Retraction Notice

Title of retracted article:	**Coherent Parameter Measurement Based on Partial Coherent Envelope Demodulation**
Author(s):	Chaoze Zhang, Laiyang Dang, Tianyu Guan, Yuqin Mao, Ligang Huang, Tao Zhu
* Corresponding author.	Email: lghuang@cqu.edu.cn,zhutao@cqu.edu.cn
Journal:	Optics and Photonics Journal
Year:	2023
Volume:	13
Number:	6
Pages (from - to):	133 - 139
DOI (to PDF):	https://doi.org/10.4236/opj.2023.136011
Paper ID at SCIRP:	126139
Article page:	https://www.scirp.org/journal/paperinformation.aspx?paperid=126139
Retraction date:	2023-09-25

Retraction initiative (multiple responses allowed; mark with **X**):
X All authors
☐ Some of the authors:
☐ Editor with hints from
  ○ Journal owner (publisher)
  ○ Institution:
  ○ Reader:
  ○ Other:
Date initiative is launched: 2023-09-25

Retraction type (multiple responses allowed):
☐ Unreliable findings
  ○ Lab error ○ Inconsistent data ○ Analytical error ○ Biased interpretation
  ○ Other:
☐ Irreproducible results
☐ Failure to disclose a major competing interest likely to influence interpretations or recommendations
☐ Unethical research

☐ Fraud
  ○ Data fabrication ○ Fake publication ○ Other:
☐ Plagiarism ☐ Self plagiarism ☐ Overlap ☐ Redundant publication *
☐ Copyright infringement ☐ Other legal concern:

☐ Editorial reasons
  ○ Handling error ○ Unreliable review(s) ○ Decision error ○ Other:

X Other: Request from the Authors.

Results of publication (only one response allowed):
☐ are still valid.
X were found to be overall invalid.

Author's conduct (only one response allowed):
☐ honest error
☐ academic misconduct
X none (not applicable in this case – e.g. in case of editorial reasons)

* Also called duplicate or repetitive publication. Definition: "Publishing or attempting to publish substantially the same work more than once."

History
Expression of Concern:
☐ yes, date: `yyyy-mm-dd`
X no

Correction:
☐ yes, date: `yyyy-mm-dd`
X no

Comment:

This article has been retracted to straighten the academic record. In making this decision the Editorial Board follows COPE's Retraction Guidelines. Aim is to promote the circulation of scientific research by offering an ideal research publication platform with due consideration of internationally accepted standards on publication ethics. The Editorial Board would like to extend its sincere apologies for any inconvenience this retraction may have caused.

Scientific Research Publishing

Optics and Photonics Journal, 2023, 13, 133-139
https://www.scirp.org/journal/opj
ISSN Online: 2160-889X
ISSN Print: 2160-8881

Coherent Parameter Measurement Based on Partial Coherent Envelope Demodulation

Chaoze Zhang, Laiyang Dang, Tianyu Guan, Yuqin Mao, Ligang Huang*, Tao Zhu*

Key Laboratory of Optoelectronic Technology and Systems, Chongqing University, Chongqing, China
Email: *lghuang@cqu.edu.cn, *zhutao@cqu.edu.cn

How to cite this paper: Zhang, C.Z., Dang, L.Y., Guan, T.Y., Mao, Y.Q., Huang, L.G. and Zhu, T. (2023) Coherent Parameter Measurement Based on Partial Coherent Envelope Demodulation. *Optics and Photonics Journal*, **13**, 133-139.
https://doi.org/10.4236/opj.2023.136011

Received: April 26, 2023
Accepted: June 27, 2023
Published: June 30, 2023

Abstract

The key parameters of laser energy concentration and coherence can be characterized by laser linewidth, which determines the detection range, measurement resolution and signal-to-noise ratio of laser precision measurement technology. Up to now, the laser linewidth is mainly measured by the energy distribution width in the frequency domain, but the coherence of the laser has not been measured or characterized directly. In this work, we propose the concept of coherent linewidth based on the coherent envelope of delayed self-heterodyne detection to directly characterize the time-frequency coherence of lasers. In the proof-of-concept experiment, we obtain the coherence coefficient through the Fourier transform of the partial coherence envelope, and then measure the coherence linewidth of the laser. The measured coherent linewidth is smaller than the traditional integral linewidth and larger than the intrinsic Lorentzian linewidth, indicating that the coherent linewidth is less affected by low-frequency 1/f noise. The concept of coherent linewidth proposed in this article can serve as a candidate method for directly characterizing the coherence of narrow linewidth lasers.

