Brillouin induced self-heterodyne technique for narrow line width measurement

P. Sevillano,* J. Subías, C. Heras, J. Pelayo, and F. Villuendas

Grupo de Tecnologías Fotónicas, Instituto de Investigación en Ingeniería de Aragón (I3A), Universidad de Zaragoza, 50018 Zaragoza, Spain

** pascual.sevillano@unizar.es*

Abstract: A novel technique is introduced for jitter-insensitive sub-KHz resolution linewidth characterization technique in ultra-narrow lasers for optical communication applications. The technique is based on self-heterodyne detection induced by Stimulated Brillouin Scattering (SBS). Non linear SBS drives the heterodyne mixing through optical frequency locking of a narrow tunable laser source and the signal under test, which is modulated in the low frequency range. Due to SBS nature, jitter variations in the optical frequency do not affect the correlation spectra measured with resolution figures up to 300 Hz, without the need for optical delay line as in conventional homodyne correlation techniques.

OCIS codes: (060.4510) Optical communications; (190.4370) Nonlinear optics, fibers; (070.4790) Optical spectrum analysis; (290.5900) Scattering, stimulated Brillouin;

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1. Introduction

Recently narrow-linewidth laser development has increased research efforts from many fields such as telecommunications, atomic physics and metrology [1–3]. The need of higher transmission rates and the development of reliable ultra-narrow lasers in communications bands make coherent communications lead the next step in this area [4,5]. Such system requires complete characterization of the laser parameters, as linewidth of the carrier is directly related to Signal To Noise ratio achievable and limits the use of Optical Phase Locked Loops for frequency locking [6,7]. The magnitudes demanded are below kHz and complete characterization is mandatory.

Traditional linewidth measurement optical techniques are based on interferometric and filtering processes [8]. Fabry-Perot interferometer-based and diffraction gratings have been widely used in commercial optical spectrum analyzers. The main disadvantage of these techniques is the trade-off between features, making it impossible to reach high performance values for all the features in the same setup. F-P interferometers go up to 1 pm with narrow spectral range but limited dynamic range (MicronOptics FFP-TF2); on the other hand, gratings offer higher dynamic and spectral range but 10 pm limited resolution (Yokogawa AQ6319). Other techniques are based on converting frequency fluctuations into intensity fluctuations via Mach-Zehnder interferometer. These techniques basically involve self-heterodyne and homodyne detection [9,10]. In both cases the beating of the signal with either a modulated or unmodulated replica of itself after traveling through a delay line provides very high resolution, up to kHz, but with technical difficulties due to the delay line. As this problem worsens with narrower lasers, tedious interpretation for delayed times below coherence time becomes necessary [9]. Later works were based on heterodyne interference with sweeping local oscillator [11,12]. In the framework of narrow optical filtering spectroscopic methods, a high-resolution optical spectrum analyzer was developed several years ago based on the narrow width, ≈10 MHz, of the SBS gain curve [13]. This technique, with wavelength sweeping along wide range, offers a high resolution (up to 0.08 pm), over full C-band, and high dynamic range (80 dB) [14], being the last developed alternative in optical filtering methods but still below self-beating methods resolution.

Owing to the interest of characterizing lasers with linewidth staying in the range of kHz, efforts have been focused in overcoming limitations in actual techniques, specially undesirable delay line related effects in interferometric methods. This paper is centered in the possibility of using SBS on that purpose. The layout of the system required is as follows. First, signal under test is intensity or phase modulated, at frequencies on the order of hundreds of MHz, and introduced into a several km long single mode fiber reel. A counter-propagating pump beam enters the other end with an optical power level enough to generate Spontaneous Brillouin Scattering, by matching one of the modulation side bands with the center wavelength of Brillouin gain profile the stimulated mode is reached (Fig. 1). The interference between the non-linearly amplified sideband and the central carrier is detected with a fast response photodiode placed in the end of the reel, and the linewidth of the signal under test is deduced through the frequency component distribution of the photocurrent mapped in an electric spectrum analyzer.

