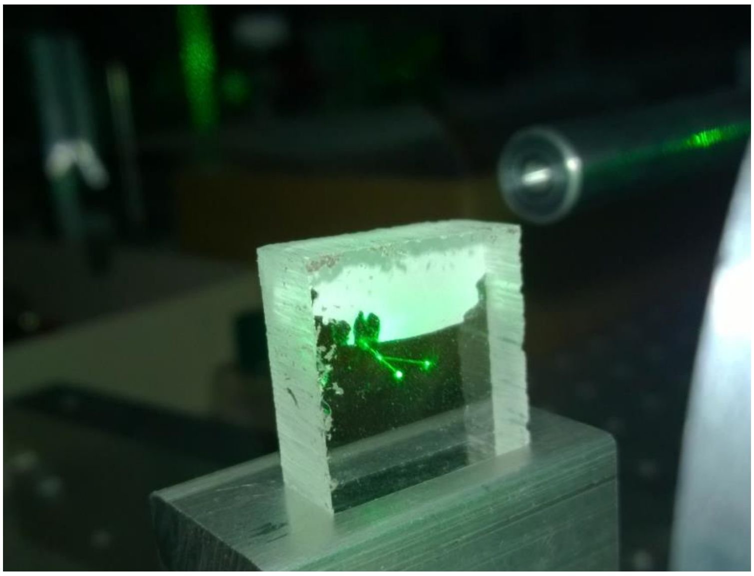
Brillouin Scattering by means of the JRS TFP-1 tandem multi-pass Fabry-Pérot interferometer



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INTRODUCTION

This short guide will focus on a typical laser light Brillouin scattering experimental setup, which includes the JRS Tandem Fabry-Pérot TFP-1 interferometer as the analysis instrument. While describing this experimental arrangement, we will discuss some of the experimental problems that most users will face while preparing a new measurement session, and will give hints on common approaches and best practices to solve them. General procedures in the use of the TFP-1 will be described step by step and will be hopefully useful as a starting point to identify the best method to adopt in each specific case. Following this guide will also be useful to familiarize yourself with the instrument controls and its behaviour.

1 A BASIC BRILLOUIN LIGHT SCATTERING SETUP

Brillouin Light Scattering (BLS) deals with the detection and analysis of laser light scattered by fluctuations of refracting index in a medium. Like in every scattering experiments, we always have a source, a system which sends light to a sample and gathers the scattered signal from it, and a measurement device with its control electronics and data gathering software.