Keywords

Laser Linewidth, Coherent Linewidth, Coherent Envelope

1. Introduction

Laser coherence plays an important role in laser precision measurement technology, such as coherent optical communication [1] [2], light detection and ranging (LiDAR) [3] [4], fiber sensing [5] [6] [7], and so on. In the LiDAR system and optical fiber communication system, the laser coherence affects its detection range [8] [9] [10]. Laser linewidth is also used as one of the manifestations of laser coherence. And the laser linewidth is also an important parameter to characterize the operating mechanism of laser. Within the laser cavity, random and cumulative perturbations of the laser frequency occur due to energy coupling between the stimulated emission and spontaneous radiation, forming the laser intrinsic linewidth [11] [12]. For the practical applications in laser precision measurement, the laser linewidth reflects the time-domain coherence of the laser, which is also closely related to the phase noise and frequency noise. Therefore, it is very important to measurement the linewidth of lasers. Current linewidth measurement methods of narrow-linewidth lasers are mainly carried out from the perspective of the energy distribution in the frequency domain, such as the heterodyne beat method [13], long-delayed self-heterodyne detection method [14], and frequency noise integration method [15] [16]. However, based on the above linewidth measurement methods by energy distribution, the laser coherence cannot be directly obtained, and the measurement process does not directly reflect the laser coherence.

In this work, we propose the concept of coherence linewidth from the coherent envelope of delayed self-heterodyne detection. With the increase of delay length, the coherence coefficient gradually decreases, and the coherent length of the laser can be measured. According to the coherence strength evolution of the coherent envelope, the coherence linewidth corresponding to the coherent length can be derived. Similar to the definition of the coherent length of the thermal light source with the visibility of Mach-Zehnder interference fringes decreased to 1/e, we define the coherent length with the coherence coefficient of the coherent envelope decreased to 1/e. Fourier transform of the partial coherent envelope is utilized as a typical demodulation method to obtain the coherence coefficient, and the optional frequency range of the coherent envelope is discussed. In the proof-of-concept experiment, a commercial laser is tested, and the measured coherence linewidth is compared with the integrated linewidth of the long-delayed self-heterodyne detection method and frequency noise method with β-separation line. The measured coherence linewidth is smaller than the traditional integrated linewidth, indicating that the coherence linewidth is less affected by the low-frequency 1/f noise. The concept of coherence linewidth proposed in this work is a candidate method of laser coherence characterization, which especially provides a useful tool for the parameter evaluation of narrow linewidth laser in the field of laser precision measurement.

2. Partial Coherent Envelope Demodulation Theory

There have been many researches on the coherent envelope [17] [18] [19], and the measured coherent spectrum obtained by delayed self-heterodyne interferometer (DSHI) can be expressed as [17]

$$S(f,\Delta f)=S_1S_2+S_3, \tag{1}$$

$$S_1=\frac{P_0^2}{4\pi}\frac{\Delta f}{\Delta f^2+\left(f-f_1\right)^2}, \tag{2}$$

$$S_2 = 1-\exp\left(-2\pi\tau_d\Delta f\right)\left[\cos\left(2\pi\tau_d\left(f-f_1\right)+\Delta f\frac{\sin\left(2\pi\tau_d\left(f-f_1\right)\right)}{f-f_1}\right)\right], \tag{3}$$

$$S_3 = \frac{\pi P_0^2}{2}\exp\left(-2\pi\tau_d\left(f-f_1\right)\right)\delta\left(f-f_1\right), \tag{4}$$

