CHAPTER 4:

Linewidth Measurements of Brillouin Fiber Lasers

In lightwave systems, information is transmitted by modulating the frequency or the phase of the optical carrier signal [1-6]. Since phase coherence of the optical carrier plays an important role, these systems are also known as coherent lightwave systems in which the detection is done by using homodyne or heterodyne detection. The basic concept behind coherent detection is the coherent combination of the optical signal with a continuous wave (CW) optical field before the detection as shown in Fig. 4.1. The CW field, known also as a local oscillator (LO) in the radio and microwave literature, is generated locally at the coherent detection receiver by using a narrow-linewidth laser.

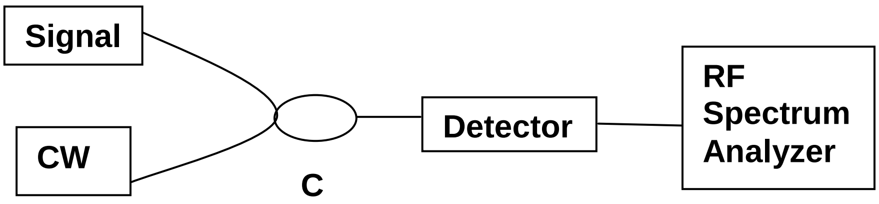


Fig. 4.1: Homodyne and Heterodyne detection for linewidth measurements

The basic operation behind these techniques is simple. The signal is combined with the CW laser in a coupler (C) and the resulting beat response is detected by a photodetector. This beat frequency which is in the radio frequency (RF) region can be analyzed by an RF spectrum analyzer (RFSA). The laser linewidth is usually inferred from the width of this beat spectrum. The optical signal can be written as

$$\mathrm{E_s} = \mathrm{A_s}\exp[\text{-i}(\omega_0 \mathrm{t} + \varphi_\mathrm{s})] \tag{4.1}$$

in which ω_0, $\mathrm{A_s}$, and φ_s are the angular frequency, amplitude and the phase of the signal, respectively. The optical field of the local oscillator is also expressed similarly by

$$\mathrm{E_{cw}} = \mathrm{A_{cw}}\exp[\text{-i}(\omega_\mathrm{cw} \mathrm{t} + \varphi_\mathrm{cw})] \tag{4.2}$$

with the assumption that the two fields are identically polarized. For any detection, a photodetector responds to the optical intensity so we have to know the incident optical power at the photodetector. It is shown by:

$$\mathrm{P(t)} = \mathrm{k}\left|\mathrm{E_s} + \mathrm{E_{cw}}\right|^2 = \mathrm{P_s} + \mathrm{P_{cw}} + 2\sqrt{\mathrm{P_s P_{cw}}}\cos(2\pi\nu_{IF}\mathrm{t} + \Delta\varphi) \tag{4.3}$$

where $\mathrm{P_s} = \mathrm{kA_s^2}$, and $\mathrm{P_{cw}} = \mathrm{kA_{cw}^2}$, denote the powers of the signal and the local oscillator, respectively and $\Delta\varphi = \varphi_s - \varphi_{cw}$ is the phase difference between the two sources. $\nu_{IF} = (\omega_0 - \omega_{cw})/2\pi$ is known as the intermediate frequency (IF). If the local power $\mathrm{P_{cw}}$ is much larger than the signal power $\mathrm{P_s}$, the first term can be ignored. The second term represents a large continuous signal which carries no information but does provide a shot noise or a white noise contribution. Basically, there are two different coherent detection techniques; the homodyne and heterodyne detection methods, depending on whether or not ν_{IF} equals zero. These detection methods can be used for the linewidth measurements which will be discussed next.

4.1 Homodyne and Heterodyne Linewidth Measurements

In a homodyne linewidth measurement, a signal is mixed with a time-delayed replica of itself. Fig. 4.2 shows the configurations for the homodyne linewidth measurement by using an unbalanced Michelson interferometer in (a) a common and (b) a traditional configuration, respectively. The optical path difference in the fiber interferometer is used to generate the beat frequency. The laser beam is split into two parts. One is the local oscillator and the other is sent to the system to be probed. The scattered light is then mixed with the local oscillator on the detector. This arrangement has the advantage of being insensitive to fluctuations in the frequency of the laser. This method can be used to evaluate the coherent length of a laser [7]. This method is sensitive to environment perturbations and the intrinsic loss of the fiber must be considered for the linewidth measurements. Figs 4.3 (a) and (b) show a more effective way of homodyne linewidth measurement by using the ring [8], [9] and the Fabry-Perot cavity [10], respectively. These configurations use a shorter delay fiber due to some roundtrip oscillation of the laser beam in them whereas the resolution is the same as the basic one shown in Fig. 4.2. The resolution of such a measurement is given by the finesse of the interferometer while the largest quantifiable linewidth depends on the free spectral range of the instrument. Commercially, Fabry-Perot interferometers have finesse between 100 and 1000, and free spectral ranges between a few 100 MHz to 10 GHz. Thus, Fabry-Perot interferometers are suitable for laser linewidth measurements of the order of MHz to a few GHz. Also, grating spectrometers can measure a spectral width in the region of 10 GHz to 100 GHz. In Fig. 4.2 (a), the laser beam is separated into two by the coupler and a long fiber spliced in one of the ways in order to delay the beam propagating in it. Then the last coupler combines the two beams in order to generate the beat frequency which in turn will be detected by the photodetector and will be analayzed by the RF SA.

