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# The effects of filtering RF source phase noise by a low noise, high quality factor actively modelocked laser on the laser's absolute and relative phase noise

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**Abstract:** The phase noise of two low noise, high quality factor actively modelocked lasers is investigated. It is found that increasing the quality factor of a laser can increase the phase noise relative to the RF source used to modelock the laser, even though the absolute noise of the laser is decreased. The filtering of phase noise from the modelocking source that causes both the increase in relative noise and the decrease in absolute noise is exploited to reveal phase noise information otherwise obscured in a high quality factor laser.

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## 1. Introduction

Low noise modelocked lasers have found use in a variety of systems such as optical clock distribution, arbitrary waveform synthesis [1], low noise synthesis of microwave signals [2], and analog-to-digital converters [3]. Some of these applications rely directly on the optical pulses, while others make direct use of the electrical signal derived by photodetecting the pulse train. In either case it is the timing jitter, manifesting itself as phase noise in the electrical domain [4], which often limits performance. This has led to the emergence of the integrated phase noise of the photodetected signal as a figure of merit for evaluating an actively modelocked laser's performance [5-11].

The appropriate description of the phase noise of a modelocked laser is application driven. When the laser signal and the system's reference signal are independent, the absolute noise is the quantity best suited to characterize overall system performance. This can be the case when the relative jitter between two passively modelocked lasers is of concern. For the lowest relative jitter numbers in passively modelocked systems, however, there is usually an active feedback control system in which the lasers are phase locked to a low noise RF source that may correlate the noise to some degree [12]. In actively modelocked lasers, the subject of this work, an external RF source acts as a master clock from which the pulse timing is directly derived. For systems where timing for all components is derived from a single master clock, correlations in the noise of system components reduce the importance of the absolute noise. For example, the relative jitter between an actively modelocked laser and the RF source used to modelock the laser is often dominated by the noise contributed by the modelocked laser only [6-9, 14]. This fact has allowed study of the noise processes originating in a modelocked laser and has led to methods to reduce this noise uncorrelated with the master clock. The implementation of feedback loops has successfully reduced the relative noise within the bandwidth of the feedback loop [14, 15]. Another successful method of reducing the uncorrelated noise has been to increase the quality factor of the laser by increasing the laser cavity length [7, 8]. The laser then must be harmonically modelocked in order to maintain a high repetition rate. The well known complication of supermode noise spurs encountered in harmonic modelocking has been thoroughly addressed, and significant improvements in the relative jitter have been achieved [8]. Another advantage of increasing the quality factor is the reduction of the linewidth of the optical mode, important in coherent communication systems [16]. There is, however, another complication that could arise associated with a high quality factor laser that would increase the relative jitter between an actively modelocked laser and the master clock. This is not the addition of uncorrelated noise (i.e. the supermode noise spurs), but the reduction of noise correlated with the master clock in the modelocked laser output. As derived by ref. [17], actively modelocked lasers will effectively low pass filter the driving source noise when transferring that noise onto the timing jitter. The fact that a modelocked laser can behave as a RF filter is exploited in coupled optoelectronic oscillator (COEO) configurations [18]. When the active modelocking is non-regenerative, the filtering effect would result in noise present in the master clock not being present in the laser output, and the relative jitter may then be dominated by the noise of the master clock. This result, however, would only be evident if the laser's quality factor is sufficiently high, since the filtering cut-off frequency is inversely related to the laser's quality factor. In this paper, two actively modelocked high quality factor lasers were used to explore this filtering effect. Furthermore, the filtering effect was exploited to reveal the uncorrelated noise contributed as well as parts of the absolute noise spectrum of one of the lasers.

