Optics Communications 341 (2015) 7–14

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Algorithm based comparison between the integral method and harmonic analysis of the timing jitter of diode-based and solid-state pulsed laser sources

N.K. Metzger [a,*], C.-R. Su [b], T.J. Edwards [b], C.T.A. Brown [b]

[a] SUPA School of Engineering and Physical Sciences, Photonics & Quantum Sciences, Heriot Watt University, Edinburgh EH14 4AS, UK
[b] SUPA School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews, Fife KY16 9SS, UK

ARTICLE INFO

Article history:
Received 21 August 2014
Received in revised form
25 November 2014
Accepted 27 November 2014
Available online 3 December 2014

Keywords:
Phase noise
Timing jitter
Semiconductor lasers
Mode-locked lasers
Pulsed laser noise
Pulse train
Laser stabilization

ABSTRACT

A comparison between two methods of timing jitter calculation is presented. The integral method utilizes spectral area of the single side-band (SSB) phase noise spectrum to calculate root mean square (rms) timing jitter. In contrast the harmonic analysis exploits the uppermost noise power in high harmonics to retrieve timing fluctuation. The results obtained show that a consistent timing jitter of 1.2 ps is found by the integral method and harmonic analysis in gain-switched laser diodes with an external cavity scheme. A comparison of the two approaches in noise measurement of a diode-pumped Yb:KY$(WO_4)_2$ passively mode-locked laser is also shown in which both techniques give 2 ps rms timing jitter.

1. Introduction

Actively and passively mode-locked lasers are ideal candidates for the generation of coherent, stable and highly periodical pulse trains. They have been the subject of intense investigation as they can be used in many applications, including high-speed optical communications, all-optical signal-processing, optical sampling and clock distribution [1]. Among these applications, some require not only high peak power and short pulse operation, but also the smallest possible timing jitter, as the fluctuation of the time interval between pulses degrades the quality of the expected system performance.

A broad bandwidth oscillator can detect timing fluctuations by monitoring the beat frequency between a modulated signal and low-jitter electrical trigger signal [2]. This enables one to easily obtain the exact timing fluctuation of an unknown optical source. Although this is an accurate method to calculate timing jitter, the equipment requirement of a broad bandwidth and a trigger-dependent source limits the practicality of such spectral measurements. These drawbacks can be overcome with the combination of a fast photodetector and an electronic spectrum analyzer. The available bandwidth of the spectrum analyzer not only facilitates measurements, but also provides important insight into sources of both correlated and uncorrelated timing jitter [2,3].

By considering the noise sideband of the power spectrum, phase noise can be distinguished from amplitude fluctuation. Whilst phase noise rises quadratically with harmonic order, amplitude fluctuation remains order independent across the full frequency spectrum [2]. Both of these effects contribute to pedestals or broad noise sidebands that prevent a clean RF signal. The single side-band (SSB) phase noise, which is identified by the carrier per resolution bandwidth, reveals information about the timing jitter. Following von der Linde's work [2], the rms timing fluctuation at a given carrier frequency f_R can be obtained from a spectral integration of noise if the rms amplitude noise remains small.

When using this method the integration boundaries need to be chosen carefully [4–12] to obtain high measurement accuracy. To solve this problem, an approach using a simplified theoretical model has been developed [2]. The harmonic approach adjusts the integration by utilizing the uppermost noise power to identify the timing jitter in higher harmonic orders. This has been verified as a valid solution [9,10], yet it remains relatively little used compared to the integration method discussed above. This is because the accuracy of harmonic analysis is greatly restricted by the highest

* Corresponding author. Fax: +44 131 451 3473.
E-mail address: k.metzger@hw.ac.uk (N.K. Metzger).

http://dx.doi.org/10.1016/j.optcom.2014.11.088
0030-4018/

harmonic order obtained; the higher the harmonic order, the more precise the timing jitter.

To date, a thorough comparison of both methods has yet to be conducted, despite Ng et al. [11] and Yoshida [12] confirming the consistent outcome of these two approaches in their own system. This publication presents two studies of the rms timing jitter calculated by the integral method as well as the harmonic analysis approach in gain-switched semiconductor laser diodes. The calculated timing jitter of 1.1 ps and 1.25 ps obtained by harmonic analysis and integral method respectively in this work, proved comparable to the 1.5 ps jitter in a Fabry–Perot gain-switched semiconductor laser diode with optical feedback [13,14]. These two algorithms were then applied to an Yb:KYW passive mode-locked lasers and yielded a free-running jitter time of 2.05 ps and 1.95 ps respectively. A similar agreement of results was obtained with an Yb:Eb:glass ultrafast laser [15].

The outcomes of this study validates the consistent measurement of timing jitter by both the harmonic analysis and integral method when tested theoretically and experimentally in mode-locked and gain-switched lasers.

2. Background to jitter measurements and algorithm development

The well-developed theory by von der Linde has been used to calculate rms timing jitter in spectral measurements [2]. This work analyzed the noise behavior in the power spectrum and found that noise varies with increasing harmonic orders. While amplitude noise remains a frequency-independent trend, phase noise increases quadratically and further becomes the main source of noise for high harmonics in RFSA. Phase noise is thus observed to have the largest contribution with respect to rms timing jitter. To compute timing jitter, there are two approaches advocated.

