Stabilization of the frequency difference between two lasers using the SBS in optical fibers
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ABSTRACT
A new method to control and stabilize the optical frequency difference between two lasers is presented. The use of the amplification features of the stimulated Brillouin scattering occurring in an optical fiber allows the stabilization and the control of the frequency difference between the lasers. A brief numerical discussion and a preliminary experimental result are also presented
INTRODUCTION
In fiber optic distributed sensors using the stimulated Brillouin scattering is of critical importance the control and the stabilization of the frequency difference between the pump and probe laser fields [1,2]. This frequency difference, about 13GHz (for 1,3μm based systems) must be controlled over a 200MHz range with a 1MHz resolution to ensure a good Brillouin gain profile measurement (which peak frequency position is related to the external variable being measured: temperature and/or strain). The stabilization criterion to be achieved is a frequency difference variation less than 1MHz over two times the light transit time (about 100μs for a 10Km fiber length).

These performance parameters could be achieved with the use of state of the art solid state lasers, as NPOR Nd:Yag lasers (which in turns aggregates costs to the system). However the frequency difference’s measurement still have to be done. This is actually done using Fabry-Perot cavities or in most of the cases using a heterodyne technique which needs a fast detector (bandwidth higher than 13GHz) and a microwave spectrum analyzer. This later, due to the slow speed of the spectrum acquisition, is only used in conjunction with Nd:Yag crystal lasers (which have good frequency stability) to control and measure the frequency shift.

When we are using less stable lasers, we must look for a fast way to measure the frequency shift if we want to stabilize it using an electronic control loop. Here we are proposing a new technique where the Brillouin gain profile is used for such task. The CW Brillouin interaction between the pump and probe laser fields has enough sensibility to implement an electronic loop capable to stabilize the frequency shift. Using the tunable characteristic of the Brillouin frequency shift (due to the temperature/strain applied in the interaction medium), the presented method is also able to control the frequency difference between the two lasers.

BASIC ASPECTS OF THE STIMULATED BRILLOUIN SCATTERING
The Brillouin light scattering may be classically described as a parametric interaction between an optical pump field, an optical probe field (called Stokes field) and an acoustic field [3-5]. Through the electrostriction phenomenon, the pump field interacts with the acoustic waves. The acoustic field causes a periodic modulation in the refraction index of the propagation medium. This induced refraction index grate scatters the pump light through the Bragg diffraction. The back-scattered light, or the Stokes light, has its optical frequency shifted as consequence of the Doppler effect associated with the diffraction grate movement, which dislocates with the velocity of the ultrasonic waves in the medium where the effect occurs.

The major SBS characteristic is the energy exchange between the counter-propagating optical fields and the acoustic wave. The Brillouin gain quantifies this energy exchange and may be approximately described as a Lorentz distribution given by

$$g_b = \frac{\Delta f_b}{2} \left[ \frac{1}{(f_p - f_s)^2 + \left( \frac{\Delta f_b}{2} \right)^2} \right] g_b^{\max}$$

and

$$f_{\text{SB}} = \frac{hv_A}{c} (f_p + f_s)$$

where $f_p$ and $f_s$ are respectively the pump and the Stokes optical frequencies, $f_{\text{SB}}$ is the brillouin frequency shift, $v_A$ is the medium acoustic waves velocity and $\Delta f_b$ is the Brillouin gain spectral width. The maximum Brillouin gain, $g_b^{\max}$, is related to several propagation medium parameters, to fused silica glass it is about 6x10$^{-11}$m/W. A system of two coupled partial differential equation describes the dynamic behavior of the counter-propagating
optical fields intensities in a situation where the pump pulse width is larger than the acoustic phonons lifetime ($t=\alpha N_A^{-1}=15\text{ns}$),

$$\frac{\partial I_s}{\partial z} - \frac{n}{c} \frac{\partial I_s}{\partial t} = -g_A I_s I_A + \alpha I_s$$

$$\frac{\partial I_p}{\partial z} - \frac{n}{c} \frac{\partial I_p}{\partial t} = -g_p I_p I_r - \alpha I_p$$