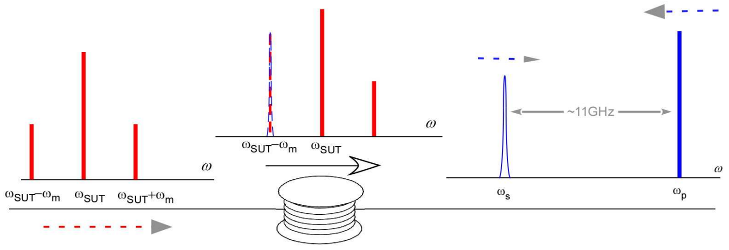

Fig. 1. Spectral description of the Brillouin Induced Self-Heterodyne technique.

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Stimulated Brillouin Scattering has been recently used in the framework of high resolution spectral analysis based on the heterodyning process of the signal under test and the Stokes wave generated by itself in a Brillouin ring laser [15]. That system can achieve resolutions reaching the kilohertz level by means of the narrow Brillouin self-stimulated laser used as local oscillator after a vast number of recirculation in the ring. This beating is fixed at the Brillouin shift frequency, ≈11GHz, which requires fast response detection. Besides, as in others heterodyne techniques, power spectral density cannot obviate the contribution of sudden jumps in the signal under test emission frequency, thus obtaining and overestimated effective linewidth instead of natural linewidth.

In comparison with other already known techniques, Brillouin induced self-heterodyning offers some advantages: it is jitter free as both contributions to detection come from the same source at the same time, there is no need of high frequency modulation such as in homodyne technique, and delay line is no longer a requirement as in practically all self-interferometric techniques. As a result of the spectral width of the Brillouin Scattering gain curve, ≈10 MHz, this method is suitable for lasers in which Brillouin scattering is efficient, i.e. are not wider than Brillouin gain width, and frequency stable enough so random phase jumps will not shift laser wavelength out of gain curve, e.g. C-Band communication lasers. This technique can achieve resolution up to hundreds of hertz limited by the acoustic properties in the Brillouin scattering phenomena.

2. Experimental setup

The experimental setup is sketched in Fig. 2. The SUT is provided by a narrow laser source (LS) with a high coherence. The optical wavelength is centered in the C band. Previous to the fiber the SUT is amplitude modulated with a Mach-Zehnder (MZ) (Photline MX) modulator. A Network Analyzer model (Agilent 8714ET), feeds the MZ with a RF pure tone frequency ω_m, in the range of hundreds of MHz. The modulated optical signal interacts non-linearly along a 7 Km length reel of single-mode standard fiber with a counter-propagating optical pump which is introduced after being properly amplified with and EDFA (Photonetics Fiberamp-BT20). The high power pump signal generates a Brillouin backward Stokes wave downshifted ≈11GHz, with respect to the original. An optical circulator allows optimum coupling between interacting beams, sources and detector in the setup. Tuning the wavelength of the pump TLS and/or the ω_m it is possible to match either band of the modulated SUT with the Brillouin backward Stokes wave generated by the pump. Typical linewidth and jitter of the SUT are well below 10MHz, which allows easily maintaining the matching condition for reaching the SBS depletion mode. Therefore, proper power transfer from the pump wave to the Stokes one is achieved. After non-linear interaction, SUT and Brillouin backscattering are detected in the fast-response photodiode (MITEQ DR-125G-A), with 12 GHz bandwidth. The electric signal from detector contains the beat between the amplified modulation side-band and the SUT carrier, which is then frequency analyzed with an Electric Spectrum Analyzer (ESA) (Agilent E-4407B). Frequency components of the auto-heterodyne non-linear mixing are found over the ω_m frequency.

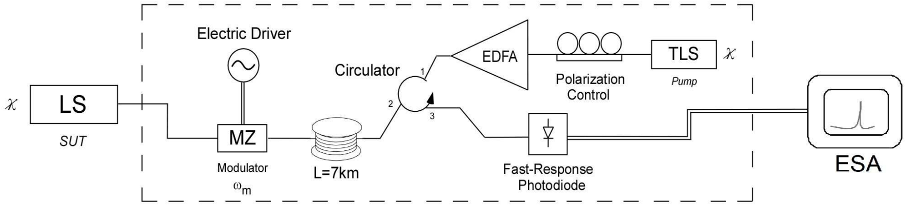

Fig. 2. Schematic of the setup necessary to perform the laser characterization. Laser Source (LS) for Signal Under Test (SUT) and tunable laser source (TLS) for the pump must be stable and narrow.