where f is the measurement frequency, Δf is the laser linewidth, P_0 is the mixed laser power, f_1 is the frequency shift of the acousto-optic modulator (AOM) and the center frequency of the coherent envelope, τ_d ($\tau_d = n_0L/c$, L is the length of delayed fiber, n_0 is the refractive index of the fiber and c is the speed of light in vacuum) is the time delay of the arm length difference, and $\Delta(f)$ is the Delta function. From Equation (4), when $f \neq f_1$, $\delta\left(f-f_1\right)=0$, $S_3 = 0$ and when $f = f_1$, $S_3 = \infty$, which has no significance in numerical simulation of the coherence envelope. Therefore, the power spectrum S can be simplified to be $S(f, \Delta f) = S_1S_2$.

From Equation (3), when $(f - f_1) >> \Delta f$, $\Delta f/(f - f_1)$ can be very small, and S_2 can be approximately expressed as $S_2 = 1-\exp\left(-2\pi\tau_d\Delta f\right)\cos\left(2\pi\tau_d\left(f-f_1\right)\right)$. Therefore, the power spectrum S can be approximately expressed as

$$S\left(f,\Delta f\right) = S_1S_2 \approx S_1\left[1-\exp\left(-2\pi\tau_d\Delta f\right)\cos\left(2\pi\tau_d\left(f-f_1\right)\right)\right]. \tag{5}$$

The interference contrast of the coherent envelope term S2 is determined by the factor $\exp\left(-2\pi\tau_d\Delta f\right)$, which shows the coherence of the laser in the two interference arms. Thus, we define this factor $\exp\left(-2\pi\tau_d\Delta f\right)$ as the coherence coefficient. When the delay time τ_d is increased, the coherence coefficient will show a decreasing trend. When the value of the coherence coefficient is reduced to 1/e, the corresponding delay time τ_c can be regarded as the coherence time of the laser, and the coherence linewidth can be further defined as $\Delta f = 1/(2\pi\tau_c)$.

In the ideal case, the S_1 function is a Lorentzian line shape. However, the practical laser signal is disturbed by the external environment noise, and the S_1 function can be therefore broadened into other line shapes, such as Gaussian and Voigt line shapes [20]. Fortunately, the environment noise is mainly distributed in the low frequency band, which mainly causes the broadening of the main peak of the DSHI spectrum, but has no significant effect on the coherent envelope. Thus, in the high frequency band of $(f - f_1) >> \Delta f$, the S_1 function tends to be slowly varying, which is denoted by the shaded parts in **Figure 1(a)**. The Fourier transform of the S_1 in these shaded parts is a low frequency baseband signal, as shown in **Figure 1(b)**. In the meantime, $S_2 = 1-\exp\left(-2\pi\tau_d\Delta f\right)\cos\left(2\pi\tau_d\left(f-f_1\right)\right)$ is composed of a constant and a non-baseband signal with τ_d as the center frequency, when f is considered as the independent variable. The Fourier transform of S_2 is shown in **Figure 1(d)**. The Fourier domain frequency has the same dimension as the delay time, so we define its Fourier transform horizontal axis as the delay parameter τ. Since S is the product of S_1 and S_2, their Fourier spectra satisfy the convolution relationship, *i.e.*, $F\left(S\right) = F\left(S_1\right) * F\left(S_2\right)$, where F is the Fourier transform operator. When the chosen shaded parts are wide enough, the Fourier transform peaks of S_2 are approximately Δ functions with different peak values, so the Fourier transform

