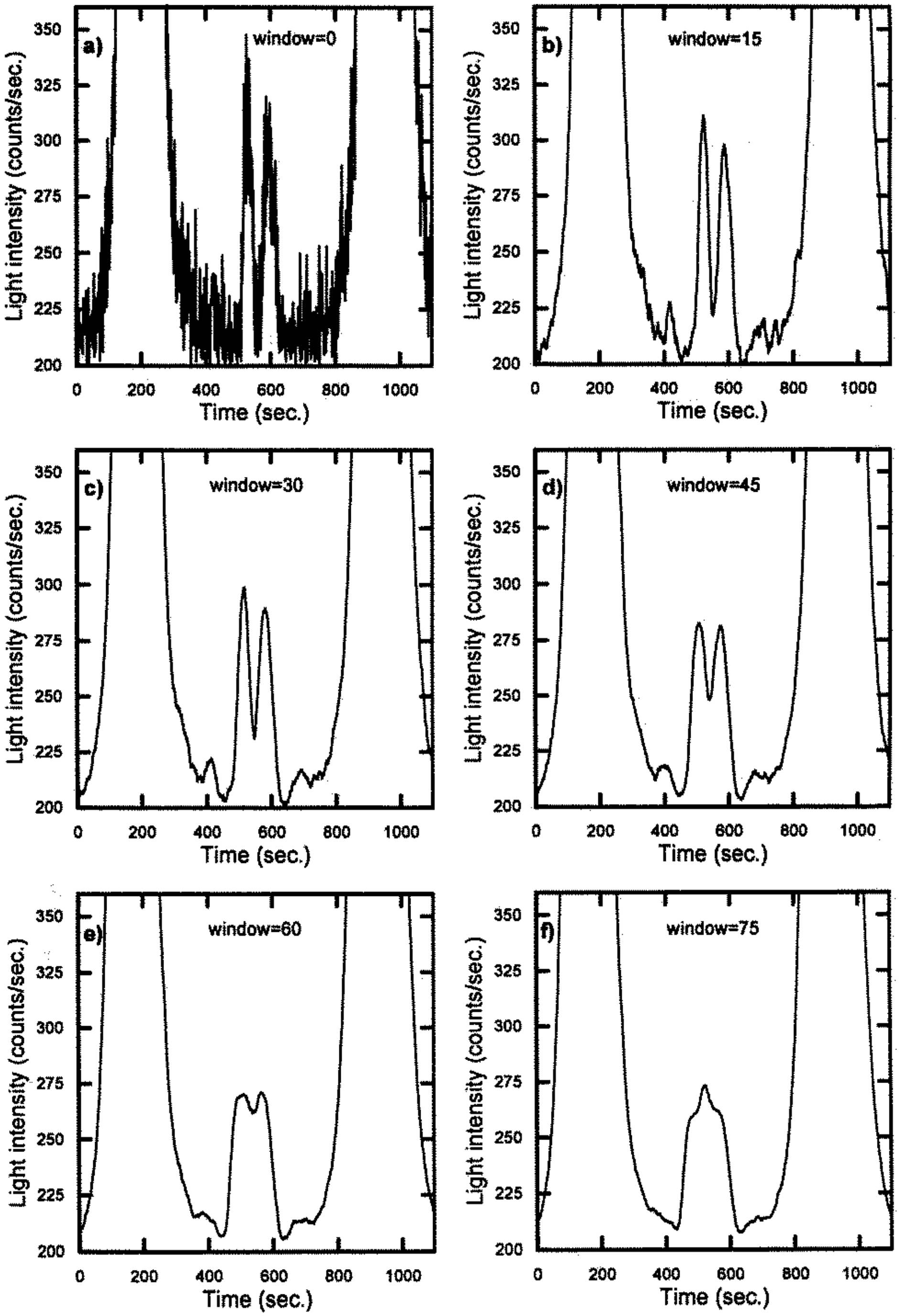

Fig. 4. Examples of the Brillouin spectra from the $LiTaO_3$ crystal after filtration by different widths of the filtration window. Each picture was created from 1100 data points.

A separate problem is the choice of an appropriate width of the "filtration window". If the width is too large, important properties of the spectrum may be lost (Fig. 4). A workable value, discovered in practice, takes the width to be comparable to half the width of a Poisson distribution of dark counts at the same input voltage as for experiments with real scattered light. As we can see from Fig. 4, the best choice of a width of the "filtration window" is the "d" case. A filtration width equal to 75 loses physical information completely.

A problem arises in connecting the PTI-614 module to the computer. This can be solved by the use of any frame grabber or external module. In our case the counter was a relatively old module giving on its output a signal in a BCD standard. An interface was designed which connects the counter with a parallel port of a PC class computer. The interface was controlled by a Pascal language program. The main task of the interface was the successive reading and transmission of numbers from the counter to the computer.

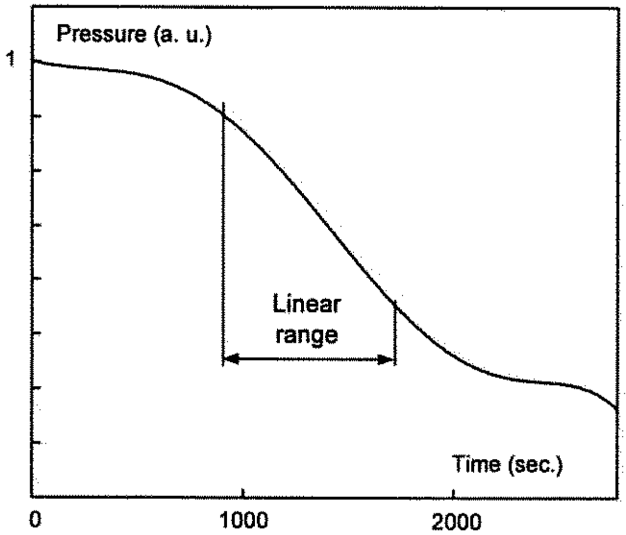

Fig. 5. Dependence of the pressure in interferometer chamber on a time. The middle of the plot provides a linear dependence useful for measurement.