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Phase modulation could also be used instead of amplitude modulation, obtaining the same result when side band stimulates Brillouin scattering. Regarding modulation frequencies, values above the 10 MHz Brillouin gain bandwidth is the only requisite, so standard signal generators can be used and no very fast response electronics is necessary for detection. The AC nature of the signal detected, with electrical spectrum centered in the SUT modulation frequency, does not require the measurement of DC or near zero frequency components contrariwise homodyne interferometry.

The signal tracked in the photodiode contains the beat between carrier and Brillouin backscattered wave stimulated by either of the modulation bands. As the phase noise of pump laser is incorporated into the Brillouin-backscattered wave [16], and SUT and pump originate from lasers devices with uncorrelated phase variations, this technique has the characteristics of a heterodyne one, so that delay line required in conventional homodyne and self-heterodyne detection for coherence loss is no longer necessary. The presence of this line has been reported as the main drawback of these techniques because the narrower the laser spectrum the longer the delay line required, so loss became a concern and signal interpretation is not straightforward [9]. On the other hand, heterodyne techniques suffer a lack of effective resolution due to relative frequency jitter between SUT and probe laser, which is not present in the Brillouin induced self-heterodyne method because of the properties of Brillouin backscattering generation. Considering the stimulation mode case, Stokes backscattered wave and stimulus are frequency locked so sudden relative frequency variations between pump and stimulus can be neglected as far as the stimulus lays in the Brillouin Stokes wave gain width, i.e. 10MHz [2]. This requirement is easily satisfied in the experimental conditions for which this measurement technique is considered for, and consequently the measurement can be thought as jitter free.

3. Results and discussion

Before presenting any measurement with the proposed technique, in order to get some data to compare, we characterize the source 1 laser (LS1), commercial tunable LS model (Agilent 8164B), by a conventional heterodyne technique with a different unit of same tunable LS model as local oscillator. The measured spectrum is shown in Fig. 3. Lorentzian shape fitting gives a linewidth of 245 kHz.

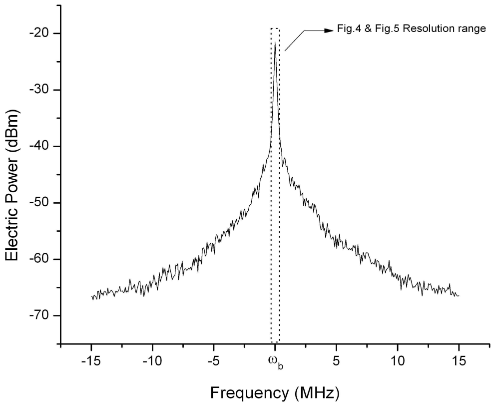

Fig. 3. Spectrum of LS1 taken by heterodyning with a laser of the same model as local oscillator. Measure was taken in a 4ms swept time and averaged over 10 measures. Spectrum is centered at the beat frequency between probe and signal.

While measurement was taken, excursions in a narrow frequency range of emission wavelength in both lasers were observed, for this reason several measurements were taken

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with a short swept time in the ESA and then averaged after tracking the beat note. Taking this into account the spectra we measured describes the statistical properties of slow frequency fluctuations in both lasers instead of an intrinsic instantaneous linewidth characterizing the ultimate coherence of the laser emission.

Now with the already mentioned setup LS1 was measured using a different unit of the same laser model as a pump source, wavelength was settled to λ_{SUT} = 1550 nm. The spectrum obtained is shown in Fig. 4. Signal was modulated with $\omega_m \approx 600$ MHz keeping the bias voltage for the MZ modulator at quadrature point. Pump power after amplification was around 20 dBm. ESA was set to 10 Hz resolution. Span was adjusted to 10 kHz.

