Correlation-based Brillouin sensing using an injection-locking technique

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The injection locking technique is successfully applied to the correlation-based technique, resulting in a simple and efficient experimental configuration. A 1-cm resolution was readily obtained and can be significantly improved.

Traditional Brillouin sensing in optical fibres using a pulsed pump are limited to a meter spatial resolution as a result of the pump spectral broadening. This well-known limit was considered for a long time as impossible to overcome until Hotate proposed a novel technique that can potentially improve the spatial resolution to the phonon absorption length that is in the 100 μm range [1]. This breakthrough was possible using an entirely different method for localizing the interaction, based on the correlation of synchronously frequency-dithered pump and probe signals. The technique was gradually improved until a 1-cm spatial resolution was demonstrated [2].

On the other hand the injection-locking technique turns out to be a very powerful method to generate the proper signals for a Brillouin interaction, i.e. a pump and probe lightwaves separated by a varying frequency in the 10 GHz range and with a 1 MHz stability [3,4]. The technique requires a limited amount of devices and can avoid the implementation of an expensive electro-optic modulator. The possibility to realize distributed measurements is also demonstrated and very clean spectra are obtained using this method.

It is thus very tempting to try to merge the two techniques, considering that the injection-locking technique can generate very simply and naturally the proper lightwaves for the correlation. We report here the first successful implementation of the correlation technique using injection-locking of two semiconductor lasers.

Once the injection-locking set-up was modified for correlation-based measurements, we improved very rapidly the spatial resolution to obtain a spatial resolution equal to the 1 cm measured using the sideband technique. This results from the excellent noise-free signals generated by the injection locking.

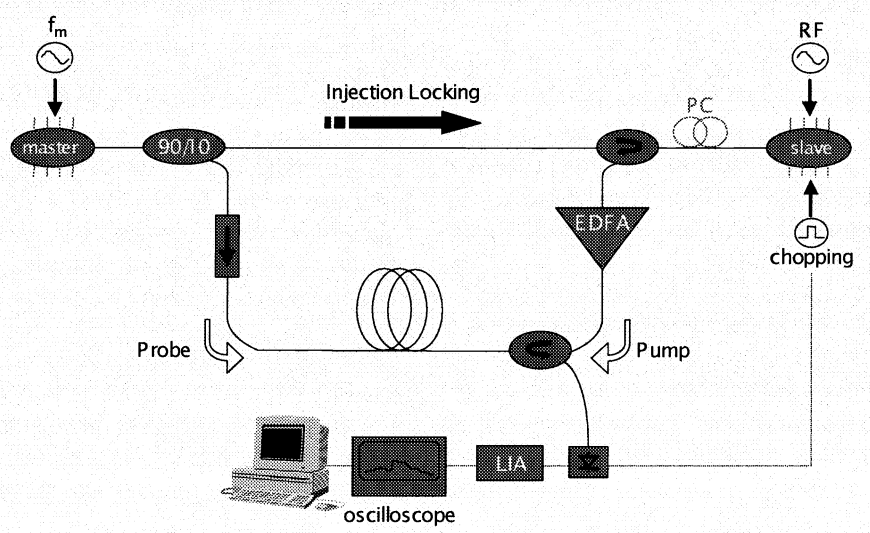

Fig. 1 Block diagram of the injection-locking experimental set-up for correlation-based Brillouin distributed measurements.

Experimental set-up

The experimental configuration for the correlation-based distributed sensing using the injection-locking is shown in Fig. 1. The semiconductor lasers are commercially available DFB modules, the slave laser having an integrated electro-absorption modulator with a 10 GHz bandwidth. Injection is performed through the built-in isolator of the slave laser. This is possible only as a result of the moderate power needed for a proper injection locking.

A first short fibre line – the locking channel - is used to lock the frequency of the slave laser to the free running master laser by injecting a small quantity of the master light into the cavity of the slave laser. This latter is directly modulated in intensity at a frequency within the Brillouin shift range, thanks to the integrated electro-absorption modulator. This creates a small sideband that will be used for injection locking.