## 2. Phase noise and phase noise measurement schemes

A number of different measurement setups that reveal different aspects of the laser noise are used in this investigation. For clarity, some basic definitions are reviewed [19]. All investigations involve measuring the phase fluctuations of a sinusoidal voltage signal, defined as

$$S(t) = V_0 \cos[\omega_0 t + \phi(t)] \quad (1)$$

Where  $V_0$  is the amplitude of the signal,  $\omega_0$  is the nominal frequency and  $\phi(t)$  is the random varying phase, assumed  $\ll 1$  radian. When this signal is mixed with another signal

$$R(t) = V_0 \cos[\omega_0 t + \gamma(t)] \quad (2)$$

in phase quadrature, the mixer acts as a phase detector resulting in a voltage signal proportional to the phase difference of the two signals:

$$V(t) = \phi(t) - \gamma(t) \quad (3)$$

where again it is assumed  $\gamma(t) \ll 1$  rad. Phase fluctuations  $\phi(t)$  and  $\gamma(t)$  relative to the ideal  $V_0 \cos(\omega_0 t)$  are termed the absolute phase noise of their respective signals. The power spectra of the absolute phase fluctuations  $\phi(t)$  and  $\gamma(t)$  are defined as  $S_\phi(\omega)$  and  $S_\gamma(\omega)$ , respectively. The three methods used here to measure the absolute noise of a source are as follows [17]:

1) Two uncorrelated sources with unequal phase noise levels. For two uncorrelated sources mixed in quadrature, the power spectrum of the voltage signal coming from the phase detector is

$$S_{\phi,\gamma}(\omega) = S_\phi(\omega) + S_\gamma(\omega). \quad (4)$$

If  $S_\phi(\omega)$  is known to be much greater than  $S_\gamma(\omega)$ , the resulting power spectrum is approximately  $S_\phi(\omega)$ . If  $S_\phi(\omega)$  and  $S_\gamma(\omega)$  are known to be equal, the result is simply twice the noise of either source.

2) Three uncorrelated sources with nearly equal phase noise. A better way to measure the noise of near equivalent sources is the three source method. The three source method involves measurements of all three combinations of sources. For three uncorrelated sources with power spectra  $S_\phi(\omega)$ ,  $S_\gamma(\omega)$ , and  $S_\sigma(\omega)$ , the phase noise  $S_\phi(\omega)$  can be determined by

$$S_\phi(\omega) = \frac{S_{\phi,\gamma}(\omega) + S_{\phi,\sigma}(\omega) - S_{\sigma,\gamma}(\omega)}{2}. \quad (5)$$

3) Frequency discriminator (FD) method. This is a single source method, where the signal from the device under test is split and a relative delay is imposed before being applied to the mixer. A schematic is shown in Fig. 1. The resulting voltage signal can be shown to be

$$S_{FD}(\omega) = 2 \cdot S_\phi(\omega) \cdot (1 - \cos(\omega\tau)) \quad (6)$$

where  $\tau$  is the relative delay between the two signals from the device under test. Because of the interference pattern it produces, an FD cannot relate accurate noise values at frequencies near the interference nulls, and is usually only used for frequency offsets less than  $\frac{1}{\tau}$ .

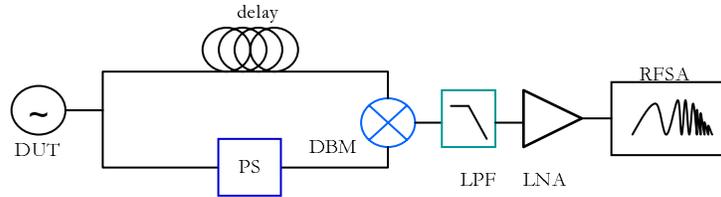


Fig. 1. Measurement schematic for a frequency discriminator. DUT: device under test; PS: phase shifter; DBM: double balanced mixer; LPF: low pass filter; LNA: low noise amplifier; RFS A: radio frequency spectrum analyzer

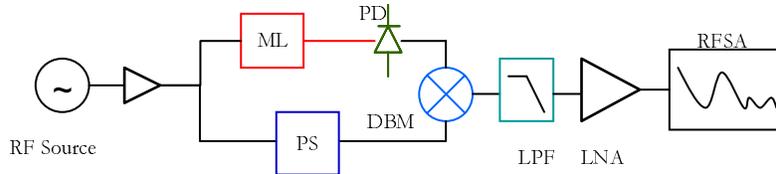


Fig. 2. Measurement of the noise of a modelocked laser relative to the modelocking source. ML: modelocked laser; PS: phase shifter; DBM: double balanced mixer; LPF: low pass filter; LNA: low noise amplifier; RFS A: radio frequency spectrum analyzer