In the traditional homodyne detection, however, two mirrors are used for reflecting the delayed laser light and the original one. Here the two optical circulators perform the same function as the mirrors when ports 2 and 3 are connected to each other. The combination of the reflected beams is done at the same coupler used for the separation of the original laser. The same process occurs in the other configurations shown in Figs. 4.3 (a) and (b). According to the analysis considered in [10],[11], when the delay time of the fiber τ_d is much larger than the coherence time τ_c, the spectral analysis of the self-homodyne signal gives full information about the linewidth of the laser radiation. The measured full width at the half maximum (FWHM) or bandwidth $\Delta\upsilon_{s.\mathrm{hom}.}$ in the self homodyne method is connected with the laser source linewidth $\Delta\upsilon_{\mathrm{L}}$ as

$$\Delta\upsilon_{s.\mathrm{hom}} = 2\Delta\upsilon_{\mathrm{L}} \tag{4.4}$$

Delay
Fiber

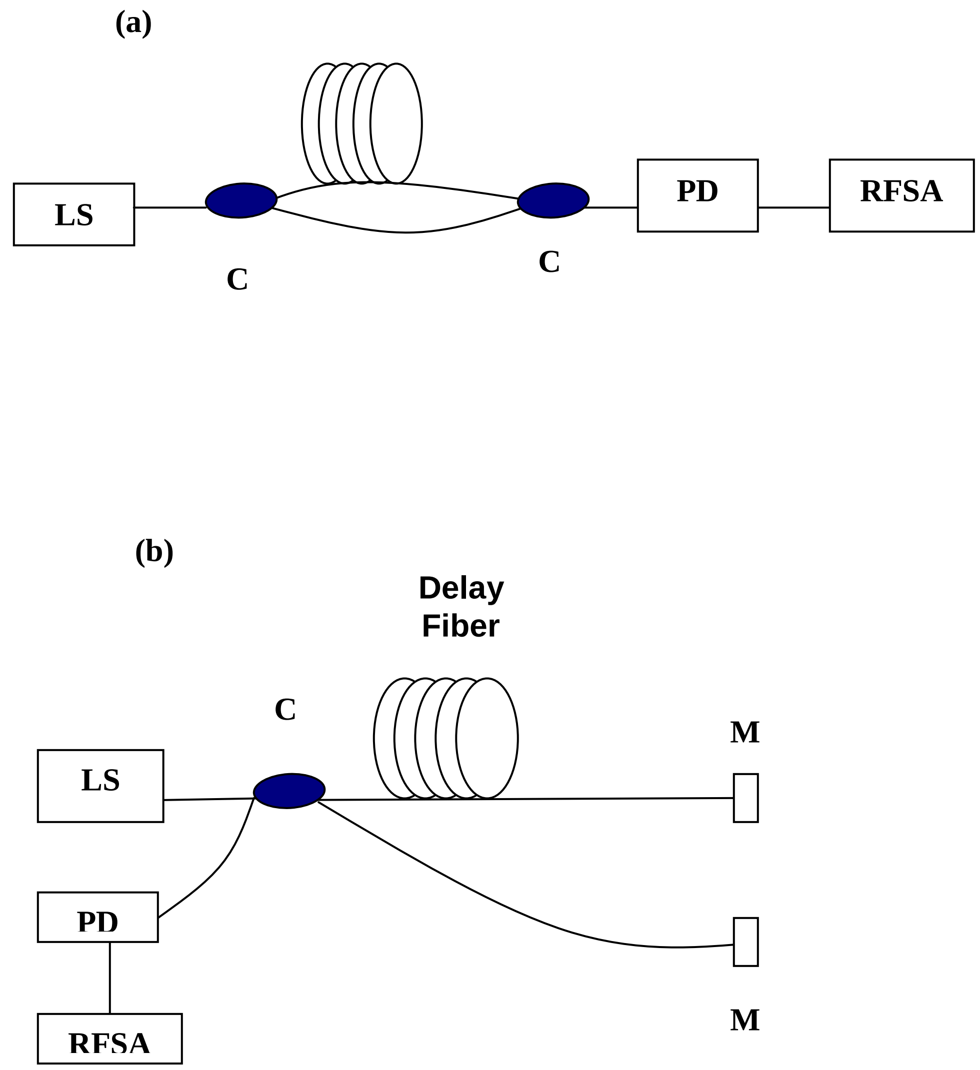


Fig. 4.2: Schematics of the different interferometers used for homodyne linewidth measurement of a laser source (LS) with an unbalanced Michelson interferometer in (a) a common and (b) a traditional configuration, respectively. The photo detector (PD) and the Radio frequency spectrum analyzer (RFSA) are used for the detection. **C** and **M** also denote a coupler and a mirror, respectively.

