Highly flexible short-pulse generation and high sensitivity sensing with stimulated Brillouin scattering in optical fibers

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Abstract. We demonstrate two novel types of applications using the same generator as a source for Brillouin multi-wavelength generation. The first is as a highly flexible picosecond pulsed laser source which is tunable in time duration, repetition rate and emission wavelength for optical clock applications in telecommunication. The second application is a high sensitivity distributed Brillouin sensors (DTS) to lower costs and widen the market sector. We demonstrate tunability of the pulsed laser source from ~15 ps down to ~3.5 ps over the whole telecommunications C-band by simply controlling the number of Stokes waves being generated forming a phase-locked Brillouin frequency comb. The repetition rate is the Brillouin frequency shift of ~10 GHz which can be tuned by changing the gain fiber within the cavity. An increase in the standard temperature sensitivity of DTS of ~1.3 MHz/°C by 6 fold is also demonstrated. This increase is of great importance in DTS, since the detection of any variation can be made faster, which can enhance the functionality of such sensors.

1. Introduction

Brillouin scattering (BS) has for a long time been considered a nuisance in optical fiber transmission systems. Several schemes for its mitigation have been explored [1], and recently, the possibility of eliminating it altogether has been suggested by Ballato and Dragic [2]. However, there have also seen many fruitful applications of BS in optical fibers. For example, slow light generation [3], Brillouin amplifier [4], Brillouin laser cooling [5], multi-channel Brillouin laser [6] and also many types of strain and temperature sensors [7-9]. Although many types of Brillouin lasers have been proposed [10], [11], we propose a novel way to emit pulses using higher order SBS Stokes waves in, based on our first demonstration in 2012 [12]. A pulse duration in the order of a few picoseconds is achieved as well as a tunability from 1540 nm to 1565 nm is demonstrated in both the time and frequency domains. We also investigate the influence of the higher order Brillouin Stokes waves to increase the temperature sensitivity of distributed Brillouin based sensors. A cross-heterodyne detection which avoids expensive spectrum analyzer by reducing the beat frequency to near DC, is also shown.

2. Theory

Stimulated Brillouin scattering (SBS) is a well-known 3rd order nonlinear effect which is caused by the coupling and enhancement via electrostriction, from a pump wavelength and an acoustic wave (acoustic phonon) which generates a backward travelling wave in optical fiber, shifted by ~10GHz, called a Stokes wave. The frequency shift is determined by equation (1) below:

\[ \nu_{\text{B0}} = 2n_p V_A / \lambda_p \]  

Where \( n_p \) is the effective refractive index, \( V_A \) the longitudinal acoustic phonon velocity and \( \lambda_p \) the pump wavelength. This Brillouin frequency shift also exhibits a linear dependence over temperature and strain which can be expressed such as:

\[ \nu_b(T, \varepsilon) = \nu_{\text{B0}} + C_T(T - T_0) + C_\varepsilon(\varepsilon - \varepsilon_0) \]  

Where \( C_T \) is the temperature frequency coefficient, \( C_\varepsilon \) is the strain-frequency coefficient and \( \nu_{\text{B0}} \) is the Brillouin frequency shift at a reference temperature \( T_0 \), and strain reference, \( \varepsilon_0 \).
the frequency comb can be represented as for a single resonant cavity scheme (which will be explained in the next section):

\[
f_{\text{comb}} = n \nu_g(T, \varepsilon) + 2n \nu_g(T, \varepsilon) + 3n \nu_g(T, \varepsilon) + \ldots + n \nu_g(T, \varepsilon)
\]  

(3)

In which \(n\) represents the number of Stokes waves being generated. For a dual cavity configuration, this will be doubled \((2n)\). The frequency shift of each element can be detected by beating a reference frequency comb source (reference temperature or strain) and a sensing source from a fiber experiencing temperature/strain variations. This lead to a beat frequency spectrum, in which the term \(\nu_{\text{ref}}\) from equation (2) cancels out and thus the only beat signal is generated from the difference in frequencies induced by temperature or strain variations, between the two fibers. This beat note can be represented by the following equation:

\[
\nu_{\text{beat}} = \nu_{\text{ref}}(T_0, \varepsilon_0) - \nu_{\text{ten}}(T, \varepsilon) = \sum_n \left\{ C_{n,T} \Delta T + C_{n,e} \Delta \varepsilon \right\}
\]  

(4)

Where \(C_{n,T}\) and \(C_{n,e}\) are the respective coefficient of temperature and strain dependence related to the \(n^{th}\) Stokes order in which the 1st Stokes wave of the reference generator will beat with the 1st order Stokes of the test generator and so on, being displayed at the output by an electric spectrum analyzer.