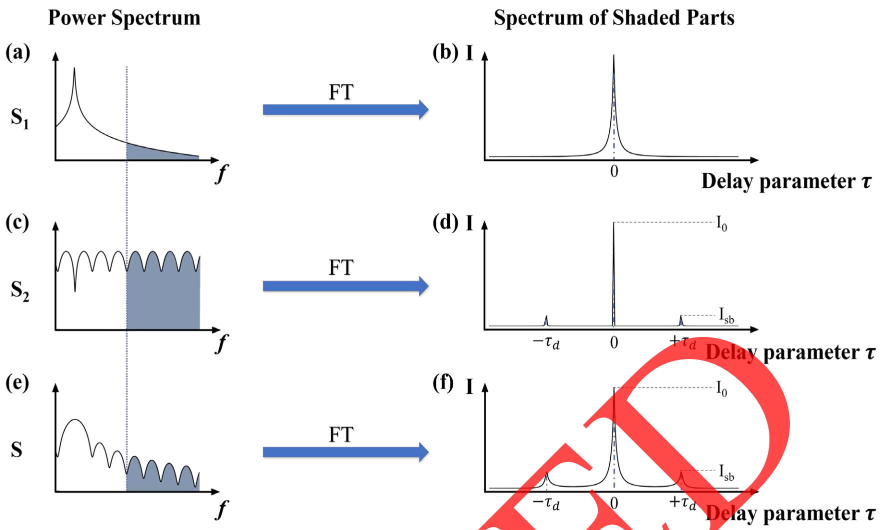

Figure 1. Partial coherent envelope demodulation for obtaining the coherence linewidth. The Fourier transform (FT) of the shaded parts of the power spectrum in (a) S1, (c) S2, and (e) S can be expressed with the delay parameter in (b), (d) and (f), respectively.

spectrum of S_1 will reappear at the three peaks of S_2 by the convolution operation, forming the Fourier transform spectrum of S, as shown in **Figure 1(f)**. The peak intensity of the baseband signal is denoted by I_0, and sideband peak intensity at the delay parameter of $\pm\tau_d$ is denoted by I_{sb}. So we can express the coherence coefficient as $\exp(2\pi\tau_d\Delta f) = 4I_{sb}/I_0$.

3. Experiment and Results

In the proof-of-concept experiment, the delayed self-heterodyne interferometer is utilized to obtain the coherent envelope of the laser, as shown in **Figure 2**. One arm passes through the AOM with 100 MHz frequency shift, and the other arm passes through a delay fiber. The two arms interference at the coupler C_2, and the heterodyne beat is detected by a photo detector (PD). The ESA is used to collect the coherent envelope spectrum.

The commercial laser under test has a nominal linewidth of kHz order (LXNLM-1550-L03-FA). The coherence envelope is measured with a series of different delay lengths, as shown in **Figure 3(a)**. **Figure 3(b)** shows the Fourier spectrum of the partial coherence envelope. The coherence coefficients are then obtained by the partial envelope demodulation method, as shown in **Figure 3(c)**. When the delay length is very short, the envelope is mostly submerged in the noise floor of the ESA and PD, resulting in a small coherence coefficient, as shown in **Figure 3(a)**. As the delay length increases, the envelope gradually appears obvious, and the coherence coefficient gradually recovers to be close to 1, under the condition that the delay length is smaller than the coherence length. With further increase of the delay length, the coherence coefficient decreases gradually, and the coherence linewidth at the coherence coefficient of 1/e is 2.985 kHz. As a comparison, the long-delayed self-heterodyne interferometry

(DSHI) method is utilized to measure the integrated linewidth. With 50-km delay fiber, the integrated linewidth obtained by Lorentz fitting is 18.031 kHz/2 = 9.016 kHz, as shown in **Figure 3(d)**. The frequency noise of the laser is also measured, and we can obtain the integrated linewidth to be 2871.05 $\text{Hz}^2/\text{Hz} \times \pi$ = 9.020 kHz based on the β-separation line, as shown in **Figure 3(e)**. From the frequency noise floor, the intrinsic linewidth can be obtained as 34.54 $\text{Hz}^2/\text{Hz} \times \pi$ = 108.5 Hz. The integrated linewidth measured by the DSHI and β-separation line is consistent. The measured coherence linewidth is smaller than the integrated linewidths but larger than the intrinsic linewidth measured by the frequency noise floor, indicating that the coherence linewidth is less affected by the low-frequency 1/*f* noise.