Another problem is the linear scanning of the Brillouin spectrum in time. The total phase difference between the mirrors of the Fabry–Perot interferometer must be scanned or controlled. In most cases, this is done by the piezoelectric method [10]. An older, less precise, but easier method is a pressure scanning [11], where an interferometer is placed in a chamber connected with a pump and with a second controlling chamber useful for valves and a capillary mounting. This allows us to remove a gas from the chambers and then leak it slowly back. Most importantly, this produces a linear range of pressure changes (Fig. 5), useful for our purposes. It means that the Brillouin spectrum can be linear scanned. Obviously, this is a function of the mechanical parameters of the equipment. In the case of our apparatus, the total volume of the chambers was equal to $6{\cdot}10^{-2}\,\mathrm{m}^3$ and the diameter of the capillary was of the order of 10^{-5} m.

3. Examples of a registered Brillouin spectrum

As was mentioned at the beginning, Brillouin light scattering consists in measuring changes of photon frequency inelastically scattered on acoustical phonons lying at the beginning of the first Brillouin zone. At the quantum level annihilation and creation processes are responsible for the typical picture of the Brillouin spectrum where lines of lowered and increased frequency can be visible. Figure 6 provides the experimental spectra of acoustic phonons registered by the use of the SPC in the transparent for laser wavelength $LiTaO_3$ crystal. Lines described as longitudinal (L) and quasi-transverse waves (T_1 and T_2) were spatially separated from high intensity elastically scattered light by the Fabry–Perot interferometer — a standard method in every Brillouin or Raman spectroscopy experiment. Table 3 provides the results of measurements in the [100] crystalographic direction (compare Fig. 6 b). The averaged values are equal to 25.60 ± 0.17 GHz and 20.36 ± 0.15 GHz.

Table 3. Example results of measurements of quasi-transverse waves frequency in the $LiTaO_3$ crystal – [100] direction.

Frequency of the first quasi-transverse wave (GHz)	Frequency of the second quasi-transverse wave (GHz)
25.62	20.40
25.68	20.46
25.44	20.33
25.46	20.41
25.81	20.38

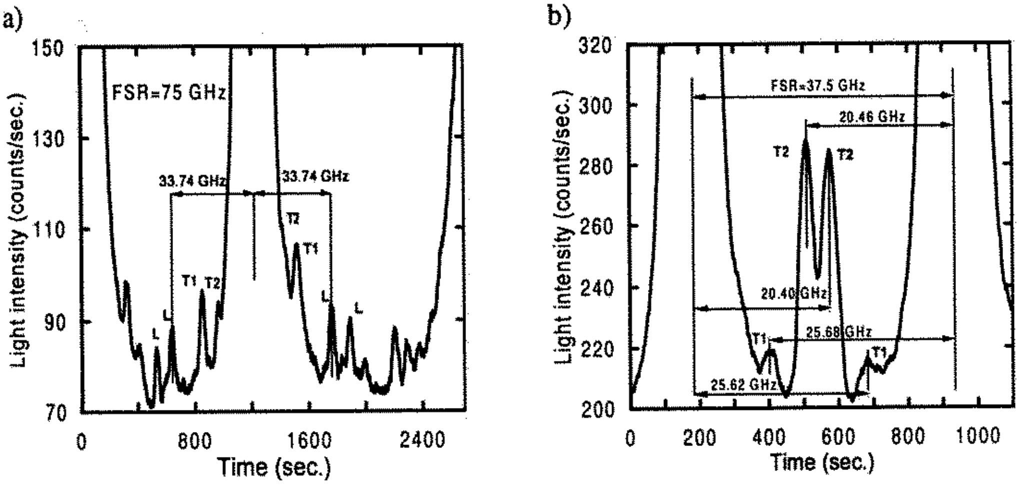

Fig. 6. Two examples of Brillouin spectra from the $LiTaO_3$ crystal for two different full spectral ranges: a) FSR = 75 GHz, the pressure range is linear only around the middle Rayleigh line. b) FSR = 37.5 GHz. Descriptions: T_1, T_2 – quasi-transverse waves, L – quasi-longitudinal wave.

The systematic error in phonon frequency measurement caused by the choice of the interferometer's full spectral range and numerical treatment of data was equal to 0.15 GHz. It is interesting to compare the amplitude of the line from elastic scattering with the amplitude of Brillouin signal with respect to the noise level. The high resolution capacity of the SPC method is evident.

4. Conclusion

Single-photon counting is one of the most sensitive methods for very low-level optical signal detection. What was described, in a simple way, is how to perform such an experiment for the registration of light inelastically scattered on acoustic hypersonic waves. Most of the equipment was designed and made in laboratory. By the appropriate choice of volume of the pressure chamber and diameter of the capillary, it was possible to obtain a linear range of Fabry–Perot scanning, which is crucial in such experiments. Simple numerical filtration was used to smooth the registered spectra. The described use of the SPC method can be applied not only in hypersonic acoustics [12], but also in other field of physics, chemistry and biology.

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