3. Experimental setup

We proposed two cavity configurations for our applications. The first cavity has even and odd Stokes waves at the output together spaced by the natural Brillouin frequency shift of \(~10\)GHz. The other has only the odd or even Stokes waves at the output, spaced by twice the frequency shift \((~20\)GHz), as shown in Figure 1.

\[
\sim 10 \text{ GHz Configuration} \quad \sim 20 \text{ GHz Configuration}
\]

Figure 1. (a) Experimental setup for self phase-locked SBS pulse generation, for a unique cavity system using even and odd Stokes waves together and (b) the even/odd Stokes separately.

For the single cavity (figure 1(a)), a Sagnac loop interferometer can be used as a reflective mirror [13] or a gold tipped mirror to allow all the Stokes waves to travel in the same direction. As for the dual cavity (figure 1(b)), a second circulator is used to separate the odd from the even Stokes waves and depending on the position of the output coupler, the user can use either. The main difference is in the repetition rate of the SBS pulsed laser, since by Fourier transform, the spacing between two frequencies determines the repetition rate of the pulse train. The total bandwidth determines the pulse duration, which in this case is unchanged.
4. Results

By controlling the power of the seed laser, and the gain of the in-cavity EDFA, it is possible to control precisely the number of Stokes waves being generated and thus the pulse duration. Figure 2(a)-(b) present this duality in which the number of Stokes waves within an arbitrary criterion of a -20 dB bandwidth are increased from 5 to 28 in the single cavity configuration, which leads to pulses changing from 15.4 ps to 3.65 ps. Figure 2(c), shows the tunability on is presented over C-band covering from 1540 nm < λ < 1565 nm.

**Figure 2.** Demonstration of the effect of the spectral width on the pulse duration for unique cavity configuration (a) Increase, from left to right, of the number of Brillouin peaks being generated and (b) decreasing of the pulse duration in regard of the number of Stokes waves generated. (c) Wavelength tunability demonstration for the duality over a range from 1540 nm < λ < 1565 nm.

To obtain the maximum number of Stokes peaks at a given wavelength, the seed wavelength must be changed appropriately as well as the tunable filter which needs to be placed within the proper spectral region which narrows the amplification bandwidth to the width of the desired frequency comb limiting the amplified spontaneous emission generated, or the self lasing cavity modes which compete with the multi Stokes Brillouin lines. This effect can be seen in figure 2(c) in which at 1540nm in the time domain, the pulses lose their coherence since the Stokes lines are competing with the other effects present in the ring cavity.

For the temperature sensor, a reference SBS frequency comb source beats with the sensing source to achieve low frequency measurements of the frequency shift, shown in figure 3(a). The common seed pump laser for the two optical circuits removes any frequency drift which can occur after recombination of the two system outputs. Each reference Stokes is compared with its equivalent in the sensing SBS fiber, therefore giving an overlapping beat spectrum. Cross-Stokes beat frequencies are restricted observation to frequencies below 1 GHz using the low frequency electrical spectrum analyser (ESA). Figure 3(b) presents experimental results of the increase in sensitivity with the Stokes order being observed where the temperature dependence with the Stokes order is shown.

5. Discussion

The main challenge for the pulsed system is to control all of the parameters to achieve a good extinction ratio in the time domain. A predominant pedestal of roughly 40% noise in the autocorrelation trace measurements is seen. Decreasing the pulse width to sub picosecond will be the next generation of SBS pulsed laser sources. As for the sensor, generating more Stokes waves will increase the sensitivity by at least another order of magnitude, as well as for show strain sensing. Temperature sensitivity improvement for a fully distributed sensor to track a variation of temperature locally with a high resolution over a long length of fiber has to be implemented.
Figure 3. (a) Experimental setup to detect the increase in the temperature sensitivity of the Brillouin based sensor by self-heterodyne detection, (b) Increase of strain/temperature sensitivity with the order of the generated Stokes wave.

6. Conclusion
Two configurations of a multi-channel Brillouin generator that can either select all the Stokes waves together or only the even/odd Stokes separately have been shown. A novel type of Brillouin pulsed laser system that can be tuned to generate pulses from 15.4 ps to 3.65 ps and that can also emit at any desired wavelength at the CW seed laser has been demonstrated. In addition, a novel method is shown to increase the temperature sensitivity as a function of the generated Stokes order of a Brillouin based sensor. In the present scheme up to $6 \times$ the standard sensitivity has been demonstrated.

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