Novel configurations based on laser injection locking applied to Brillouin fibre sensing

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Injection locking of two DFB semiconductors opens new possibilities to generate effective signals for fibre sensing. This is illustrated through the application to distributed Brillouin sensing that shows significant progress with respect to established techniques.

In 1665 the famous scientist Christiaan Huygens observed two clocks hanging on the wall. He noticed that the pendulums of the clocks began to oscillate in phase if the clocks were brought close enough to each other, but oscillated independently when hung further apart. Huygens explained the coupling between the two clocks by mechanical vibrations transmitted through the wall. This anecdote is one of the first documented observations of the coupling of two oscillators by injection locking.

The injection of a weak periodic signal into a more powerful free-running oscillator may give rise to a variety of injection locking phenomena. Typically the initially free-running oscillator (named the *slave* oscillator) leaves its own resonant frequency to synchronize itself with the external signal; it then gets phase locked to the injected signal from the so-called *master* oscillator, which thus controls the slave oscillator without being influenced by this latter. Injection locking effects may occur in virtually any kind of self-sustained oscillators, such as mechanical, electrical and laser oscillators.

In this paper we shall address the important case for applications in which two DFB semiconductor lasers are in a master-slave configuration. We first present the advantages of injection-locking for optical signal processing and then show that the benefits of injection locking go beyond the simple case of a faithful replication of the master spectrum by the slave. Finally we demonstrate the application of injection locking to the important case of Brillouin fibre sensor and we show for the first time distributed measurements achieved using such a configuration.

Principle

The experimental realization of an injection-locking using pigtailed DFB lasers is in essence extremely simple, as shown in Fig. 1. Care must be only taken to properly isolate the master laser from any light injection from the slave and to make the polarisation states of the 2 lasers matched within the slave cavity.

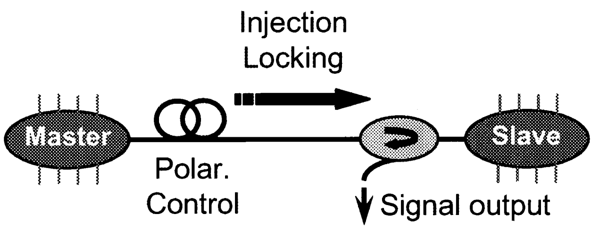

Fig 1 Basic injection-locking configuration of 2 DFB semiconductor lasers. The circulator isolates the master from any light of the slave and provides a lossless output.

An important parameter is the so-called *static locking range* $\Delta\nu_{max}$, that corresponds to the maximum difference between the free-running frequencies of the master and the slave making the frequency locking possible. In other words the frequencies of the 2 lasers must be tuned to lie within an interval $\Delta\nu_{max}$ to enable the stable locking of the slave onto the master frequency.

According to standard models the static locking range is closely related to the ratio ρ between the injected master and the slave emission powers within the slave cavity [1,2]. It follows a square root relationship:

$$\Delta\nu_{\max} = \frac{V_g}{2L}\sqrt{(1+\beta_c^2)\rho}$$

where V_g is the group velocity, L the laser cavity length, and β_c is the linewidth enhancement factor.

This equation shows that the higher the power injection ratio ρ, the broader the frequency locking range $\Delta\nu_{max}$. It turns out actually in standard DFBs that for values of ρ above $2\cdot10^{-5}$ unwanted relaxation oscillations are observed in the slave spectrum. And for $\rho>2\cdot10^{-4}$ the spectrum turns fully chaotic [1]. For $\rho=2\cdot10^{-5}$ the static locking range $\Delta\nu_{max}$ is typically between 500 MHz and 1 GHz. It means that the free-running frequencies of the 2 lasers must be initially very close to observe injection locking.

Inversely a power injection ratio below 10^{-6} results in an injected power so low that it is dominated by the Rayleigh scattered slave light from the pigtail and to a static locking range comparable to the laser linewidth.

