FM Noise Measurement of Single-Frequency Lasers

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Abstract — The results of the frequency (FM) noise measurements of single-frequency lasers using the optical heterodyne method are reported. The distributed feedback (DFB) diode lasers, the DFB fiber lasers and two types of the external cavity diode lasers (ECDLs) were studied. The technique is based on the direct measurements of the optical FM noise with RF phase noise analyzer (PNA) and is traceable to primary RF phase noise standards.

Keywords— frequency noise; phase noise; single-frequency lasers; optical heterodyne; direct measurements

Single-frequency lasers are widely used in various application areas, such as atomic clocks, reference frequencies dissemination, gravimetry, optical fiber communications, sensing applications, microwave photonics, laser spectroscopy, LIDARs and etc. For many applications, the most important parameter of the single-frequency lasers is the "spectral purity", characterized by FM noise *Sv*, spectral linewidth and frequency stability. It should be noted that frequency noise is the most informative parameter, since it can be used to calculate both spectral linewidth [1] and frequency instability [2]. In the optical range, the FM noise *Sv* (in units of Hz^2/Hz) is usually measured in contrast to the radio frequencies (RF), where the phase (PM) noise *L* (in units of dBc/Hz) is typically used. The FM noise *Sv* is related to the PM noise *L* as $Sv=2\times f^2\times 10^{0.1\times L}$, where *f* is offset frequency (Fourier frequency). Optical FM noise spectra are typically measured using experimental setups with fiber delay lines or interferometers and the traceability of measurement results may be unclear issue.

The self-heterodyne frequency discriminators based on fiber delay lines are usually used for the FM noise measurements of the single-frequency lasers [3]. The calibration of the measurement noise floor is the main difficulty of this technique [4]. Another approach to measure the FM noise of the single-frequency lasers is the optical heterodyne method [3]. The RF beat note signal of two lasers (the laser under test and the heterodyne laser) is obtained with a photodiode. Then the PM noise of the beat note (that is sum of PM noise of the lasers) can be measured. But the frequency of the beat note of free-running single-frequency lasers is very unstable, which makes it difficult to measure their PM noise with RF PNAs or signal source analyzers (SSAs) [3]. In this work we used PNA to measure PM noise of the beat notes. In some measurements, a RF "digital" frequency divider was used to reduce PM noise of the beat notes. The RF frequency divider reduces the PM noise of input signal by 20×lgN (in units of dBc/Hz), where N is division coefficient. Using the divider by 8, we measured PM noise of more than +100 dBc/Hz at 1 Hz offset frequency [5]. Also, postprocessing of beat note signal captured in the time domain to derive the FM noise power spectrum was reported [6].

In this paper direct and traceable FM noise measurements of free-running single-frequency lasers with a RF PNA are presented. A photodetector and a Rohde & Schwarz FSWP8 PNA were used in common optical heterodyne setup shown in Fig. 1. The photodetector consisted of a photodiode and a bias-tee. Typical range of optical power on the photodiode was from 1+1 to 5+5 mW. Polarization controllers and polarization-sensitive isolator were used to adjust the power of each laser on the photodiode. The polarization-dependent isolator also provides the same polarization of the beams combined on the photodiode. All measurements were performed at least three times to ensure reproducibility.

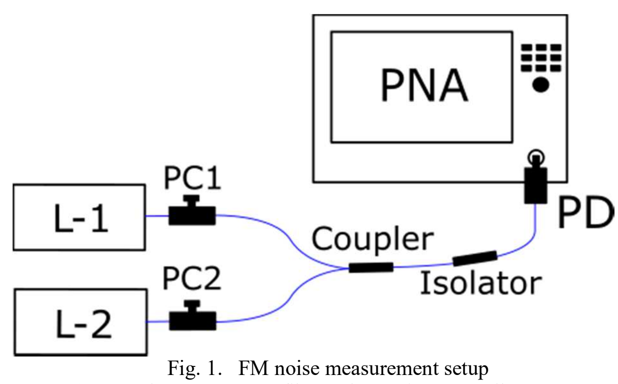

Fig. 1. FM noise measurement setup
(L-1,2 – lasers, PC1,2 – fiber polarozation controllers, PD – photodetector)

First, the PM noise of the beat note of two DFB fiber lasers (Koheras BASIK by NKT Photonics) was measured. Then one of the BASIK lasers was used as heterodyne laser for the PM noise measurements of two DFB diode lasers, the integrated tunable laser assembly (ITLA) ECDL and the RIO ORION ECDL.