The master light (wavelength 1557 nm, maximum power 30 mW and half-bandwidth close to 1 MHz), used as the probe for Brillouin sensing, is frequency-dithered at a rate f_m and amplitude Δf. This is achieved by directly modulating the current of the laser, as in the classical technique. Of course there is an associated residual intensity modulation that turns out to have a minor impact in this configuration, as explained below.

The first lower sideband of the slave laser (pump signal) is locked to this injected signal and then takes the same frequency characteristics as the master light [5,6], including phase noise. But the slave emission does not contain the intensity modulation of the master, so that a constant intensity is actually emitted by the slave. For sensitive lock-in detection the Brillouin interaction efficiency can be easily periodically suppressed by unlocking the slave laser. This is actually achieved by slightly changing its bias current, so that its free-running emission frequency shifts out of the locking range.

Since a higher sensitivity is obtained when the pump is chopped, the slave was chosen to be the pump and the master the probe. In addition the slave emits at a constant power, resulting in a flat response due to the constant pump power.

The proper injection-locking condition is checked by observing the slave emission spectrum using a Fabry-Perot interferometer. The system is properly set when the slave spectrum shows the typical aspect of a broad amplitude FM modulation spectrum, i.e. 2 symmetric peaks as shown in Fig. 2. A broad FM amplitude Δf extending to several GHz is possible, as the frequency locking range depends only on the injected power [7]. The amplitude Δf is a critical quantity, since a larger Δf means a better spatial resolution.

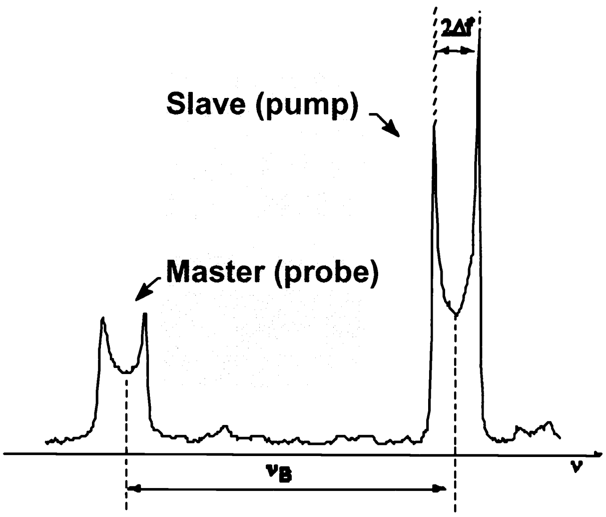

Fig. 2 Fabry-Perot scan of the emission of the slave laser under proper operation, showing the typical FM spectrum and the identical modulation spectra of master and slave lasers.

The second fibre line – the measurement channel - is dedicated to the Brillouin sensing. A 10% fraction of the master light is used as the probe signal, while the slave light is redirected by an optical circulator to an EDFA for amplification to make the suitable pump signal. An isolator is inserted to avoid the master light to be perturbed by the pump power. The local amplification of the probe light is chopped by the periodic presence of the pump in the Brillouin interaction range and is detected by a slow photodetector followed by a lock-in amplifier (LIA).

Data are then collected by an oscilloscope synchronized to the frequency sweep of the FM modulation, corresponding to a position scan along the fibre. A trace is recorded for a set of microwave frequency difference between the two waves, in order to get the complete distributed Brillouin spectrum.

Unlike the standard correlation-based Brillouin technique [1], the zero-order correlation peak is placed at the position of the slave laser cavity. This makes the design of the experiment easier by avoiding a double length measurement channel. Nevertheless care must be taken to avoid the presence of any correlation peaks within the spare fibre segments.

Results

Fig 3 shows 2 distinct Brillouin shift measurements performed over 15 cm of standard optical fibre. A hot spot is realised by placing the fibre on small Peltier thermo-elements (1 cm and 2 cm respectively). The frequency-dithering modulation is $f_m = 22$ MHz, which is slightly smaller than the Brillouin linewidth, and the frequency modulation amplitude extends up to $\Delta f = 4$ GHz. The curves show a plateau even for a 1 cm hot spot, demonstrating a resolution better than 1 cm.