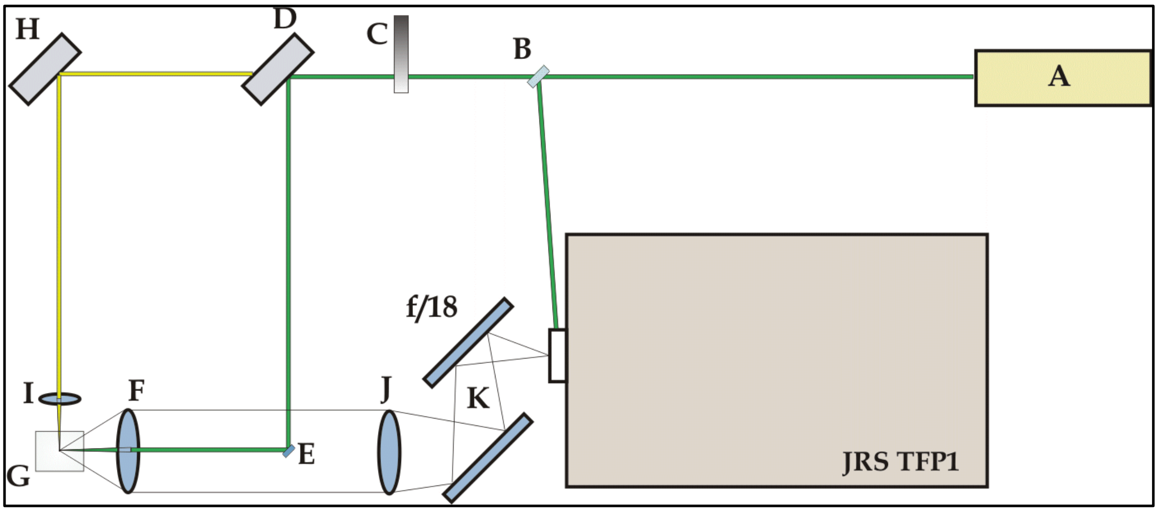

Fig. 1

The typical setup we will refer to is described in Fig. 1: the laser light source **A** generates a narrow collimated beam that hits a beamsplitter **B** (for example a window with AR coating) which sends a small part of it to the JRS TFP1 reference input. The beam then passes through a variable optical density filter **C**, then a slide-in mirror **D** is used to send light alternatively to a back-scattering or to a 90° scattering path (the second one identified by yellow colour). When the mirror **D** is along the path, the light is sent to a small mirror **E** (this could be either a small elliptical mirror or a small 90° prism) and then focussed onto the sample **G** though the central part of a large diameter, short focal length lens **F**. When **D** is removed, light is instead reflected by a second mirror **H** and goes through a smaller lens **I**, whose focus coincides with **F**'s one. In both cases, scattered light will be gathered from the same sample volume by lens **F** and focussed to the input pinhole by a final gathering lens **J**. A couple of mirrors **K** is used to steer the beam inside the instrument, so that both the entry point and the incidence angle can be precisely set. The diameter and focal length of lens **J** must be chosen so that the light beam just fills the f/18 entrance aperture of the interferometer.

1.1 Laser source

The source used by most JRS customers will be a green laser device, commonly a diode pumped solid state (DPSS) laser, or an Ar^+ gas laser device. Solid state laser sources are cheaper and smaller and are available with an output power form a few tens of mW to 2 W or more, with fixed or variable power output.

The first important parameter is obviously the power output from the source. Since Brillouin scattering is a rather inefficient physical mechanism, it would be in principle good to use as much power as possible on the sample, to increase the signal intensity and reduce the measurement time required for an experiment. Increasing the power, unfortunately, also concentrates a very high power density in the micrometric-sized spot of the focussing lens: if the sample is not perfectly transparent or if the scattering is made on the surface of a solid sample, this could lead to local heating of the sample, or even damage of the sample. In case of doubt, a series of measurements at increasing laser power can clarify if a dependence of Brillouin signal from incident power emerges.

Even if the laser source has a variable power output, it is often advisable to have a variable neutral density optical filter (like **C** in Fig. 1) in the light path, since many sources will have significantly better performance in a specific range of power output, with respect to power stability, beam shape or spectral quality.

The spectral quality of the laser source is the second important parameter. Even in best quality single mode laser sources, additional weak lines are produced, in the range of some GHz to tens of GHz from the main laser wavelength. These could produce unwanted spurious peaks if a strong reflected light fraction is sent to the instrument, or equivalently when a very long measurement time is required in order to see a weak sample spectral feature. In case these features should show and cannot be reduced to acceptable levels, JRS can provide an etalon filter (product series TCF) to "clean" the laser light and attenuate strongly these modes.

Every laser source needs some time to reach a stable output condition. It is normal to see variations in intensity, beam shape and divergence during warm-up, so it is suggested to allow warm-up time before starting a precise instrument tuning.

1.2 Optical system for light focussing and signal gathering

In order to observe scattered light from the sample, the laser beam must be directed and focussed to the region of interest. The JRS-1 interferometer requires a part of the laser beam for self tuning and stabilisation, the beam splitter **B** in Fig. 1 is used to send less than 0.5 mW of light inside the instrument. It is useful to have this beam splitter on a kinematic mount, so that the quantity of reference light entering the instrument can be changed by slightly moving the beam around the reference input aperture.

In our back scattering configuration, the same lens will be used to bring the beam to a (generally transparent) sample and to gather light. A small elliptical mirror, or small right angle prism, or a transparent large window with a silvered central spot, are generally used to send the incoming beam to the sample through the centre of lens, while the full surface lens will gather scattered light from the focus point, which coincides with the scattering volume. It may also be necessary to discard the very low angle scattered light, which carries an enormous amount of elastic light, not containing useful information.

If a test of the instrumental setup is required, a transparent poly methylmethacrylate sample (PMMA or Plexiglas) with polished surfaces is a very good sample to use. A Plexiglas block is inexpensive and resistant to shock, has a negligible power absorption, produces a very intense BLS back scattering signal and a noticeable Stokes Raman scattering, so that the position of one or more beams inside it is evidenced by orange colour when green laser protection goggles are used; it can thus be used for safe alignment of multiple beams in space.

As an alternative the 90° configuration can be used. In this case the special mirror E would not be needed once the alignment of the gathering optics **F** and **J** is given. In homogeneous media like

Plexiglas, the 90° configuration allows the detection of transverse as well as longitudinal Brillouin modes; both these features are weaker than longitudinal modes in the back-scattering configuration, and it is critical in this case that the foci of lenses **F** and **I** coincide.