In summary a power injection ratio in the range of 10^{-5} is ideal to properly achieve injection-locking. This corresponds approximately to the amount of power that leaks through a standard isolator in the isolating direction, so that a standard DFB isolated pigtailed module can often be used unmodified for injection locking by simply feeding the master light into the slave pigtail and then through the built-in isolator. This injection ratio condition is valid for static emission. When the lasers are modulated and the emission frequency is swept, a higher ratio is usually required for a proper locking.

Configurations for the generation of advanced signals

Beyond the trivial case of injection locking when the slave laser simply perfectly replicates the master CW emission, it is less known that more interesting configurations can be set up to achieve more sophisticated signals. In particular the traditional drawback of mixed FM-AM modulation resulting from the direct modulation of a laser diode can be overcome to a wide extent using injection locking. Traditionally pure AM, FM and SSB modulation spectra are obtained using a single or a combination of expensive external modulators. It can be shown that the same result can be obtained with excellent performances using an injection-locking scheme with 2 DFB lasers that is frequently very cost-effective.

Pure AM modulation: This is achieved by operating the master laser in CW mode and modulating the current of the slave at the modulation frequency. The carrier of the slave locks on the master emission line, resulting in no frequency dithering and therefore no unwanted FM modulation, as shown in Fig. 2, where the spectrum is substantially narrowed and becomes symmetrical as expected for pure AM. The amount of injected power into the slave must be carefully set to obtain the proper emission characteristics.

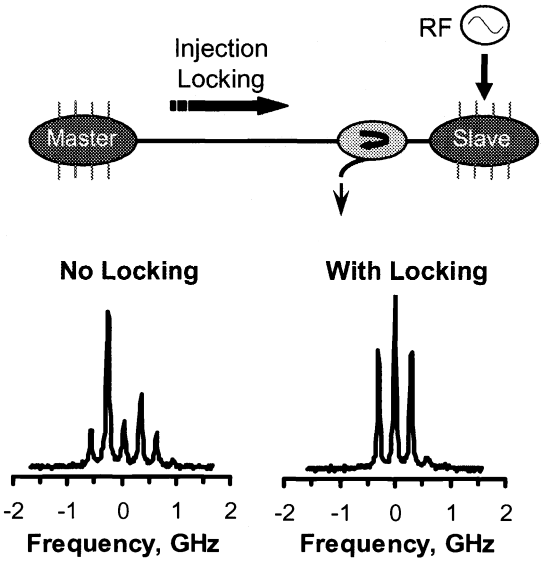

Fig 2 Injection-locking configuration for pure AM modulation. Spectrum of the slave laser is shown before and after locking to the master laser

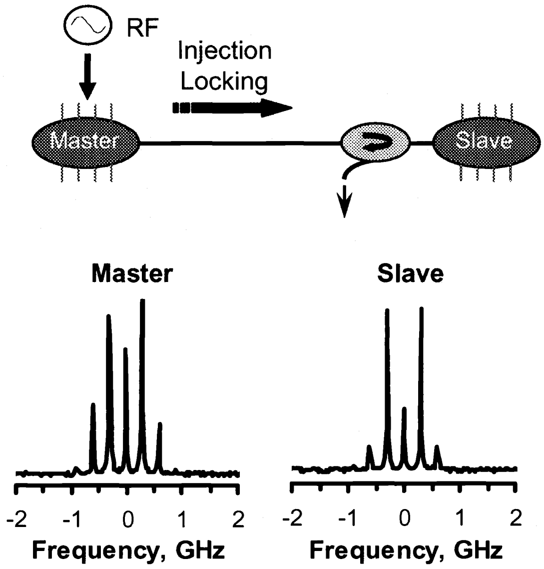

Fig 3 Injection-locking configuration for pure FM modulation. Spectra of the master and of the slave laser are shown.