Other noise measurement schemes employed in this study measure the relative phase fluctuations of two sources whose absolute noise is correlated to some degree (corresponding to a system with a master clock). In this case, the relative phase noise does not depend so much on the absolute noise of each component as it does the degree of noise correlation between them. In reports of noise in actively modelocked lasers, a measurement setup like the one depicted in Fig. 2 is often used [5-9, 13]. Here, the phase noise of the modelocked laser is compared to that of the RF source used for modelocking. The terms residual noise and relative noise are often both used to describe such a measurement. We reserve the term residual noise for the noise contribution of the laser uncorrelated with the RF source, such as ASE and vacuum fluctuations noise. Since quite often the relative noise is equivalent to the residual noise, the two are not always distinct. This is the case when the laser is noisier in the absolute sense due to ASE and vacuum fluctuation contributions. For high quality factor lasers, however, the absolute noise of the laser can be less than that of the RF source as a result of the filtering of the RF source noise when transferring it onto the timing jitter. In this case the relative noise is quite distinct from the residual noise.

### 3. Experiments and results

#### 3.1. Devices under test

The devices used to test the filtering effect are an RF source and two high quality factor lasers, one semiconductor based and one erbium fiber based. The RF source is an Agilent 8254A, 250 kHz--40 GHz frequency synthesizer with the low noise option, and is used to provide the timing signal for both the erbium and the semiconductor based lasers. A diagram of the semiconductor based laser is shown in Fig. 3. A 100 meter fiber delay is incorporated into the cavity to generate a high quality factor. Active modelocking at a frequency near 10 GHz is achieved via a Mach-Zender type electro-optic modulator in the cavity ring. The cavity length is about 108 m, yielding a free spectral range of about 1.85 MHz. Since some of the noise measurement schemes used involve modelocking two lasers at the same frequency, small tunings of the free spectral range of the laser were necessary. To adjust the free spectral range, both dispersion and changing the physical cavity length were exploited. The cavity dispersion was utilized by tuning the intracavity optical bandpass filter to set the optical spectrum to where the target modelocking frequency was a multiple of the longitudinal mode spacing. Fine tuning was achieved with a short free space section with one fiber launcher on a

translation stage. The erbium based laser used is similar to the semiconductor laser in many respects, both cavities containing the same basic components, including an optical bandpass filter, electro-optic modulator, and an optical isolator. The erbium based laser's free spectral range is 1.68 MHz, close to that of the semiconductor based laser, indicating a cavity length of about 119 m.

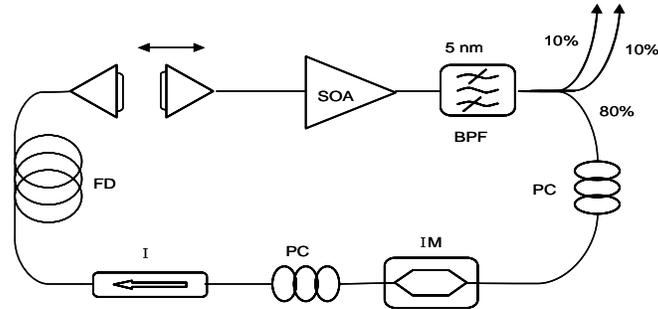


Fig. 3. Semiconductor based fiberized ring laser schematic. BPF: bandpass filter; PC: polarization controller; IM: intensity modulator; I: isolator; FD 100 meter fiber delay; SOA: semiconductor optical amplifier

### 3.2. Frequency discriminator and relative noise measurements

In order to determine if there is any significant filtering of the RF source noise by either laser, FD measurements on all three devices were performed. The results are shown in Fig. 4. Although the interference pattern of the FD measurement precludes precise knowledge of the absolute noise, it does not prevent the examination of the relative phase noise fall-off of the three devices. Beginning at frequencies below 100 kHz, there is a significant departure of the absolute phase noise of the semiconductor laser compared to that of the RF source indicating a filtering of the RF source noise when it is transferred onto the timing jitter. The absolute phase noise of the erbium laser is lower still, signaling a much lower cut-off frequency (and higher quality factor) than the semiconductor laser.