It is generally easy to see where the focus of the intense incoming laser beam lies and to position the focus very close to the ideal position of the scattering volume, possibly after mounting the focussing lens (**F** in Fig. 1) on a movable platform and the sample holder (**G** in Fig. 1) on a movable and/or rotatable stage. After the instrument is operating and the signal from the sample is visible, it will be possible to further optimize the focus position and obtain the largest signal intensity, reducing as well the elastic light fraction, by tilting the reflective surfaces away from the beam direction and keeping the focus position as far as possible from reflective surfaces.

1.3 Instrument input beam setup

Two mirrors (**K** in Fig. 1) are used to send the scattered light inside the instrument. In this position the beam will be generally too weak to be visible, but it is nevertheless necessary that the entrance to the instrument is properly set.
In order to do that, we will suppose that the final lens **J** has been properly placed with its axis coincident with the gathering lens one (**F** in Fig. 1), and with its focus lying on the entrance pinhole plane of the instrument. In this case, it will be only necessary to ensure that the scattered beam comes orthogonally and centred on the pinhole. We can thus suggest the following procedure :

- Ensure that the interferometer's detector is switched off, so that a strong light beam cannot hit the sensitive surface. The output pinhole wheel can also be set at middle between two positions in order to safely block the beam. Move the input selector on the interferometer input pinhole turret from the ordinary "MEASURE" position to the "VIEW" position.
- Attenuate the incoming beam by means of the filter (**C** in Fig. 1) and place an unpolished metallic surface (a piece of brass is generally fine) on the focus of the lens. It is possible to realize when the focus is lying on the surface by looking at the speckles of light sent out from the point of incidence. Be careful to use safe (low) laser power levels.
- Switch on the camera pinhole viewer and select the larger input pinhole. You should see the image of the metallic sample and an intense green spot produced by the scattered light. Reduce further the intensity if the green light is saturating the camera sensor.
- Adjust iteratively both the steering mirrors **K** in order to obtain both the following conditions :
  - the beam entering position is centred with respect to the smallest pinhole (you can progressively move the beam while reducing the pinhole size)
  - the beam comes orthogonally to the pinhole plane : this can be checked by manually placing a small mirror immediately before the entrance pinhole and looking to the centring of the reflected light with respect to the incoming light.
- When a satisfactory alignment has been obtained, remove the metal sample and place again the real sample, restore the original laser power level, switch off the camera viewer software and place the input selector back to the "MEASURE" position. It is always a good practice to leave the detector off and screened until needed.

2 INSTRUMENT PREPARATION FOR MEASUREMENTS

The external setup should be now ready, and providing that the lens focus is correctly positioned inside the sample volume, a very weak scattered light beam should be entering the instrument. The following steps can be taken to prepare the instrument for measurement :