Delay
Fiber

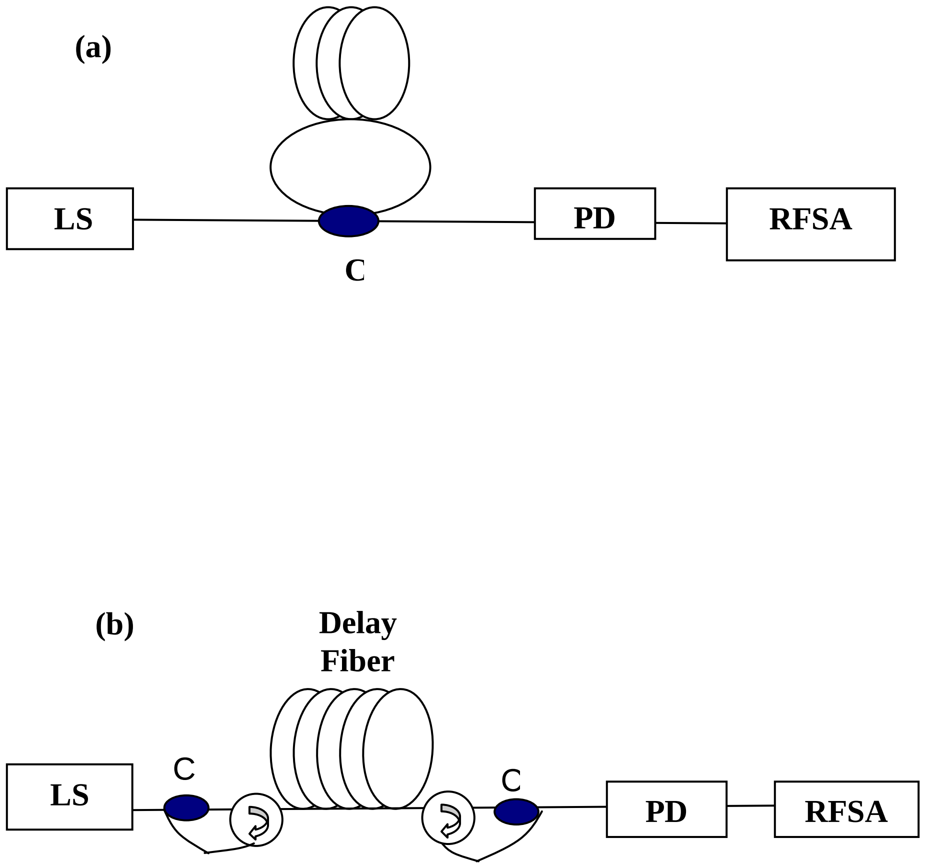


Fig. 4.3: The more effective way of the homodyne linewidth measurement of the laser source (LS) by using (a) a ring, and (b) a Fabre-Perot cavity. C and OC refer to a coupler and an optical circulator, respectively. The photo detector (PD) and radio frequency spectrum analyzer (RFSA) are used for the beat frequency detection.

According to Eqs. (2.2) and (2.3), if the loop has a free spectral range (FSR) $\Delta\upsilon$ and a finesse F, the system can measure the minimum linewidth as

$$\delta\upsilon = \frac{\Delta\nu}{\mathrm{F}} \tag{4.5}$$

where $\Delta\upsilon$, the FSR can be obtained by

$$\Delta\upsilon = \frac{c}{nL} \tag{4.6}$$

in which L is the length of the fiber in the loop and n is the refractive index of the fiber in the loop. In the Fabre-Perot cavity, $2L$ must be used instead of L in Eq. (4.6) due to the distance doubling in a roundtrip. The finesse of the ring cavity can be shown to be

$$\mathrm{F} = \frac{\pi}{2}\left\{\sin^{-1}\left(\sqrt{\frac{(1-bL)^2}{4bL}}\right)\right\} \tag{4.7}$$

where L and b are obtained as

$$L = \exp\left[-(\alpha l + s)\right] \tag{4.8}$$

$$b = (1-k)^{\frac{1}{2}}(1-\delta)^{\frac{1}{2}} \tag{4.9}$$

in which α is the electric-field loss coefficient of the fiber, s the loss experienced by the electric field at the splices, k the intensity coupling ratio of the coupler, and α the excess intensity loss of the coupler. Since the resolution is proportional to finesse, the resolution is influenced by the coupler strength, the excess loss introduced by the couplers, the fiber and the splices [8]. To measure an ultra-narrow linewidth we have to use a longer fiber and access lower finesse due to increased loss in fibers. Using a ring resonator with a free spectral range of 8.5 MHz, a linewidth 100 KHz corresponding to a finesse value of 85 was obtained. Due to the limitation on the available light source, we have to use longer fibers to measure narrower linewidths. In order to compensate the fiber loss, an optical amplifier can be place in the fiber loop. This method is not suitable for the ultra-narrow linewidth lasers since it needs very long fibers (>10 km). This is a drawback for homodyne linewidth measurement; when the coherence time of the laser is greater than the storage time of the resonator, there is a limitation on the resolution [12]. In addition, the amplitude noise and the phase noise are mutually overlapped in this detection; this is also known as the delayed self-homodyne detection due to using a laser source.

Another more effective method for linewidth measurement is the heterodyne method which can be formally done in two ways. Different setups are employed for different linewidth regimes. One method so called the delayed self-heterodyne measurement is attractive for narrow bandwidth laser measurements in the region of a few 100 kHz to 100 MHz. In the simplest way of this method as shown in Fig. 4.4 (a), an asymmetric Mach-Zehnder is formed in such a way that one path is significantly longer than the other. Here, an amplitude optical modulator (AOM) such as an acousto-optical Bragg frequency shifter is spliced in the longer path in order to shift the frequency. Then the delayed-frequency-shifted signal in the long path is combined with the signal in the short path by using a coupler. The resulting beat frequency can similarly be detected by using a fast-response photodiode and an RF spectrum analyzer [13]. By forming a ring resonator as shown in Fig 4.4 (b), the effective fiber length can also be increased in the heterodyne linewidth measurement as the homodyne counterpart.