(2)

where $z$ is the spatial variable in the optical field propagation direction, $t$ is the time and $\alpha$ is the optical absorption coefficient. This equation system has analytical solution only when the pump and Stokes fields are continuous (CW fields, null time derivative). Assuming $\alpha=0m^{-1}$, the solution is

$$I_s(z) = \frac{b_s I_s(0)}{b_0 - e^{-aL}}$$

$$I_p(z) = \frac{b_p e^{-aL}}{b_0 - e^{-aL}}$$

$$b_p = \frac{I_p(0)}{I_s(0)}$$

$$I_{s0} = I_s(0) - I_r(0)$$

(3)

Equations (1) and (3) could be used to investigate the dependence of the probe power after the Brillouin interaction, i.e. $P_S(z=0)\propto I_d(z=0)$. Figure 1 presents the relationship between $P_S(z=0)$ and the frequency difference ($f_p-f_d$) for several fiber lengths.

Figure 1: Relationship between $P_S(z=0)$ and ($f_p-f_d$).

STABILIZATION PRINCIPLE

A simple scheme that could be used to implement our stabilizing technique is shown in figure 2. In that, we used a cw pump laser source and a tunable cw probe/Stokes laser source. The two isolators are used to prevent the reverberation of the counter-propagating beams in the laser cavities. The used fiber could be a common telecommunications single mode fiber. Two polarization controllers could be used to adjust the polarization state of the inserted laser fields. Also, an optical circulator to increment the detected power in D2 could replace the coupler C1. The detectors could be common optical power detectors (low bandwidth, good SNR).

As we see in figure 1 the spectral profile of the emerging Stokes power, on D2, could be well described by a Lorenz distribution:

$$P_{D2} - P_{D1} \left[ e^{-at} + k \left( \frac{\Delta}{2} \right)^2 \right] = P_{D1} \left[ e^{-at} + k \left( \frac{\Delta}{4f^2+\Delta^2} \right)^2 \right]$$

(4)

where $f=(f_p-f_d)-f_{DB}$ and $k$ is an amplification factor that depends on the fiber the length and the insertion powers. If we have low absorption coefficient and a short fiber length we could approximate $e^{-at}=1$.
To stabilize the frequency difference we will use this spectral profile to implement an electronic feedback loop that will force $P_{D2}$ to be constant (preferable in a high derivative region within its spectral profile). In other words, to force the emerging probe power to be constant will also force the frequency difference $(f_P-f_S)$ to be constant. It can be shown that equation (4) has two maximum derivative points:

$$f_0 = \frac{1}{\sqrt{3}} \Delta \left[ f_s - f_s^{(0)} - f_{wa} \right]$$

observe that $\left( f_s - f_s^{(0)} = f_0 + f_{wa} \right)$

In the way to have maximum sensibility, i.e. maximum $dP_{S}(z=0)/df$, we must operate near the maximum derivative points. Using the positive slope point, region A in figure 1, we may found a linear relationship for the spectral profile in (4) near $f_0$:

$$P_{S}(f - f_0) - P_{S} \left[ \left( \frac{1}{8} + \frac{3}{8}k \right) + \frac{3\sqrt{3} k}{4} \Delta f \right]$$

To implement a simple proportional control we must define an error relationship that will be used to generate a signal to control the probe laser frequency. So we define the error as

$$Error(f) = P_{S}(f = f_0) - P_{S}(f - f_0)$$

Now we are able to predict the sensibilities of our stabilization method

$$\Delta Error \left( \frac{\Delta f}{M} \right) = P_{S} \left( \frac{3\sqrt{3} k}{4} \right)$$

where $\Delta f$ denotes the absolute value and $\Delta f = f - f_0$. Using the parameters of figure 1, for a fiber length of 100m: $k=0.8343$, $\Delta = 61MHz$, $P_{D2}(z=0)=10mW$ and $P_{D2}(z=L)=1mW$, we predict an frequency sensibility of about $18\mu W/MHz$. In other words, $18\mu W$ power variations in the $P_{D2}$ signal could be associated with $1MHz$ laser frequencies difference variations. This power variation could be easily measured with common optical power meters. The control of the lasers frequencies difference could be achieved through the tuning characteristic of the Brillouin frequency shift, $f_{DB}$, with temperature ($\sim 1.24MHz/^\circ C$) or strain ($0.06MHz/\mu e$) applied to the interaction medium [1,2]. Remembering equation (7), $f_0$ depends on $f_{DB}$, so as the stabilizing technique is based on zeroing the error, then as $f_{DB}$ changes $f_0$ also changes, forcing $(f_P-f_S)$ to change in consequence.