The measurement results (Fig. 2) are in good agreement with test reports of manufacturers for the BASIK and the RIO laser. The Lorentzian spectral linewidth of 53 kHz calculated from the measured FM noise (at 100 kHz offset frequency) matches with the test report of 54 kHz for the new DFB diode laser. The results are also consistent with measurements of analogous lasers using the self-heterodyne technique [4, 7, 8]. The fiber lasers have the lowest FM noise. The RIO laser also shows good FM noise performance with sub-kilohertz Lorentzian linewidth. The "old" and "new" DFB diode lasers have significant differences in FM noise at large offsets. The Lorentzian linewidth of the "old" DFB is about 300 kHz. At the same time, the Lorentzian linewidth of the “new” DFB laser is about an order of magnitude smaller.

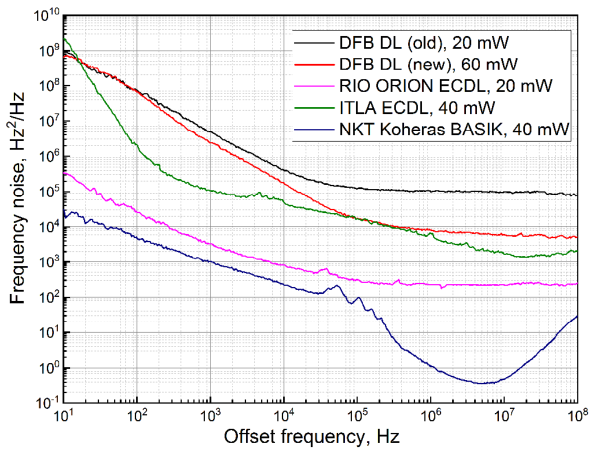

Fig. 2. The results of the FM noise measurements

The optical heterodyne method does not require fiber delay lines and any calibration of the measurement setup, in contrast to self-heterodyne techniques. Another advantage of the method is a wide range of the offset frequencies. The maximum value of the offset frequency is limited by the photodetector bandwidth, beat note frequency (which may be higher than the 3dB bandwidth of the photodetector) and the maximum offset frequency of PNA or SSA. The minimum offset frequency is usually determined by the high PM noise value of laser under test, which increases at low offset frequencies. PNA and SSA manufacturers do not specify the maximum values of measured PM noise. Some instruments failed to measure the PM noise of drifty and noisy beat notes or indicated unreproducible and unreliable measurement results in our experiments. The use of RF frequency dividers allowed us to measure PM noise of more than +100 dBc/Hz [5] and to extend the offset frequency range to mHz level. We note that the RF frequency dividers introduce additive PM noise, which can affect the PM noise measurement of the beat note. Evaluation of the frequency divider additive PM noise and its impact on the measurements are currently under investigation.

The optical heterodyne technique allows one to perform the direct measurements of the FM noise of the laser under test using RF PNA or SSA (provided that the FM noise of heterodyne laser and photodiode noise are much less than the FM noise of the laser under test). The FM noise of heterodyne laser and photodiode noise increase measurement uncertainty compared to PNA or SSA specification. It was shown that measurement of additive PM noise of photodiode is difficult experimental task [9]. On the other hand, flicker noise of photodiodes is much less than PM noise of free-running single-frequency lasers. In practice, relative intensity noise (RIN) of lasers can affect the optical heterodyne FM noise measurements because the RIN results in amplitude noise of the beat note. We note that some PNAs have amplitude noise suppression function.

Moreover, the optical heterodyne FM noise measurements are traceable to RF primary PM noise standards. The optical heterodyne technique can be used as reference method to evaluate other measurements. The main disadvantage of the optical heterodyne method is the need for heterodyne laser with low FM noise. We note that if there are three lasers with similar FM noise values, the three-cornered hat method can be used to measure the absolute value of the FM noise for each laser [10].

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