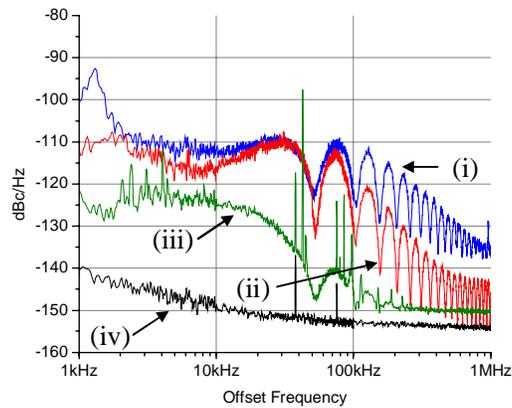


Fig. 4. Frequency discriminator measurements of the RF source (i), the semiconductor laser (ii), and the fiber laser (iii). Curve (iv) is the noise floor.

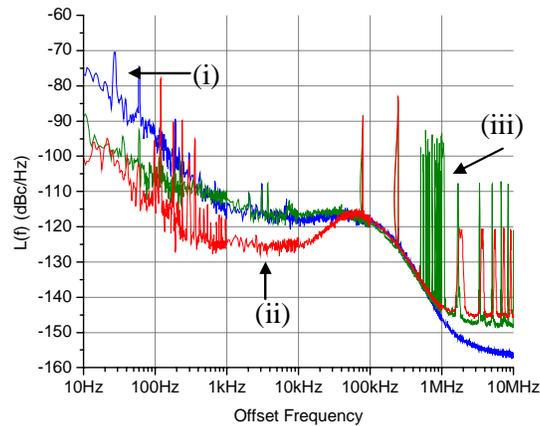


Fig. 5. Residual noise measurements using the setup in Fig. 2 of the semiconductor laser (ii), and the fiber laser (iii). The absolute noise of the RF source is shown in curve (i).

Figure 5 shows how this filtering manifests itself in the relative noise and demonstrates the necessity of distinguishing between relative noise and residual noise in high quality factor lasers. Here the semiconductor noise and the erbium laser noise, both measured relative to the RF source, are shown (the measurement setup is shown in Fig. 2). Also, the absolute phase noise of the RF source (determined by using the three source method) is plotted for comparison. The filtering corner frequencies, estimated from FD measurements, are  $\sim 50$  kHz and 5 kHz for the semiconductor laser and erbium laser, respectively. Regions of the relative noise spectrum for both lasers where filtering is significant are clearly dominated by the RF source absolute phase noise. For example, when the signal from the RF source is compared to the semiconductor laser, the absolute noise of the RF source begins to contribute to the relative noise at an offset of 10 kHz, and continues to do so out to 1 MHz. This is the noise bump in Fig. 5, curve (ii). The effect of the RF source absolute noise on the erbium laser-RF source relative noise, as indicated by the equivalence of curves (i) and (iii), stretches from 1 kHz to 1 MHz. The noise spurs, multiples of 1.85 MHz on curve (ii) and multiples of 1.68 MHz on curve (iii), are the supermode noise spurs of the semiconductor laser and the erbium laser, respectively. Examining the absolute noise plots of Fig. 4 and the relative noise plots of Fig. 5 demonstrates the need to consider the laser's low noise application when evaluating phase noise. With the given RF source, the semiconductor laser would be preferred to the erbium laser when there is correlation between the phase noise of the RF source and the laser. On the other hand, if the reference by which the laser's phase noise is measured is uncorrelated, the lower absolute noise (excluding supermode noise spurs) of the erbium laser dictates that it is preferable to the semiconductor laser.

Aside from these absolute and relative phase noise measurements, further investigations were made in which the filtering effect of a high quality factor laser was exploited. Two different setups were used, shown in Fig. 6. The setup in Fig. 6(a), where the signal generated from one laser is used to modelock another, is referred to as the "lasers in series" configuration and is capable of revealing otherwise obscured residual noise. Likewise, when the relative noise of two lasers driven by the same source is measured, the setup is referred to as the "lasers in parallel" configuration. This setup, shown in Fig. 6(b), reveals information about the absolute noise of the semiconductor laser.