Pure FM modulation: In this case the current of the master laser is modulated at the modulation frequency while the slave is operated in CW mode. The instantaneous frequency of the slave laser locks onto the instantaneous emission line of the master. The slave shows no significant change of its emission power, resulting in a pure frequency dithering, as shown in Fig 3 where the slave spectrum is broad and symmetrical. Here the operating condition requires that the instantaneous frequency range lies within the locking range.

SSB modulation (optical frequency shifting): This is simply achieved by modulating the current of the master laser and by locking the slave on one of the modulation sidebands. The frequency difference of the 2 lasers is thus perfectly stable [2,3,4]. It must be pointed out that the slave laser may be locked as well on a higher-order sideband, resulting in an optical frequency difference that is a multiple of the applied modulation frequency. This is particularly convenient in the microwave domain and locking up to the fifth harmonic was successfully achieved in our team.

It is also possible to apply the current modulation to the slave and to obtain the same result. In this case one of the modulation sideband of the slave laser locks onto the master CW emission. This is formally equivalent when one considers the modulation process in the laser as a coherent coupling between two waves separated by a frequency given by the modulation. Of course an external modulator of any type can be used as well. Such a scheme may be more convenient in some experimental configurations, such as the Brillouin experiment described below.

Other smart configurations are possible using the large potentialities of injection-locking. Let just mention the possibility to make a very simple optical frequency sweeper [5].

Configuration for Brillouin sensing

The schematic diagram of the injection locking configuration for Brillouin sensing is shown in Fig 4. 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 built-in electro-absorption modulator. This creates a small sideband that will be used for injection locking.

It must be pointed out that the injection locking is performed through the built-in slave isolator in the blocking direction. The leakage power resulting from the imperfect isolation (35dB) turns out to be sufficient to lock the slave laser. This feature makes possible the use of a standard commercial device with no further modification.

This configuration provides 2 outputs with distinct optical frequencies showing the ideal stability given by the microwave generator. These outputs can be simply delivered in 2 separate fibres using couplers

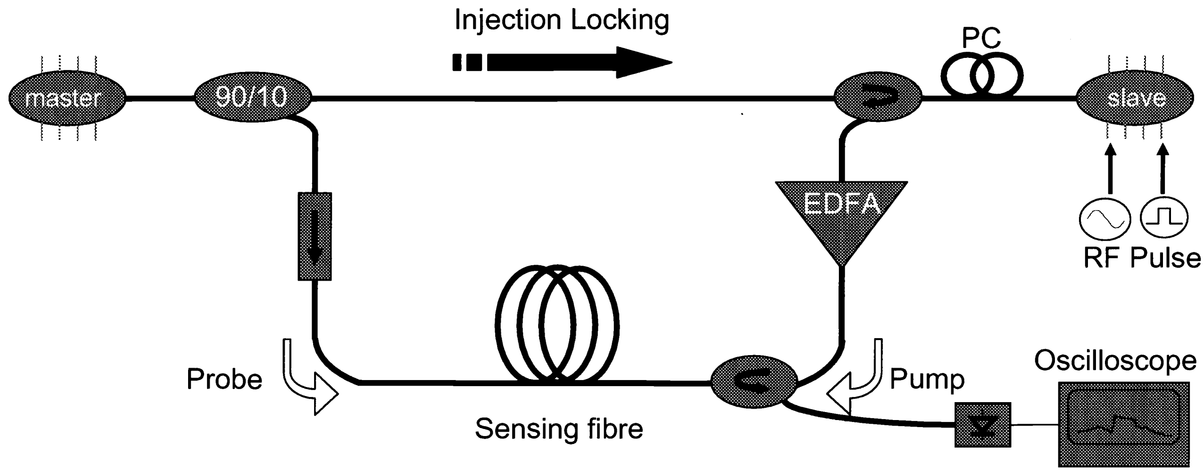

Fig. 4 Schematic diagram of the injection-locking configuration for Brillouin sensing. The master injection into the slave is performed using a dedicated short fibre channel to secure a stable injection as far as amplitude and polarisation are concerned. Note that the probe light is supplied by the master and the pump by the slave, since the master emission is maintained steady.

and circulators, as shown in Fig 4. The role of the pump can be played by either the master or the slave [6]. It just depends on which sideband the slave is locked (upper or lower). Unlike the sideband technique [7] no other idle wave is present in the set-up, except the residual modulation sideband with very low amplitude. This turns out to very significantly improve the noise characteristic of the technique.