Delay
Fiber

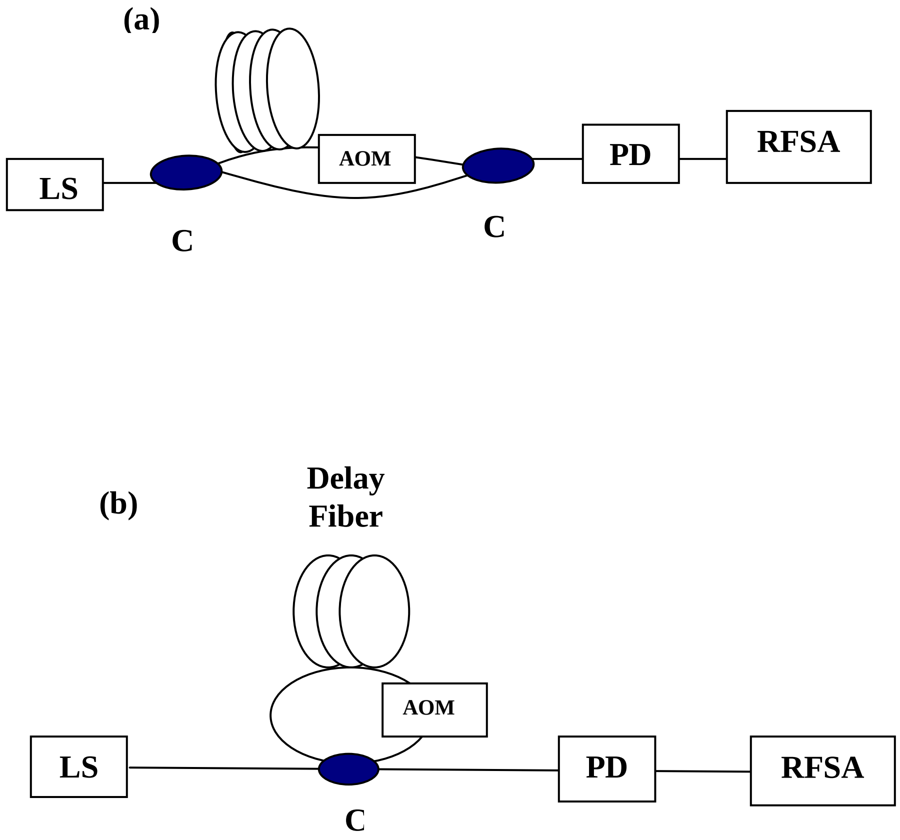


Fig. 4.4: The delayed-self heterodyne method for narrow linewidth measurement of a laser source (LS) using (a) unbalanced Michelson interferometer and (b) the ring cavity. The amplitude optical modulator (AOM) is used to shift the frequency. The photo detector (PD) and radio frequency spectrum analyzer (RFSA) are used for the beat frequency detection and C is a coupler.

This linewidth measurement can be true if the delayed time τ_d imposed in the long path is much greater than the laser coherence time τ_c so that the two fields incident on the detector are not coherent. Thus, the validity of this method is often cited as [14]:

$$\tau_c << \tau_d \tag{4.10}$$

where the delayed time τ_d and the resolution of the interferometric method $\Delta\nu_{res}$ are related through

$$\tau_d = \frac{nL_d}{c} \cong \frac{1}{\Delta\nu_{res}} \tag{4.11}$$

in which L_d is the fiber delay length.

In other words, the coherence length must be shorter than the fiber length. Otherwise, measurements are still possible, but the interpretation of the beat signal becomes more difficult and requires intricate data post-processing routines. In fact, the analyses are generally based on a white frequency noise spectrum as the dominant contribution to the laser linewidth. For diode lasers, this is a valid assumption, as the optical linewidth stems primarily from spontaneous emission-induced refractive index changes in the semiconductor [15]. However, in the case of fiber lasers, the spontaneous emission contribution is extremely small, i.e. in the region of a few hertz and the linewidth behavior is instead overwhelmingly dominated by frequency noise and the linewidth is no longer white-noise in nature, but has a low frequency spectrum in the region of kHz [15],[16],[17]. In fact, condition in Eq. (4.10) is not sufficient for the delayed self-heterodyne interferometer to be accurate when applied to the linewidth measurement of fiber lasers since their noise behavior is not frequency-independent [18]. In addition, fiber delay lines with lengths 100 km or more are not used commonly in the delayed self heterodyne interferometry linewidth measurement due to increased propagation losses although a 11 km delay fiber length incorporating an erbium doped fiber amplifier for compensating the loss was experimentally demonstrated for determining a fiber laser characterization [16],[17]. Measurements on narrower laser linewidths around a few hertz or less are accomplished by detecting the beat signal of two identical uncorrelated lasers which will be discussed in the following for measuring the linewidth of Brillouin fiber lasers.

4.2 Laser Linewidth Measurement Using a Brillouin Fiber Laser

Improved laser sources recently indicate narrow linewiths in the sub-megahertz range with enhanced coherence properties. Among all fiber lasers, the linewidth of Brillouin fiber lasers has been experimentally determined in various ranges from 3.84 Hz to 2.8 kHz [19],[20],[21]. The ultra-narrow linewidth measurement is a challenge because the self- homodyne or self-heterodyne techniques require long delaying fibers which is impractical for fiber lasers due to propagation losses. However, the laser linewidth measurement can also be done by evaluating the beat signal resulting from the interference of the laser with another uncorrelated laser as has been done in [19],[20],[21]. This method requires another laser either with a comparable well-known spectrum or with an extremely narrow and ignorable linewidth. In this thesis, by using the later method, a Brillouin fiber laser is applied to measure the linewidth of an uncorrelated tunable laser source (TLS) which has two organized wide and narrow linewidths. The linewidth of the Brillouin Stokes $\Delta\upsilon_{\mathrm{BS}}$ is proportional to the Brillouin pump linewidth $\Delta\upsilon_{\mathrm{p}}$ as shown theoretically [22]:

$$\Delta\upsilon_{\mathrm{BS}} = \Delta\upsilon_{\mathrm{p}}\left(1 - \frac{\pi\ l\Delta\upsilon_{B}}{\mathrm{v}\ \mathrm{Ln}(R)}\right) \tag{4.12}$$

where $\Delta\upsilon_{B}$ is the Brillouin gain bandwidth , l is the fiber length, v the velocity of light in the fiber and R is the coupling ratio. Therefore, a narrow linewidth TLS is used to generate a narrow BFL linewidth. By using the narrow linewidth BFL instead of the CW laser in the heterodyne configuration as shown in Fig. 4.1, the linewidth of the wide and narrow uncorrelated TLS can be measured. Here, the TLS and the narrow BFL are used to replace the signal and CW in Fig. 4.1.