- Select a suitable choice of input and output pinholes sizes. The optimal pinhole choice depends on mirror spacing (refer to the plot in section 3.4 of the interferometer operator manual), while the output pinhole should be set to at least 1.5 times the input size. In our case, we could select a 200 μm input pinhole and a 300 μm output one for optimal resolution.
- Check that the anti-vibration insulation units are correctly operating (both the power LED and the enable yellow LED should be lit on the vibration isolation control unit, with all the red LEDs off), if not proceed as follows :
  - Press the black button on the vibration isolation and switch on the control units.
  - Wait until all the red lights go off, then press the "enable" button.
  - The vibration isolation when the yellow LED stops blinking and remains on. Note that a behaviour different to the one described, or the emission of a high frequency sound from inside the interferometer enclosure, could indicate troubles inside the vibration isolation systems.
- Check that the control unit is switched on, or eventually power it up. Do the following steps :
  - ensure that the detector is off (LED red on the front panel); eventually, power off the detector by means of the switch on the rear side of the interferometer control unit.
  - disable the shutter operation by setting the windows switch to "shutter off"
  - ensure that automatic mirror alignment stabilisation is also disabled (the switch on the control unit front panel must be in the lower position, and the X/Y indicator LED strips react if the corresponding knob is turned)
  - check the scan amplitude LED strip is reporting a scanning movement of the interferometer mirrors, and that it is symmetrically scanning around the central yellow LED; if this is not happening (the scan is asymmetric) :
    - Reduce the scan amplitude value to zero by rotating fully counter clockwise the corresponding knob. The scan amplitude LED strip should now stop scanning and show a single LED.
    - Open the interferometer lid, apply the adjustment tool to the transducer adjustment screw (refer to image in figure 4.2 of the instrument's operator manual) and rotate it gently in order to re-centre the scan amplitude position to the central yellow LED. A very small movement will generally be sufficient.
    - Close again the instrument lid
- Ensure that the instrument optics is in the alignment configuration by checking that the switch on the front wall of the instrument is in the "alignment" position. If not, use the switch.
- Estimate a suitable mirror spacing, according to the expected inelastic frequency shift for the features you want to detect. In our example, to observe light scattering from longitudinal elastic modes in back-scattering geometry from a Plexiglas sample at room temperature and using a 532 nm wavelength laser beam, and have the peak at 3/4 of the first free spectral range, the mirrors should be set to a distance of 7 mm: the peaks are expected to be around 16 GHz and the instrumental free spectral range (FSR) will be slightly more than 21 GHz; we recall that the FSR is defined as c/2d, where c is the speed of light and d is the mirror spacing. Check the actual mirror spacing by looking at the gauge behind the front instrument cover (remove the round cap) and, if necessary, change the spacing to the desired value as follows (refer also to section 2.5.3 of the operator manual) :
  - position the knob on the front wall in the "Z" position.
  - move the horizontal switch on the front interferometer panel to right (to increase the spacing) or to left (to decrease), until the gauge is indicating the right value. The speed of the motion increases with time up to a maximum. For big changes (larger than 2-3 mm) it could be advisable to move the mirrors in successive steps, partially re-optimizing the peaks at every stop, so that the mechanical misalignment due to the operation remains under control. If you move too far and lose the peaks just move back by a mm or so and you should find the peaks again.
  - remember to close the cap on the gauge position after setting the space.
- Check that the scan amplitude distance indicated by the LCD display on the control unit matches the requirements of the experiment. In the case of a Plexiglas sample, we want to see a single FSR scan, so the value can be set to about 520 nm.

After these steps, the instrument is ready for specific alignment, calibration and measurement.

3 MIRRORS ALIGNMENT AND CALIBRATION

When the interferometer mirrors lose alignment, as always happens when the instrument has been switched off or otherwise left without stabilisation for several minutes, they need to be manually realigned. This is done by means of the "alignment mode" optical configuration. If you followed all the steps of the previous section, this mode should be already selected.
To align the mirrors at the currently selected mirror spacing, proceed as follows :

- close the input pinhole by setting it between two positions, or otherwise block the input with some kind of screen, so that no light can enter the instrument through the input pinhole.
- switch on the detector
- select 1024 channels on the control unit channel number switch (10^{10} position).
- start the GHOST application on the data gathering PC and start observing the signal. For a proper configuration and use of this application, please refer to the specific manual from JRS.
- the two interferometers should produce two series of negative peaks with respect to a flat noisy intensity level. When slightly less than a single order is scanned, up to 4 peaks (2 + 2) should be visible in the range (in Fig. 2, FP1 is already aligned and produces larger negative peaks, while FP2 is not completely optimized yet). Do the following :
    - By moving the X1+Y1 knobs and X2+Y2 knobs, identify the peaks produced by mirror FP1 and FP2. Notice how the Z knob on the control unit is able to shift the whole spectrum sideways, while the ΔZ knob shifts only the FP2 peaks.
    - Check the level of light, that could be safely set to up to 300 counts per scan when operating at 1024 channels. This level is related to the intensity of the reference light entering the instrument, and can be changed by moving the reference beam sideways, so that a variable fraction of it can reach the instrument.
    - try to obtain the narrowest and deepest peak shape for both FP1 and FP2, and look at the LED strips indicators for X and Y. If anyone of the indicators is on the red positions or quite close, it is advisable to re-centre them by using the corresponding mirror motors (refer also to section 2.5.4 of the operator manual). In this case, move the mirror motors knob to the appropriate position and use the horizontal switch on the instrument front panel to move them in one sense or the other. Look what is happening to the peaks to understand if you are moving in the right sense. After this correction, it is advisable to put the front knob to the "off" position.