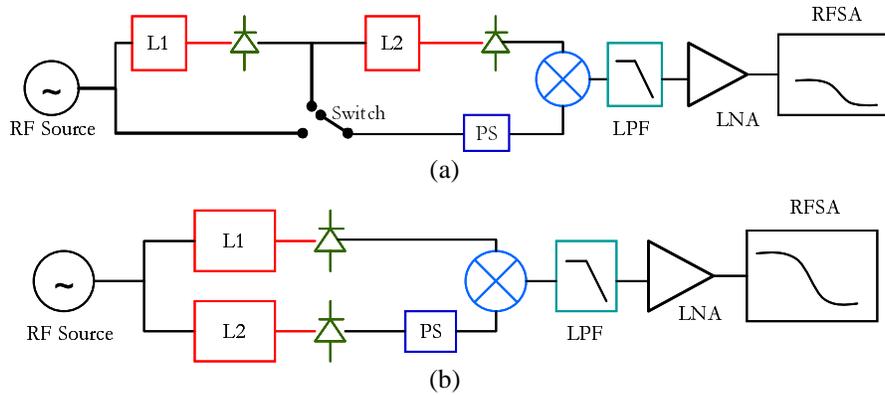


Fig. 6. “In series” (a) and “in parallel” (b) measurement schematics. The noise of L2 in (a) can be measured relative to either the RF source or L1 depending on the position of the switch.

### 3.3. Lasers in series configuration

When the absolute phase noise of an RF source has rolled-off to a level sufficiently low at the cut-off frequency of a modelocked laser, no significant filtering of the RF source noise by the laser will take place. In this case, the relative noise will be dominated by the residual noise of the modelocked laser. In lieu of such an RF source, the filtering effect of another laser with a higher quality factor can be used to generate a low absolute noise signal for modelocking, thereby revealing the residual noise. The setup used to do this is shown in Fig. 6(a). As shown, the RF source is used to modelock the erbium laser. The output of the erbium laser is photodetected, amplified, then used to modelock the semiconductor laser. The noise of the semiconductor laser can then be measured relative to either the erbium laser or the RF source. It should be noted that although the absolute phase noise of the signal from the erbium laser is quite low for frequencies below 1 MHz, strong supermode noise spurs at multiples of 1.68 MHz will feed into the semiconductor laser. Discussions of the noise measured for the “lasers in series” configuration are therefore separated into effects seen above 1 MHz and effects seen below 1 MHz. The semiconductor laser’s noise relative to the erbium laser for frequencies below 1 MHz is shown in Fig. 7(a). Note that the noise bump of Fig. 5 is no longer present. Given the cut-off frequency of the semiconductor laser and the low absolute noise of the erbium laser’s signal in this part of the noise spectrum, the relative noise of Fig. 7(a) can only be the residual noise of the semiconductor laser. The semiconductor laser’s phase noise relative to the RF source below 1 MHz is shown in Fig. 7(b), where it is seen that the most of the noise spectrum is dominated by the RF source absolute noise.

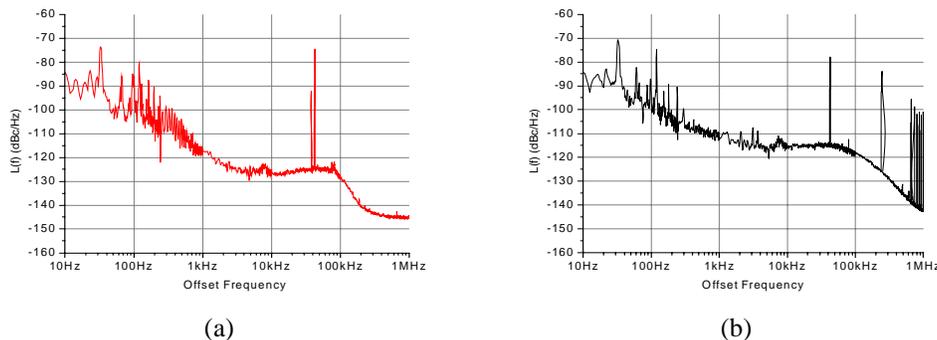


Fig. 7. “In series” phase noise measurements below 1 MHz. (a) Semiconductor laser noise relative to the erbium laser (b) Semiconductor laser noise relative to the RF source