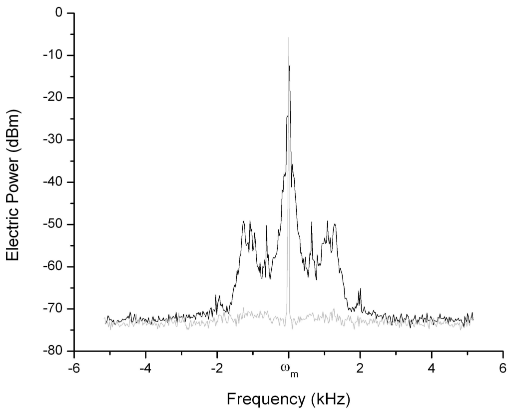

Fig. 4. Heterodyning Spectrum of the LS1 laser measured by the non-linear mixing technique, 10 kHz span centered in the modulation frequency. Resolution bandwidth was set to 10Hz, swept time to 2.5s and values averaged over 20 measures. Electric modulation spectrum is plotted in grey color.

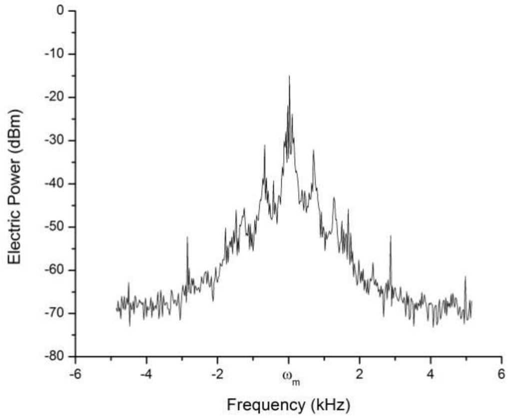

Fig. 5. Heterodyning Spectrum of the LS2 laser measured by the non-linear mixing showed in a 10 kHz span centered in the modulation frequency. Resolution bandwidth was set to 10Hz, swept time to 2.5s and values averaged over 20 measures.

Gray plot in Fig. 4 represents the spectrum signal measured by the detector when the pump is off, in that case no amplification of sideband is present and, as shown, the electric spectrum presents just the pure tone frequency at ω_m, for the amplitude modulation mode.

The second laser source (LS2) measured was another commercial tunable LS model (New Focus 6528-LN) with linewidth believed to be wider than LS1 according to manufacturer specifications. Wavelength was settled at $\lambda_{SUT} = 1550$ nm and modulation frequency this time was $\omega_m \approx 300$ MHz. Amplification values and modulation point was kept the same as in previous measurement. ESA was set to 10 Hz resolution bandwidth. Span was adjusted to 10 kHz. Spectrum obtained is plotted in Fig. 5.

In both figures the pattern displays the jitter-free natural linewidth of the laser. Because of partial transmission of pump phase noise to the Brillouin wave, complete evaluation of the exact relationship between measured spectra and linewidth caused exclusively by phase noise in the SUT will require a further thorough characterization of this cross-phase mixing phenomenon. Resolution is determined by the spatial period of the slower oscillation that one acoustic wave can undertake along the effective interaction length with the light in the Brillouin scattering effect. This spatial period can be at most of the order of one coherence length of the Brillouin effect, in order to be transferred to the scattered optical wave. Thus, a Brillouin effective bandwidth of the order of 10 MHz (coherence length in the order of 20 m [17]), and a sound speed of about 6 km/s in the fiber, yields to a frequency resolution around 300 Hz.

4. Summary

In summary we have proposed a new technique for linewidth characterization of narrow lasers emission lines based on self-heterodyning but getting rid of the main drawbacks of conventional methods, and so, obtaining interesting features. The need of an optical delay line is overcome thanks to non-linear Brillouin effect. Properties of stimulated backscattering result as well in a jitter insensitive technique. Low-frequency modulation of the SUT is used; hence no DC noise in detection is present opposite to homodyne detection. The ultimate resolution of the technique is limited by the coherence length of the Brillouin phenomena with results up to 300 Hz. This set of advantages makes this technique a choice for linewidth measurements in communications band for ultra-narrow lasers, with better achievable resolution than filtering techniques but simpler implementation than interferometric ones. In the latest class of high-resolution filtering devices, stimulated Brillouin scattering is used as a selective filter at a wavelength that can be swept over a wide range, scanning the measured spectrum. In this case, the proposed technique allows the explorations of narrow lines in the measured spectrum using the same kind of interaction to implement self-heterodyne interferometry, and going further of the 10 MHz resolution limit of the primary filtering.

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