For this reason the master laser was selected to deliver the probe signal, since it is CW operated with no modulation and thus contains a pure single frequency. This is the only detected signal and the noise is consequently minimized. The power of the slave laser is boosted through an erbium-doped fibre amplifier to act as the pump in the Brillouin interaction. As for most other techniques [7] the Brillouin gain spectrum is scanned by simply changing the microwave generator frequency. Care must just be taken to ensure that the locking range exceeds the frequency scanning range.

As described so far the configuration makes possible the measurement of the Brillouin gain spectrum only integrated all over the entire length of the fibre placed in the measurement channel [2,6]. But it is well-known that the best benefit of Brillouin sensing is the possibility to perform distributed measurements using a localized interaction. This is traditionally achieved using a pulsed pump or probe wave for long range measurements and by retrieving the local information in the time domain.

In the injection-locking configuration this could be simply achieved by inserting an external intensity modulator operated as a switch just before the erbium-doped fibre amplifier. But the set-up would suffer from the same drawbacks as the sideband techniques, namely the use of an expensive and

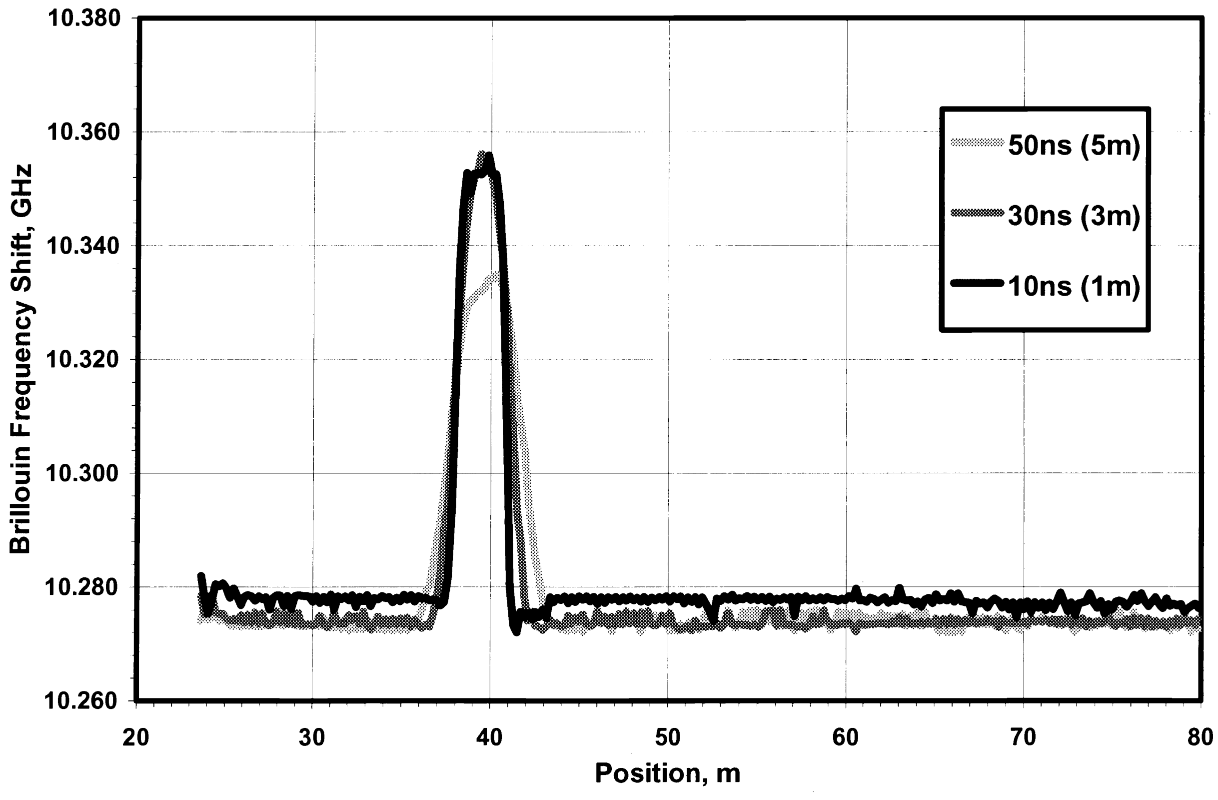

Fig 5 Distributed measurements of Brillouin frequency along a 100 m fibre subject to a 2 m hot spot, with different pulse widths. The 50 ns (5 m) pulse does not fully resolve the hot spot, as expected. The length of the abrupt transition between the room temperature segment and the hot spot corresponds to the pulse width, showing no transient effect due to a non-instantaneous locking and demonstrating the rapidity of the process. The noise is remarkably low, even with a 1 m spatial resolution, considering the low pump power of 60 mW and the small amplification contrast, accordingly.

poorly available electro-optic modulator.

Another solution was investigated by directly modulating the pump laser current, i.e. the slave in the injection locking set-up. Using a pulse current to turn on the laser is actually impracticable, since the transient behaviour during the turn-on process results in a delayed oscillatory response of the laser power. The duration of this transient behaviour is typically comparable to the required pulse width in a distributed Brillouin measurement (10-50 ns).

