

Ultra-Narrow Linewidth and High Frequency Stability Laser Sources

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Abstract: This paper deals with improving the coherence length of both fiber and semiconductor lasers using a linewidth reduction system and absolute frequency-locking. The resulting linewidths are below the kilohertz level and relative frequency stability greater than 2×10^{-12} for 100s averaging time.

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1. Introduction

Ultra-narrow linewidth lasers for which the ratio of the spectral width to the central frequency is in the 10^{-11} range or less offer the possibility to generate interference pattern with very long optical path delay or to realize spectral analysis with very high resolution. They open new applications for high precision interferometric distance measurements and for coherent detection schemes. Very long baseline interferometers being developed for gravitational wave detection (VIRGO, LIGO), or accurate control of fiber length for millimeter wave reference signals distribution in large radiotelescope arrays (ALMA) [1] benefit from these lasers. Laser telesensing, laser vibrometry, fiber distributed sensing are also applications where such lasers are key components.

It is possible to improve the noise performance over a limited frequency band by using a linewidth reduction system. Such a system operates by frequency-locking the laser on a frequency reference that displays lower short-term frequency noise than the laser itself. However, the natural frequency drift of the frequency reference generally shows up over longer time scales and a means to control this drift has to be implemented. It is possible to do so by locking the laser frequency on a very stable molecular or atomic reference.

The linewidth of a laser source, or even its lineshape, is not sufficient to characterize the spectral performance of a laser in interferometric applications, especially when the frequency noise of the laser differ from ideal white or flicker frequency noise. In these cases, the spectral distribution of the laser's frequency noise is the best indicator of performance. This is especially true for lasers equipped with linewidth reduction systems since the frequency locking loops essentially reshapes the frequency noise of the laser according to the loop bandwidths. Furthermore, the time over which the optical spectrum is observed can also modify the effective noise levels that are perceived by the observer.

This paper presents a comparative study on the frequency noise characterization and linewidth specification for DFB fiber lasers and DFB semiconductor lasers either free-running or equipped with a linewidth reduction system. The benefits of the different combinations are stated in terms of the frequency noise spectral density, coherence length, laser lineshape and Allan deviation. Furthermore, we have investigated the impact of absolute frequency-locking of these lasers on a two-photon transition in rubidium.

2. Narrow linewidth laser sources

The power spectral density (PSD) of phase noise $S_j(f)$, or its equivalent PSD of frequency noise, $S_n(f) = f^2 S_j(f)$, completely determines the spectral quality of the laser source, its coherence length, its linewidth and its frequency stability [2]. A typical laser source is characterized by a $S_n(f)$ having a $1/f$ behavior at low frequencies and a white noise plateau for higher frequencies. These natural contributions in the PSD of frequency noise add up to the external noise such as the ones from the laser pumping scheme or external vibrations to the laser system. The sum of all contributions inherently limits the attainable coherence length and laser linewidth.

DFB fiber lasers (FL) and DFB semiconductor lasers (SCL) are used in fiber sensing applications. In more specific applications where the laser linewidth and laser coherence are of concern, DFB FLs have an edge because of their natural linewidth being of the order of 100 Hz compared to the typical megahertz level for DFB SCLs. However, SCLs are less sensitive to environmental perturbations and have proven their long term reliability in complex systems.

3. Phase noise reduction (short term stability)

Laser phase or frequency noise reduction can be achieved based on electrical feedback techniques similar to those described in [3], [4] and [5] where a frequency discriminator in a servo loop provides the needed correction signal. Such an approach is schematically represented in Figure 1a) where the output of the frequency discriminator is zero shifted prior to the loop filter in order to provide an error signal which is fed back to the laser fast correction scheme. This approach is referred as a linewidth reduction system because of its resulting effect on the lineshape of the laser.

Simple and cost effective linewidth reduction systems were designed and tested at TeraXion and their applications show a significant improvement on both DFB FLs or DFB SCLs performances.

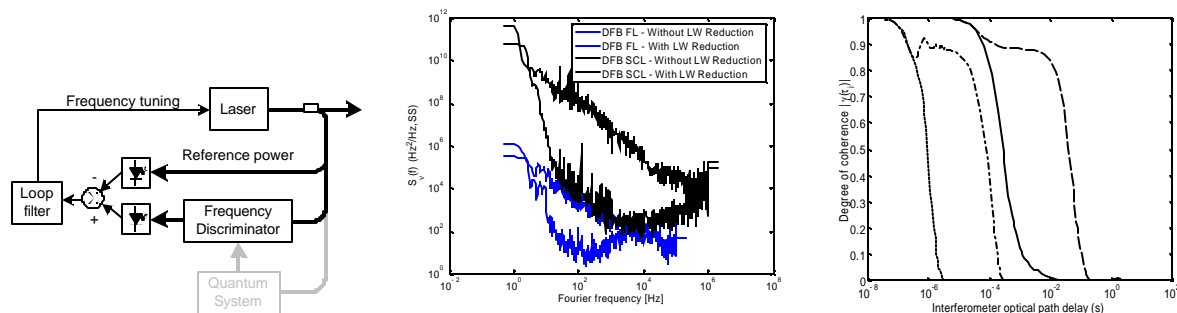


Figure 1: a) Ultra-narrow laser source equipped with a linewidth reduction system. b) Power spectral density of frequency noise for a DFB fiber laser and DFB semiconductor laser with and without linewidth reduction systems. c) Degree of coherence as a function of interferometer delay. From left to right, SCL without LW reduction, SCL with LW reduction, FL without LW reduction and FL with LW reduction, respectively.