As mentioned above, noise spectra of the semiconductor laser above 1 MHz may be influenced by the presence of the supermode noise spurs from the erbium laser. Figure 8(a) shows the semiconductor's phase noise relative to the erbium laser from 1 to 10 MHz. Two sets of supermode noise spurs are seen, the stronger set coming from the erbium laser, and the weaker set at multiples of 1.85 MHz are the supermode noise spurs of the semiconductor laser. The fact that the supermode spurs from the erbium laser appear in this noise measurement indicates that they may be filtered by the semiconductor laser. Whether or not this is so can be determined by examining the semiconductor phase noise relative to the RF source, shown in Figs. 8(b) and 8(c). Here it is seen that the strength of the erbium laser's supermode spurs in the output of the semiconductor laser depends on the frequency separation from the supermode spurs originating in the semiconductor laser. This interesting result indicates that the filtering effect is periodic with the periodicity equal to the free spectral range of the laser.

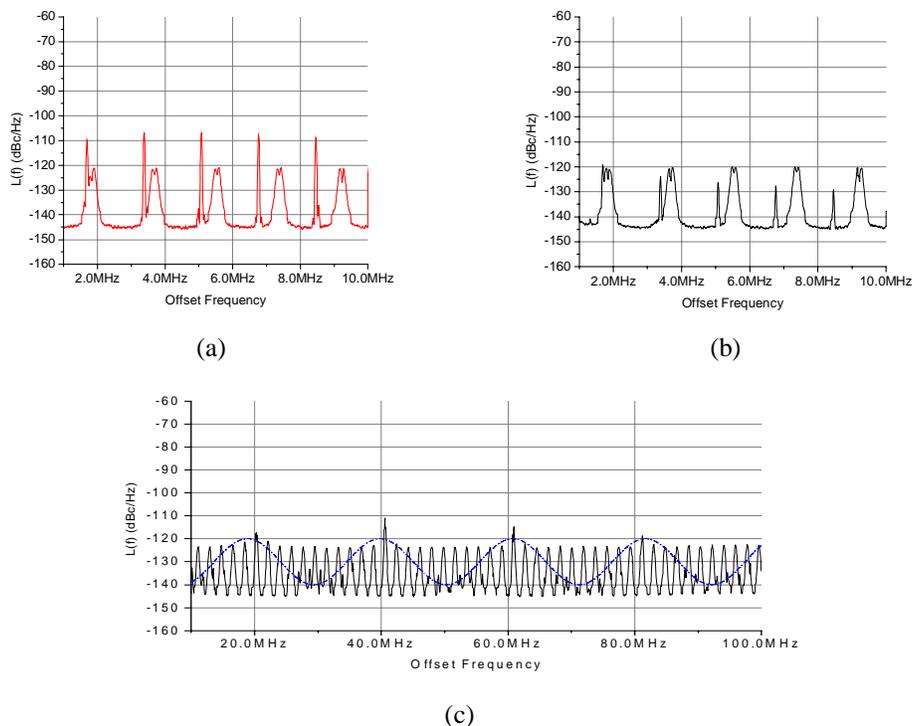


Fig. 8. “In series” phase noise measurements above 1 MHz. (a) Semiconductor laser noise relative to the erbium laser, 1 MHz to 10 MHz. (b) Semiconductor laser noise relative to the RF source, 1 MHz to 10 MHz, where a filtering effect is apparent. (c) Semiconductor laser noise relative to the RF source, 10 MHz to 100 MHz, showing the periodicity of the filtering. The blue dotted line of (c) shows the varying strength of the erbium laser's supermode spurs.

### 3. 4. Lasers in parallel configuration

New information can also be gleaned from high quality factor lasers when they are arranged “in parallel” as in Fig. 6(b). If the two lasers are equivalent, this setup will reveal the residual noise of either laser (after a 3 dB correction). For lasers with very different absolute phase noise levels, the “lasers in parallel” configuration instead yields information about the absolute noise of the laser with the higher absolute phase noise. For the lasers used here, the semiconductor based laser is known to have a much higher absolute phase noise for offset

frequencies of 10 kHz to 1 MHz. The result of the “in parallel” measurement is shown in Fig. 9(a). The absolute noise of the semiconductor laser dominates the noise measurement in the 10 kHz to 1 MHz range. To verify this, the measured data was multiplied by the FD transfer function of Eq. (6) and compared to the FD measurement of the laser. The excellent agreement of the two plots is shown in Fig. 9(b). The deviation of the two plots at large offset is due to the different configuration of amplifiers, both optical and electrical, used for the two measurements causing different noise floor levels. Note that unlike the FD measurement, the “in parallel” configuration reveals the absolute noise of the interference pattern that precludes an accurate representation of the absolute noise.