The experimental setup for generating a BFL is shown in Fig. 4.5 with a coupler and a long single-mode fiber (SMF) acting as a traditional ring resonator. The BFL is pumped by an external cavity tunable laser source (TLS) which is amplified by an erbium-doped fiber amplifier. The maximum power of the amplified Brillouin pump (BP) is approximately 14.3 dBm. The BP is injected into the resonator from port 1 through port 2 of the optical circulator in an anti-clockwise direction. The generated backward-propagating SBS oscillates inside the resonator in a clockwise direction to generate the backward BFL, which is coupled out via a 3-dB coupler. From port 2, the BFL is then routed into an optical spectrum analyzer (OSA) through port 3 by the optical circulator. The SMF used in the experiment is 25 km in length and has a cut-off wavelength of 1161 nm with a zero dispersion wavelength of 1315 nm and a mode field diameter of 9.36 µm. The output laser is characterized using an OSA with a resolution of 0.015 nm while the linewidth of the laser is measured using an electrical spectrum analyzer and the heterodyne beat technique [23].

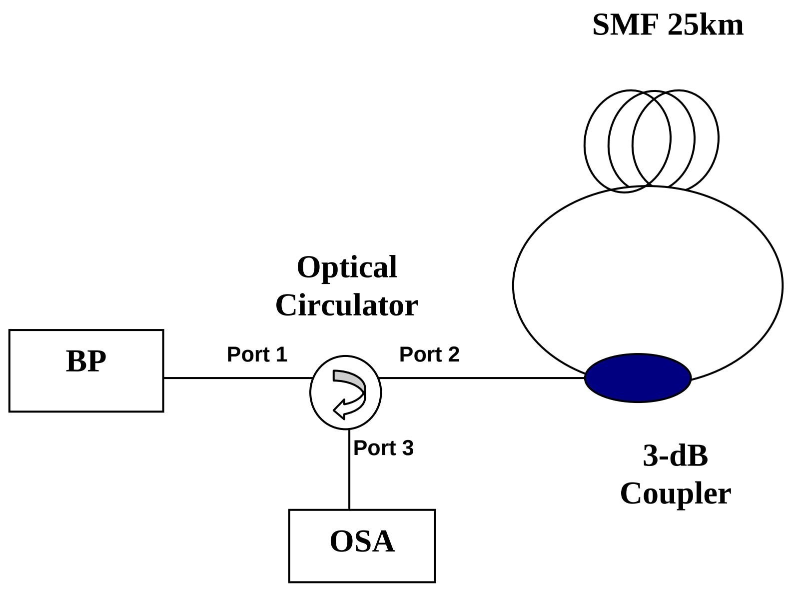


Fig. 4.5: The Experimental set up for generating a Brillouin fiber laser in using a Brillouin pump (BP) which is a tunable laser source (TLS) amplified by an EDFA in the narrow TLS linewidth setting.

Fig. 4.6 (a) and (b) compares the BFL output spectrum at different BP linewidth settings with BP powers of 4.5 dBm and 14.3 dBm respectively. Both figures show three simultaneous lines: anti-Stokes at around 1549.9 nm, BP reflections at 1550 nm, and BFLs at around 1550.1 nm so that the Brillouin shift is about 0.086 nm. The anti-Stokes signal is observed at a shorter wavelength due to four-wave mixing between the BP and the Stokes line. Although the anti-Stokes power is almost unchanged, the powers of the BP reflections and BFL lines increase as the BP power increases due to Brillouin-induced crosstalk between the lines [24]. With the BP wide linewidth setting, the BFL power as shown in Fig. 4.5 (b) is relatively lower as compared to the BP narrow linewidth setting in Fig. 4.5 (a).