Figure 1b) shows the PSD of frequency noise of a DFB FL and a DFB SCL equipped or not with a linewidth reduction system. The fiber laser exhibits dominant $1/f$ noise with no visible white frequency noise, while the semiconductor laser displays $1/f$ noise at low frequency and white frequency noise beyond 100 kHz. These PSD were measured using a fibered interferometer as a frequency discriminator, which was maintained in quadrature with a low bandwidth servo loop (0.1 Hz).

Since the linewidth reduction systems attenuate the frequency noise of the laser over a limited band, the resulting PSD of frequency noise is no longer a combination of white and $1/f$ noise, and the resulting coherence profile cannot simply be scaled by a corresponding factor. Indeed, Figure 1c) shows that the linewidth reduction has relatively little effect for short interferometer delays, and some coherence is lost whether it is activated or not. At some point, however, the coherence stops falling, forms a plateau, and then falls off to zero due to the ever present $1/f$ frequency fluctuations.

The linewidth reduction systems reduce the FWHM linewidth of the fiber laser from 119 Hz to 6 Hz, and the semiconductor laser from 411 kHz to 400 Hz. The resulting effect is that the coherence length of the fiber laser increases from 56 km (in fiber) to 8000 km at 50% coherence, and from 200 m to 16 km for the semiconductor laser. In both cases, however, these specific linewidth reduction systems do not provide improvements for coherence levels higher than 90%.

4. Long term stability and accuracy

The laser linewidth reduction system based on a discriminator significantly improves the short term stability of a laser. When the laser long term stability is a critical parameter, it is necessary to introduce an additional component to the system to compensate external fluctuations for which the frequency discriminator is sensitive.

Quantum systems based on atomic or molecular transitions have proven to be effective for compensating lasers long term frequency fluctuations [6]. Simple linear absorption scheme in gas cell can provide relatively good frequency stability with minimal complexity. However, when one is facing greater frequency restrictions, it is often necessary to use Doppler-free atomic transition as reference. This was done at TeraXion where a narrowed linewidth laser, either a DFB FL or a DFB SCL, was frequency-locked to a two-photon transition in rubidium.

The resulting DFB FL system features a laser frequency of 192 642.5712 GHz (or a wavelength of 1556.210842 nm) with a linewidth less than a few tens of Hz for a measurement time of 1 ms and a long term stability better than 2×10^{-12} over 100 s averaging time. A similar stability was achieved with the SCL, but some degradation of the linewidth (1.4 kHz) was caused by the insufficiently filtered noise on the absolute frequency.

Figure 2a) shows the PSD of the frequency noise of the Rubidium-locked laser equipped with a linewidth reduction. The results are for both a fiber laser and a semiconductor laser. Figure 2b) shows the corresponding Allan deviation.

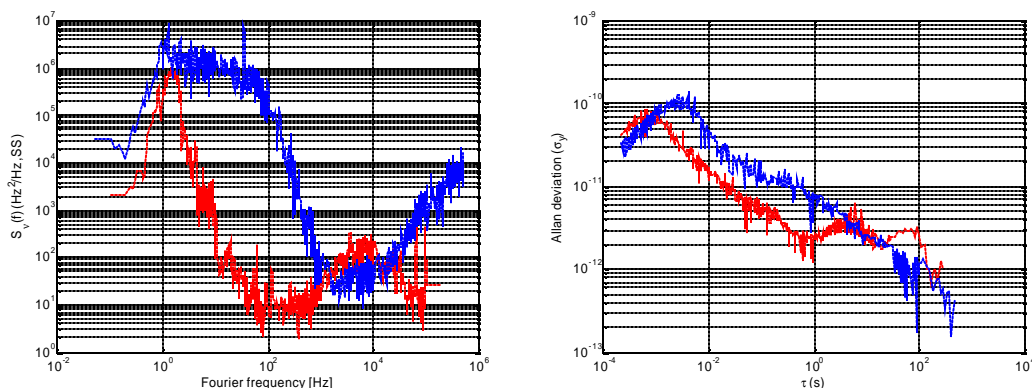


Figure 2: a) Power spectral density of the frequency noise of the DFB FL (lower curve) and DFB SCL (upper curve). Both lasers are narrowed linewidth and frequency-locked to the rubidium transition. b) Corresponding Allan deviation.

These lasers are highly suitable as an optical frequency standard in the 1550 nm region, especially in interferometers where optical path delays of more than 50 km are of interest or in which low phase is a requirement.

5. Conclusion

Very long baseline optical interferometers and high resolution optical spectrum analyzers require highly stable narrow linewidth laser sources. DFB fiber lasers and DFB semiconductor lasers are good candidate for such applications. We have shown that their phase noise can be reduced by many orders of magnitude over a relatively broad Fourier frequency range when locked to a phase sensitive optical reference. The resulting linewidth for the DFB fiber laser goes from 120 Hz to 6 Hz while the DFB semiconductor linewidth goes from 410 kHz to 400 Hz for a measurement time of 1 ms. For longer measurement times, the laser frequency can be locked to a highly stable atomic reference based on a two-photon transition in rubidium atoms. We have shown in that case that the frequency stability of the SCL and FL can reach 2×10^{-12} levels but with some degradation of the linewidth (1.4 kHz) in the case of SCL.

6. References

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