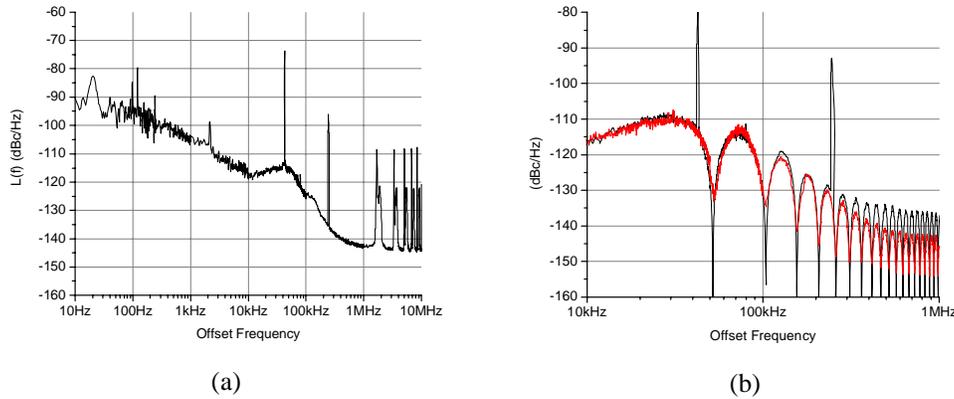


Fig. 9. (a) Lasers “in parallel” measurement and (b) the comparison of the “in parallel” measurement multiplied by the FD transfer function to the FD measurement of the SL. The red curve in (b) is the FD measurement, and the black curve is the lasers “in parallel” measurement multiplied by the FD transfer function.

#### 4. Discussion and conclusion

The filtering of the RF source noise when it is transferred onto the timing jitter of an actively modelocked laser can be understood in terms of the quality factor of the laser as follows. In the optical frequency domain, active modelocking can be understood as the creation of sidebands about an optical longitudinal mode at a frequency offset equal to the modelocking rate. When the frequency difference between the longitudinal mode and the created sideband equals a multiple of the longitudinal mode spacing, the sideband injection locks the two longitudinal modes. The locking bandwidth, that is, the range of RF frequencies for stable injection locking, depends on the linewidth of the longitudinal modes, and therefore depends on the quality factor of the laser. In other words, as the quality factor increases, the range of RF frequencies that can influence modelocking decreases. This decrease in the range of RF frequencies manifests itself as a filtering of RF source noise when transferring that noise onto the timing jitter. Since sidebands created at any multiple of the longitudinal mode spacing can injection lock, RF noise centered at any multiple of the laser’s free spectral range will influence the timing jitter. The filtering of RF source noise is therefore periodic with a periodicity equal to the laser’s free spectral range and a cut-off frequency inversely proportional to the laser cavity quality factor. Any property upon which the linewidth of the laser depends, be it cavity length, linewidth enhancement factor, cavity loss, etc., will change the bandwidth of the filtering. Changes to the driving conditions of the master clock such as detuning or power level changes do not seem to have much effect on the filtering bandwidth, however the increased residual noise associated with detuning could obscure any changes [8, 17].

In summary, investigations into the phase noise of high quality factor lasers showed how timing fluctuations relative to the signal used to modelock the laser can increase with the quality factor, although the absolute noise of the laser is decreased. Both the reduction of the

absolute noise and the increase in the relative noise are due to the filtering of the noise spectrum of the RF driving source when that noise is transferred onto the timing jitter. This indicates that for systems using modelocked lasers and a master clock, a balance must be reached between reducing noise uncorrelated with the master clock and increasing the relative noise due to the filtering effect. Also, experiments were performed using two high quality factor lasers that took advantage of the filtering effect to reveal aspects of the residual and absolute phase noise of the laser with the lower quality factor. Furthermore, these experiments demonstrated that the filtering effect of harmonically modelocked lasers is periodic, with a period corresponding to the free spectral range of the laser.