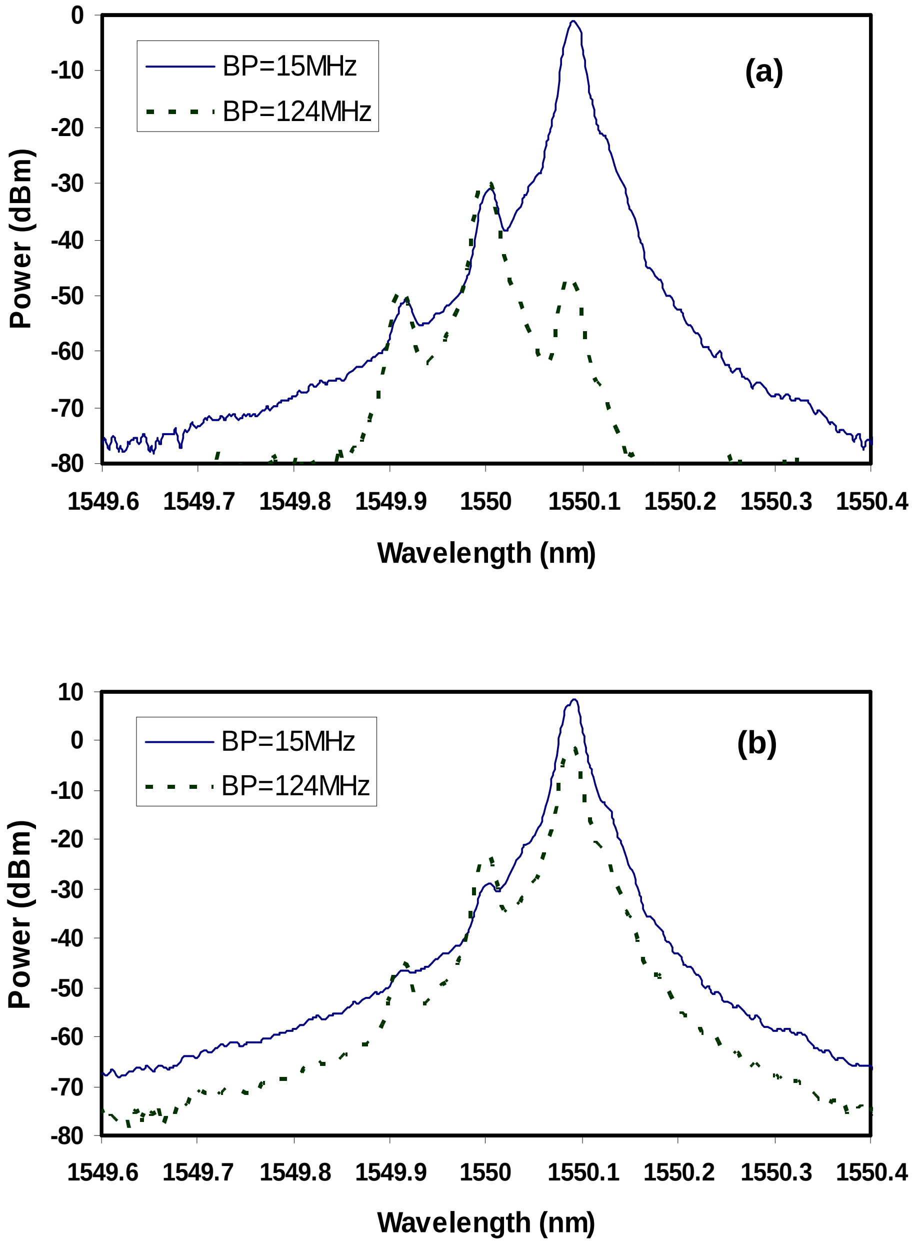


Fig. 4.6: The BFL output spectrum for different narrow and wide BP linewidths (15 MHz and 124 MHz) at BP power (a) 4.5 dBm and (b) 14.3 dBm.

For measuring the TLS linewidth, the power of the Brillouin pump (BP) and the BFL are set to be equal at around -5 dBm whereas their frequencies are slightly different but around 1550 nm to generate the beat frequency. The (2×2) 3-

dB coupler is used to combine the both BP and BFL waves as shown in Fig 4.7. The heterodyne beat spectrum between the TLS and the narrow independent BFL is shown in Fig. 4.8 for (a) a wide and (b) a narrow TLS linewidth setting, respectively. The measured TLS linewidths are obtained at 124 MHz and 15 MHz for wide and narrow TLS linewidth setting, respectively.

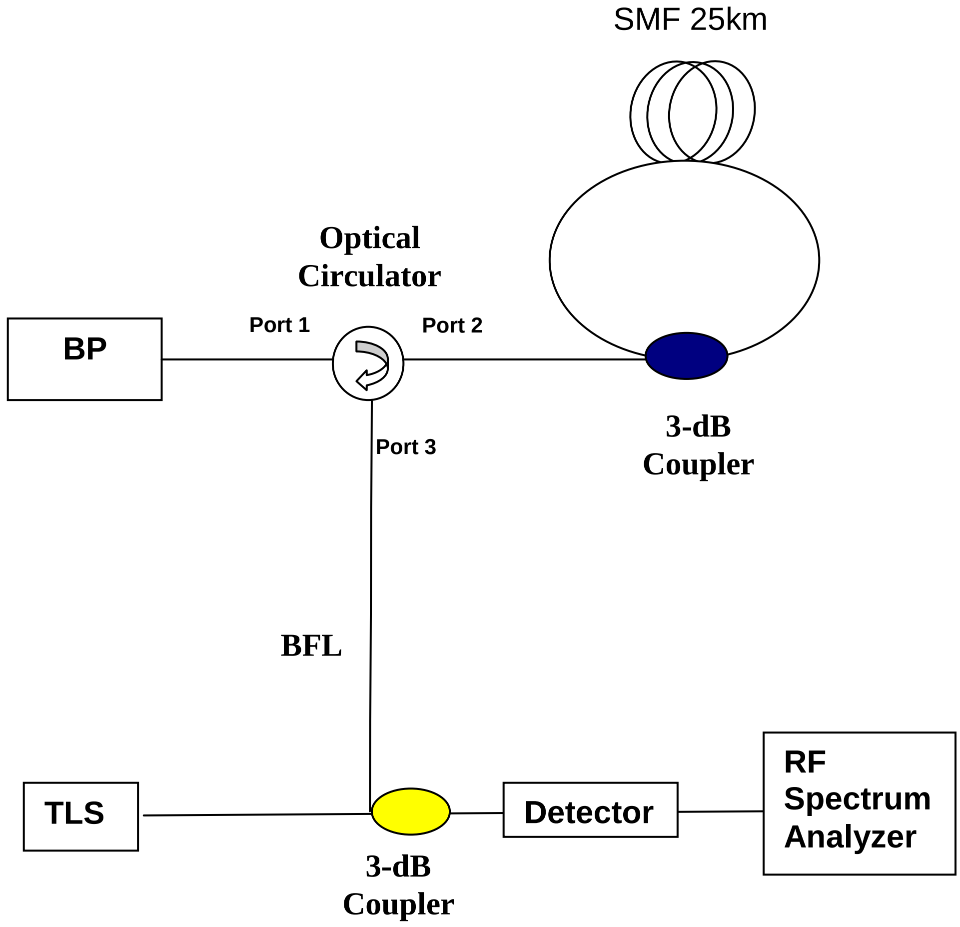


Fig. 4.7: The experimental setup for heterodyne linewidth measurement of a tunable laser source (TLS) by using a Brillouin fiber laser (BFL) in the heterodyne technique.