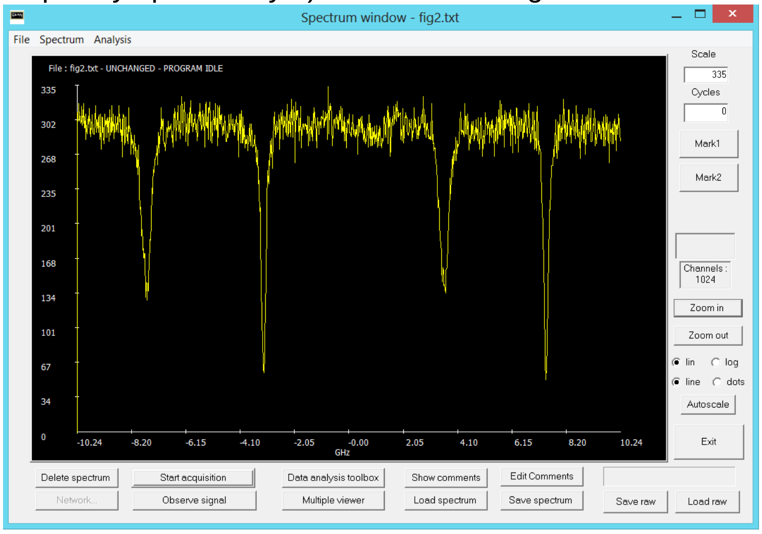

Fig. 2

At this point, the instrument is ready for tandem mode setup and measurement, but often at this point frequency shift calibration is needed. This calibration is necessary in order to have a precise scaling of the frequency axis, i.e. to know with the best accuracy which is the scan amplitude, in

GHz, while a measurement is performed. Refer to the GHOST software manual on how to do calibrate the frequency shift axis.
As an alternative, a quicker but less accurate estimate can be obtained for the scan amplitude indicated by the front panel LCD by means of the formula :

$$\Delta\nu = \frac{\Delta L}{\lambda} \text{ x FSR},$$

where $\Delta\nu$ is half the frequency range scanned, ΔL is the range of motion of the piezoelectric transducers as reported by the LCD display, and λ is the laser wavelength used. This formula is also used in the software spectrum comments window of the GHOST application.
The reliability of this value can decrease with time and should be periodically checked by comparing with a precise calibration, eventually compensating any drift (see operator manual section 4.2.1). If this has been done, the LCD value can be used as calibration in low precision measurements or for instrument testing, or to quickly estimate the position of spectral features appearing on a new sample.
Once a calibration has been done, it will be valid until one or more of the following things happen:

- ✓ the distance of the mirrors is mechanically changed by moving the Z motor
- ✓ the scan amplitude range is changed
- ✓ the scan amplitude range indicator is centred by rotating the internal screw with the needle tool

Other operations, like switching on and off the detector, opening or closing the lid, changing the pinhole sizes or switching from tandem to alignment mode and vice versa, will not change the frequency shift range.
After a calibration of the frequency range has been completed, a measurement can be performed :

- set the number of channels (i.e. accumulation time per channel) to the preferred value; in the case of Plexiglas, it should be possible to obtain a very good spectrum in a reasonable measurement time even at the largest setting (10^{10}).
- start observation of the signal in the GHOST software (if not already in place)
- align the interferometers so that all the alignment peaks look as sharp and as deep as possible
- moving the Z knob, change the position of the features referring to FP1 until one of those is in the horizontal centre.
- move the ΔZ knob to drag one of the FP2 features to the horizontal centre as well.
- move the front panel switch to TANDEM mode and wait until a peak appears at the centre.
- move the knobs ΔZ, X2+Y2 and X1+Y1 (we suggest this order, iteratively) in order to increase the intensity of the peak as much as possible. It should be possible to increase the peak intensity at least up to the previous alignment mode peaks negative intensity.
- when no further optimization is apparently possible, switch on the stabilisation control on the control unit.
- move the shutter control switch to the (upper) "window" position. The noise of the shutters closing and opening should be heard, while the software starts to paint in a different colour the regions where shutters are operating, i.e. where the windows are set. The window positions and width are to be set properly according to the measurement conditions, using the five little white knobs at the right on the control unit front panel. In our case, we will need only a single window at the centre of the spectrum: rotate the upper knob to enlarge or reduce the amplitude for the central window, and rotate fully counter clockwise (zero width) the knobs for the second and third windows width in order to disable them. Experimenting with window positioning and width is not harmful for alignment or for the instrument.
- put back the input pinhole wheel to the correct input pinhole position, or remove the screen for scattered light in front of it; counts related to Plexiglas signal peaks should start to appear within the spectrum. If necessary, zoom in or out to change the gain.
- stop observation mode in the software and start acquisition of measurement. The length of the measurement depends on the signal strength : in the case of Plexiglas, 100-300 cycles should be already sufficient for a good spectrum quality. Save the data file.