The gradual transition from ambient temperature to the hot spot does not show the limitation due to the spatial resolution. It results simply from the thermal conduction along the optical fibre. The actual resolution cannot be simply visualized from these measurements, the 1 cm resolution being granted by obtaining the same value for the Brillouin shift in the 2 experiments. But by comparing the length of the plateau with the actual sample length, we can estimate the spatial resolution to be 4 mm.

The step-like aspect of the Brillouin frequency distribution along the fibre results from the yet imperfect processing of the data. We are working at developing an algorithm dedicated to the special case of the correlation technique.

To avoid the problem related to thermal conduction we are also developing short strained segment of fibre, so that sharp transitions can be observed. This is under preparation.

Conclusion

For the first time we have experimentally demonstrated that the injection locking technique can be efficiently applied to the correlation-based method for distributed Brillouin measurements. Performances equivalent to those reported to date for the classical technique were readily obtained, namely a 1 cm spatial resolution.

But the technique can be still improved by increasing the injected power into the slave, so that a larger frequency dithering amplitude may be obtained. This would require special DFB modules with no built-in isolator. Such modules are still unavailable off the shelf.

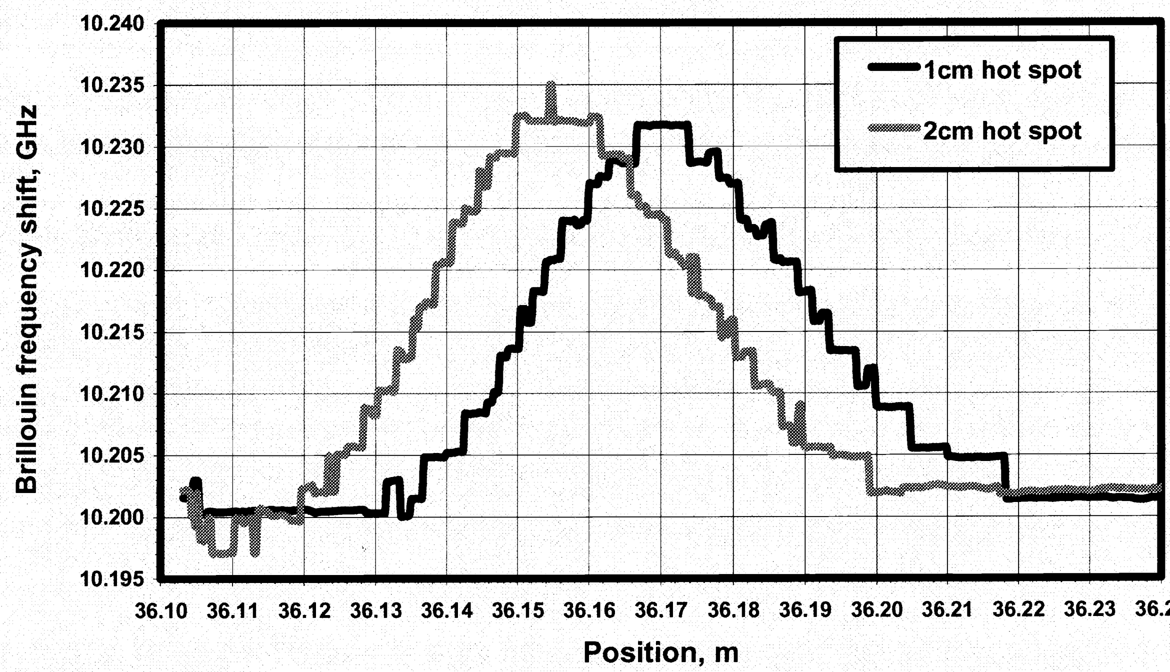

Fig. 3 Measurement of 2 different hot spots at 60 degC, with dimensions of 1 and 2 cm, respectively. The smooth transition results from the thermal conduction along the fibre and does not indicate the spatial resolution.

We are confident that a 1 mm spatial resolution can be obtained in a near future using the injection locking technique. Nevertheless the fibre itself as sensing element is already observed to be the limiting factor, regarding the 3 cm decay length related to intrinsic thermal conduction and the strain non-uniformity associated to the fibre finite cross section.

References

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