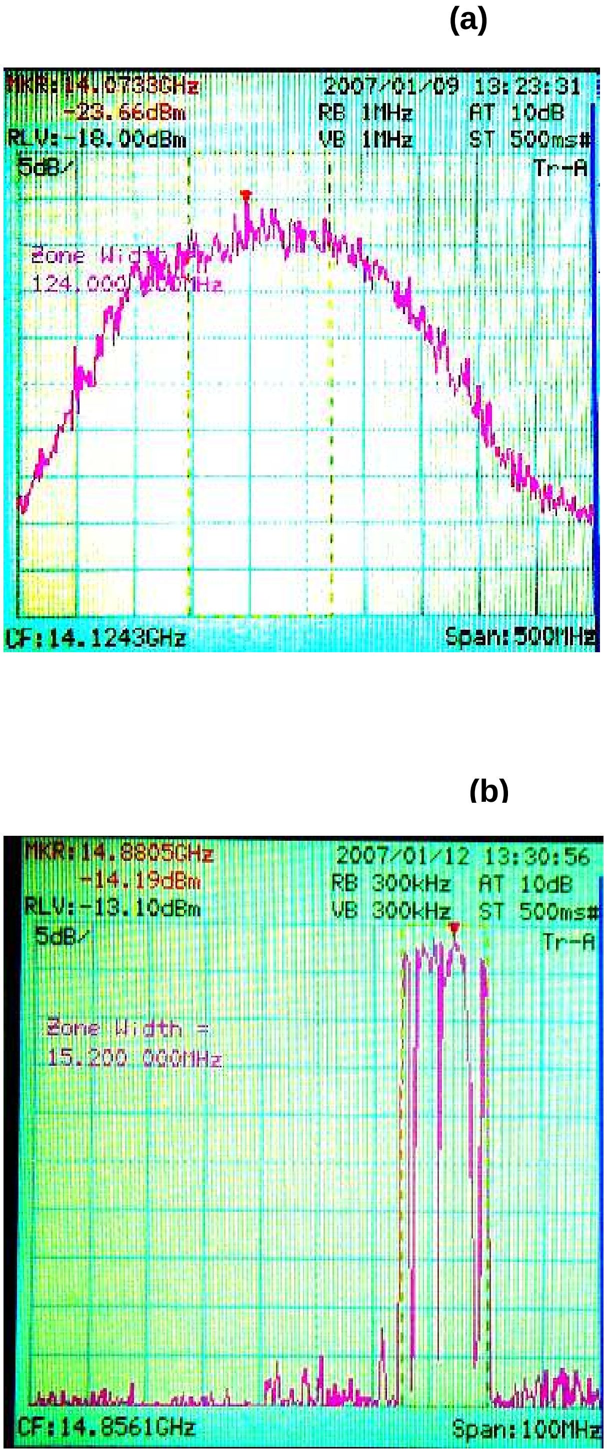


Fig. 4.8: Heterodyne beat spectra between the narrow BFL and the TLS at (a) a wide and (b) a narrow linewidth setting which are measured 124 MHz and 15 MHz, respectively.

In addition, in order to obtain BFL linewidth, two similar but independent BFLs are used to generate the heterodyne beat spectrum using an experimental setup as shown in Fig 4.9. A (2×2) 3-dB coupler is used to combine both BFL spectra. As before, the two BFLs are the same in power but have slightly different frequencies to generate the beat frequency in the detection rang of the RF spectrum analyzer shown in Fig. 4.9.