The first approach, the integral method, uses the integration of the entire SSB phase noise to calculate the rms timing jitter. This approach assumes that the amplitude fluctuation is negligible in affecting the power spectrum. The second, harmonic analysis, is a simplified version of the integral method. This utilizes the whole power spectrum and then retrieves the uppermost noise power and full width at half maximum (FWHM) noise bandwidths in high harmonic orders for the calculation of rms timing jitter. Both methods have been validated to be correct theoretically and experimentally [3,9,11,12,16,17].

In order to compare rms timing jitter efficiently, these two methods were implemented in Matlab. The content of these programs for harmonic analysis and the integral method will be discussed in the following sections.

2.1. Algorithm for harmonic analysis

Before calculating rms timing jitter, harmonic analysis requires information from the RFSA trace. A fluctuation-free pulse train is seen to have a delta RF linewidth. However, once the pulse encounters phase noise, an undefined phase relation between each pulse will result in the broadened linewidth RFSA trace shown in Fig. 1. After the red crosses (P_B), the power spectrum encounters noise interruption.

In Fig. 1, P_A denotes the peak of the RFSA trace. P_B and P_C represent the power of the maximum noise level and the averaged noise floor respectively.

The rms timing jitter can be estimated [2] with Eq. (1), given prior knowledge of parameters P_A, P_B, P_C, Δf_{res} resolution bandwidth (RBW), Δf_J (the FWHM of noise bands), round trip time T, and the harmonic order n of the measured RFSA data in Eq. (1).

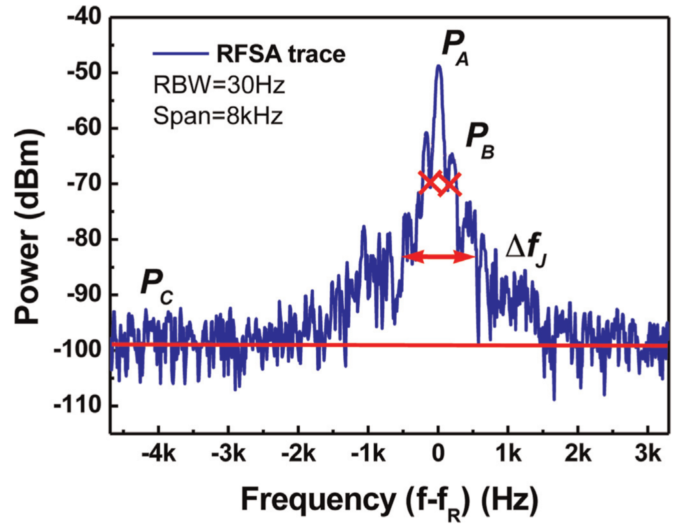

Fig. 1. The RFSA trace obtained with Matlab (RBW = 30 Hz). The RFSA trace shows large noise interference until the trace reaches the noise floor. P_A marks the peak of the RFSA trace. P_B represents the power of the maximum noise level and P_C the averaged noise floor while Δf_J is the FWHM level between P_c and P_B. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

$$\Delta t = T(2\pi n)\left[\left(\frac{P_B}{P_A}\right)_n \frac{\Delta f_J}{\Delta f_{res}}\right]^{1/2} \tag{1}$$

where Δt symbolizes the rms timing jitter. P_B the uppermost noise level (red crosses in Fig. 1) is determined automatically as illustrated in Fig. 2.

Initially, the unprocessed RFSA data is convoluted with a moving average filter generated by the analysis program to remove spurious aliasing ripples. From this filtered curve Fig. 2(a), the algorithm is able to extract its slope. The slope of the raw RFSA data and its filtered curve slope are both depicted in Fig. 2(b) by the blue curve and red dotted curve, respectively. Looking back at the original data in Fig. 2(a), it can be seen that the uppermost phase noise has a local minima, shown in the expanded (c). Furthermore, the local maximum or minimum points in Fig. 2(c) will have a value of approximately zero at the same frequencies in (d). It is not surprising that the extreme values usually result from the transition in slope. Therefore, to find the uppermost noise, the program can rely on the transition point of the slope. In other words, values where there are zero crossings Fig. 2(d) correspond to the extreme values of (c).

Similarly P_A and P_C can both be obtained from a standard maximum and minimum search function where P_C was taken as the average noise floor. The points (f_{J1} and f_{J2}) both have powers of $(P_B+P_C)/2$ in the power spectrum, where the corresponding frequency distance between the two points determines the FWHM of the noise bandwidths $\Delta f_J = f_{J1} - f_{J2}$. Roundtrip time T, harmonic order n, and RBW can be retrieved from the RFSA trace. This method assumes no correlations between the intensity and phase noise of the pulses [2]. When timing-jitter fluctuations between pulses are uncorrelated in time a Lorentzian shaped RFSA trace is obtained. Correlations between timing fluctuations tend to produce traces that are Gaussian in shape [6]. In the first case the accuracy of the prediction of the jitter will suffer however the algorithm will still give a fast qualitative prediction as shown in experimental section.

2.2. Amplitude fluctuations

Although amplitude noise remains a small value for most frequencies, it nevertheless influences the power spectrum regarding