If no new measurements have to be taken, the instrument can be left even for a long time in the stabilised condition. The stabilisation control will keep alignment between the mirrors as long as possible. If some operation is done in the sample area, that could send strong light inside the instrument, it is recommended to screen the input pinhole; this will not prevent the instrument to remain aligned, since the stabilisation circuitry runs only on the reference light. The detector can be also switched off, but in this case the optimisation system will not work anymore and the alignment will be soon lost.

If the interferometer is not needed anymore and it needs to be switched off we suggest to :

- Switch off the stabilisation system.
- Screen the input pinhole or put its selection wheel in an intermediate position .
- Switch off the detector.
- Stop observation or acquisition on the software.
- Switch off the control unit.
- Disable vibration isolation and then switch off the vibration isolation control unit.

4 DATA ANALYSIS

After completing any real measurement, a data analysis session is usually necessary to obtain valuable physical information from them. After making 100 cycles of acquisition in the backscattering configuration, a BLS spectrum from Plexiglas could look like the one depicted in Fig. 3. The visible components are:

- a central and very intense peak produced by elastic light coming from the reference beam, used for alignment of the instrument. This peak is usually only meaningful as instrumental response function.
- a pair of Brillouin peaks produced by the interaction of incoming light with longitudinal acoustic waves inside the sample, at about 16 GHz. When operating in 90° scattering, the frequency will be lower and a couple of additional peaks due to transverse modes could be present as well.
- a white noise floor, in the order of a few counts per second per channel, produced by the photon counter independently from any possible signal produced by the sample.

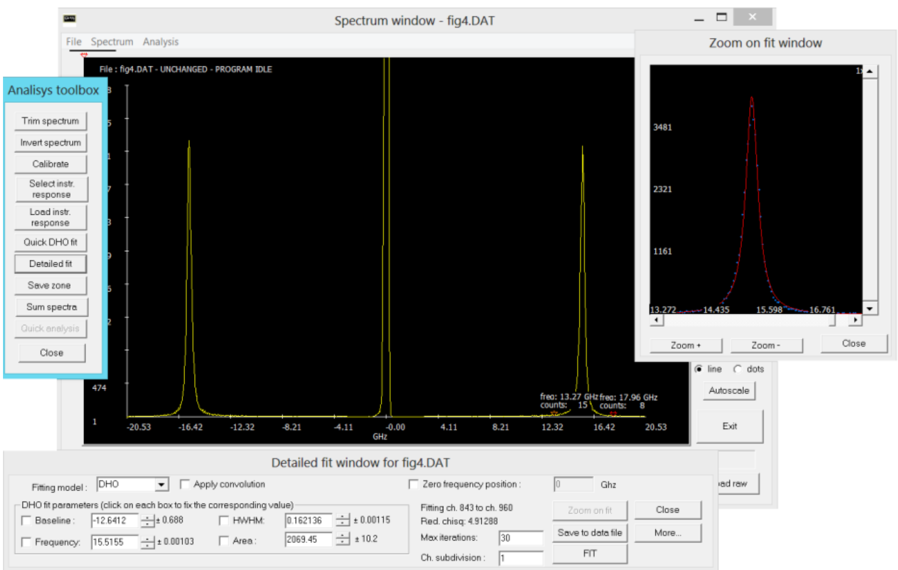

Fig. 3

The Brillouin peaks are the only part of interest in this case; peaks produced by sound waves in glassy materials can be normally analysed by means of a Damped Harmonic Oscillator function (DHO). One of the visible BLS peaks can thus be selected and analysed by means of GHOST fitting tools, as done in Fig. 3 (refer to GHOST manual for details). A frequency of 15.5 GHz was obtained, together with an apparent line half width of 0.16 GHz.

These values can be related to the speed and attenuation of hypersonic elastic waves inside the material, providing that the index of refraction at the wavelength used is known. In the simplest case, the formulas to be used are

$$\begin{cases} c = \dfrac{\omega}{q} = \dfrac{2\pi \cdot f}{q} \\ \alpha = \dfrac{4\pi \cdot \Gamma}{c} \end{cases},$$

where c is the speed of sound, ω and f are respectively the angular frequency and frequency of the Brillouin peaks, q is the light scattering exchanged wavevector, α is the sound extinction coefficient and Γ is the Brillouin peak half width.