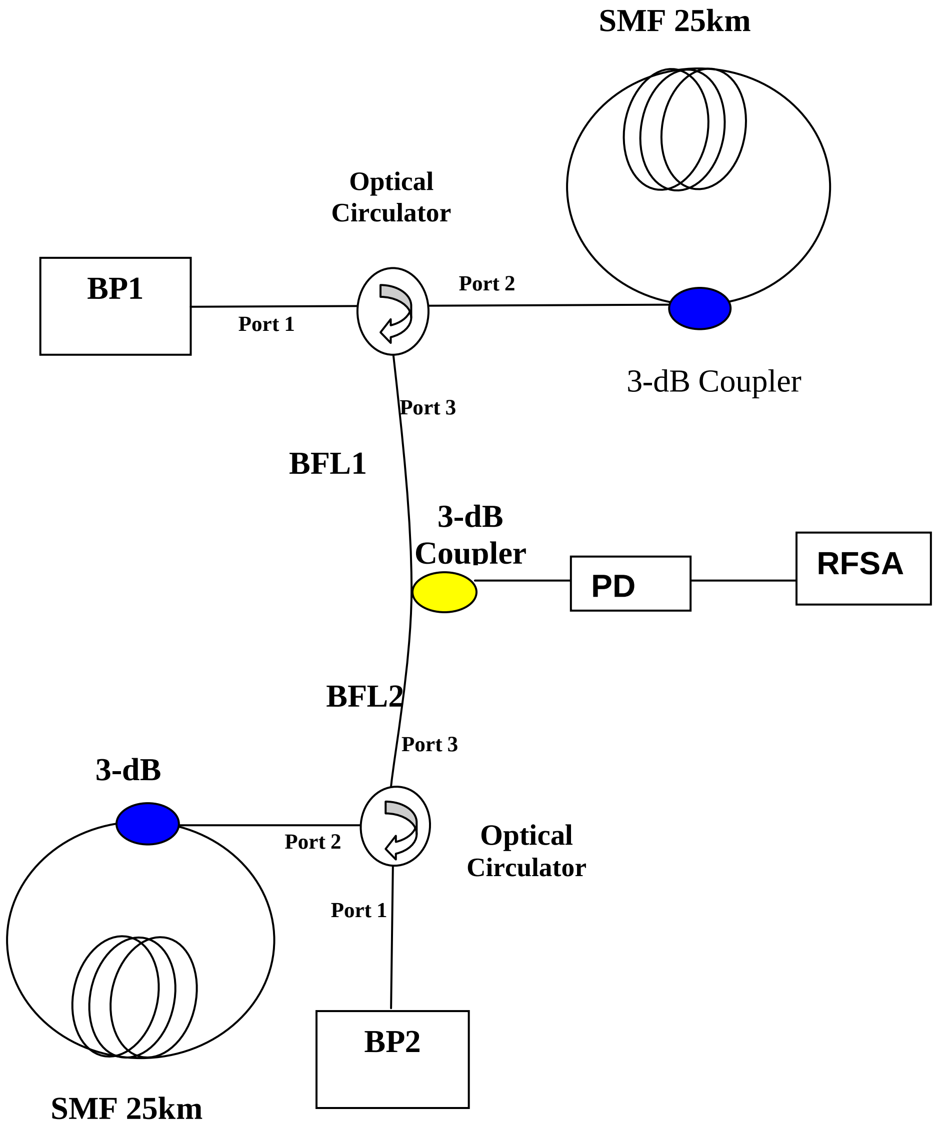
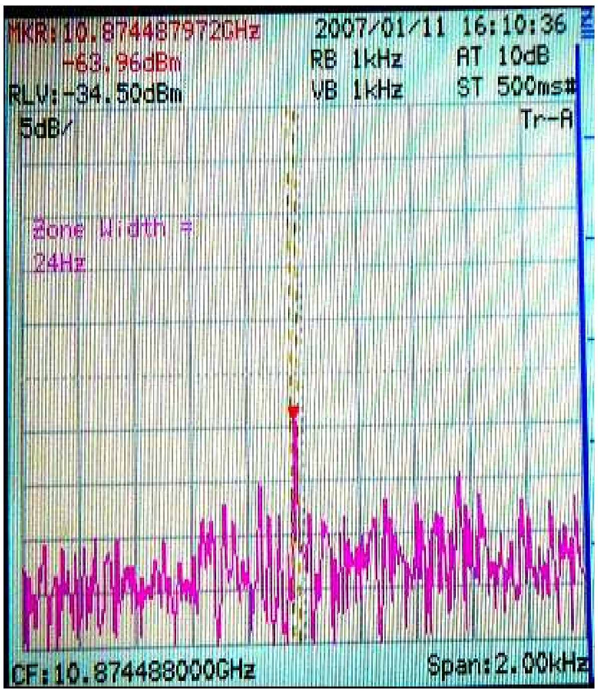


Fig. 4.9: The experimental setup for measuring the BFL linewidth by using two independent BFLs in the heterodyne technique.

Fig. 4.10 shows the measured beat frequency spectrum at the different BP linewidth setting 124 MHz and 15 MHz, respectively. As shown in Fig. 4.10 (a) and (b), the BFL linewidth is obtained at about 8 Hz and 24 Hz using the BP linewidth 15 MHz and 124 MHz, respectively. The smaller BP linewidth generates the smaller BFL linewidth as expected from the theory [22].

(a)



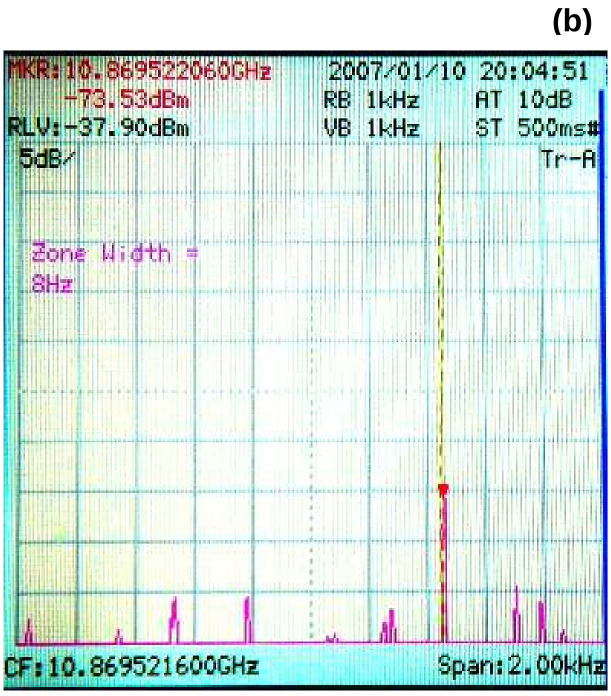


Fig. 4.10: The heterodyne beat spectra between the two similar independent BFLs generated by the TLS linewidths (a) 124 MHz and (b) 15 MHz.

In summary, the Brillouin fiber laser has experimentally demonstrated its ability for laser linewidth measurements of values less than a few 100 MHz to a few Hz regions, according to this thesis. The major advantage of this linewidth measurement system seems to be widely independent of the source wavelength by generating the uncorrelated BFL at a fixed frequency around the source which is the TLS or other independent BFLs in this work. The other advantage of this method is its simplicity which only requires widely available standard optical components. Although the BFL linewidth has been confidently reported to be 3.84 Hz with the BP linewidth at 100 kHz [21], here, BFL linewidth is measured at 8 Hz and 24 Hz by using the BP linewidth measured about 15 MHz and 124 MHz, respectively [25]. The demonstrated BP linewidth is acceptable according to our provided instrument information and the determined BFL linewidth is in the range reported by the others [19], [21], [22].

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