**SIMPLE CONTROL MODEL**

Using the software *Mathworks Simulink* we implemented a numerical model to simulate the proposed control method. Figure 4a shows a simple block model for the control loop. Low-pass filters limit all block elements bandwidths. We use a proportional control with a bandwidth adjusted to impose a dominant pole in the control loop (to diminish 2nd and 3rd order effects which could cause instabilities). We omitted the gain blocks, which defines the equipments sensibilities, just to simplify the presented model. The external frequency jitter generator emulates a lasers frequency difference change due to external factors. The Brillouin amplification block is implemented using equation (4). To define the power stabilization point, $P_{D2}(f_0)$, we use the measured Stokes insertion power times a gain factor. This will diminish the influence of the Stokes insertion power fluctuations in the frequencies difference. The control loop will stabilize the amplified power $P_{D2}$ and as we explained before, this will also stabilize the optical frequencies difference between the two lasers.

**Figure 4**: Block Model (a), simulation of the time behavior of the lasers frequency’s difference (b).

Figure 4b shows the numerical simulation for the time behavior of the frequency difference as function of the control gain value. The external frequency jitter amplitude is 5MHz. It can be seen that with a 1K control gain, the frequency amplitude is slight reduced to about 3MHz, without transient oscillation. As the gain is
increased to 10K the system becomes less stable, transient oscillations are present, however the frequency amplitude is reduced to less than 400kHz. So, because of the gain/instability tradeoff, care must be taken during the control circuit design, leaving some parameters to be adjusted during the experimental tests.

**FINAL REMARKS**

The preliminary results were obtained using a simple setup, like that in figure 2. We used a low noise proportional controller, common optical power detectors (Newport 1830/C), a NPOR tunable Nd:Yag pump laser (Lightwave 125, λ~1319nm, jitter<200kHz/s, drift<50Mhz/hour), a tunable external cavity probe laser (NewFocus 6234, λ~1319nm, jitter<1MHz/s) and a common SMF28 optical fiber (g_b~4x10^{-11}m/W, f_DB~12,75GHz, Δf_gb~60MHz [1]). The maximum power detected in D1, as result of the Brillouin amplification, was 1.7mW. The minimum power was 0.4mW (without Brillouin amplification). Using equation (4) we estimated the Brillouin amplification’s spectral profile arising in P_{D1}. Before turning on the control, the laser’s frequency difference was first adjusted in the Brillouin gain region. The control stabilized P_{D1} around 0.6mW with a 2mW peak-to-peak variation, during, at least, 5 minutes. Figures 5 allowed us to estimate the frequency difference’s variation: ~410kHz. Operation points with higher slopes were avoided because of the gain/instability tradeoff. A higher gain implies in a better performance (more sensibility, lower jitter) but also implies in a more instable loop.

![Figure 5: Experimental estimation of the frequency difference variation.](image)

We presented a new method to stabilize and control the frequency difference between two lasers using the CW stimulated Brillouin scattering in an optical fiber. We showed how to use the Stokes amplification to implement the control, however the pump depletion could also be exploited to the same purpose. A brief theoretical discussion was done followed by a simple numerical simulation. Discussions in topics like the spontaneous noise during Brillouin amplification, the detectors noise, the laser power fluctuation and the control dynamics, were omitted in benefit of a fast communication. We also presented a preliminary experimental result that motivates further studies on the proposed control. Future work will focus on the use of the proposed control as an active part of a fiber optic distributed Brillouin sensor.

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**REFERENCES**