We found another solution to overcome this problem, considering that the frequency response of a fully emitting laser exceeds 1-2 GHz. The pump laser is always on and its operating current is set, so that none of the emission lines (carrier+sidebands) lie inside the locking range and the Brillouin gain spectrum. It is sufficient to lower the laser bias DC current by a couple of milliamps, corresponding to a frequency shift slightly greater than 1 GHz. The slave laser is therefore unlocked and its emission is out of the Brillouin gain spectrum, so that no interaction takes place and the observed probe signal shows no variation in the time domain.

When a current pulse is applied to the slave to move its free-running frequency into the locking range, it rapidly locks and the interaction takes place. When the pulse is stopped, the locking condition is no longer satisfied and the slave free-running frequency is again out of the locking range and of the Brillouin spectrum, so that no interaction is possible. The Brillouin interaction is therefore possible only during the pulse duration, just like in the classical time-of-flight technique, even though the pump is always emitting and shows therefore no transient turn-on behaviour. A frequency coding in the time domain simply substitutes the classical power coding.

The only unknown parameter is the actual time needed for the slave to lock on the master frequency. Theoretical models show that this time is significantly shorter than 1 ns, so that we implemented this frequency-coding configuration with confidence. Fig 5 shows the obtained distribution of Brillouin frequency along a 100 m fibre with a 2 m hot spot using different pulse widths. It clearly shows that the measurement is possible even with pulses as short as 10ns (1 meter) and the hot spot is perfectly resolved in this case.

These measurements were obtained with a pump power of 60 mW. The quality of the measurement was surprisingly good and the observed noise much lower than in the sideband technique using a Mach-Zehnder modulator [7]. This is certainly due to the absence of co-propagating waves at other frequencies with the probe signal.

Conclusion

In this paper it is demonstrated that injection-locking is a powerful technique to generate efficient signals for sensing applications. In particular interesting modulation schemes can be simply obtained without using a set of costly extra devices. This is illustrated by the application of injection locking to Brillouin distributed sensing.

The first results are definitely promising, demonstrating the flexibility of the technique and the excellence of the obtained signals with moderate equipment. This results in low noise signals that make possible to still improve the range and the resolution of the Brillouin sensing.

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