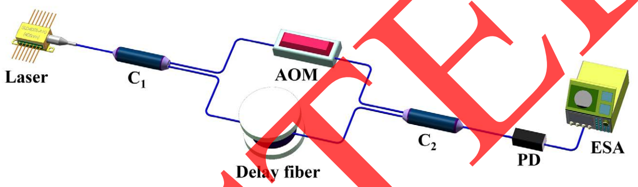

Figure 2. Experimental setup of the delayed self-heterodyne interferometer to measure the coherent envelope. C_1 and C_2: couplers; AOM: acousto-optic modulator; PD: photo detector; ESA: electrical spectrum analyzer.

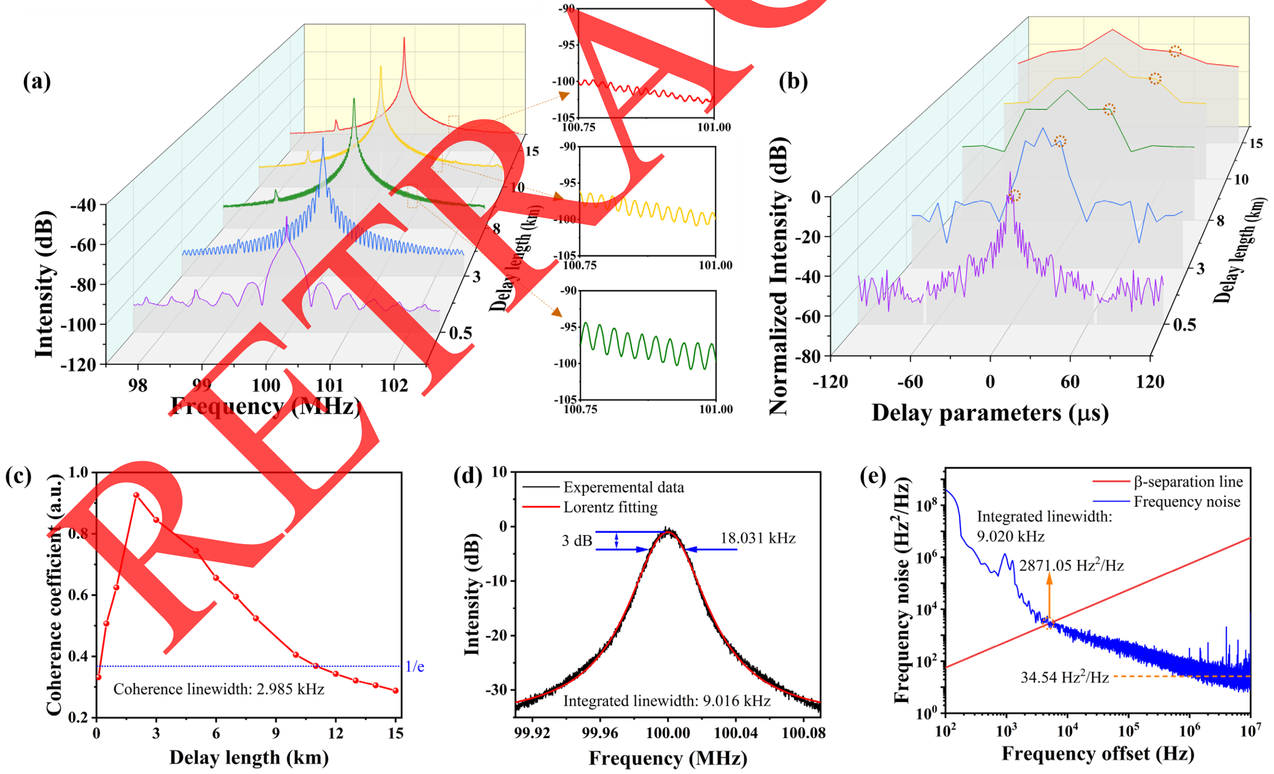

Figure 3. Experimental results of the kHz-level linewidth laser. (a) Coherent envelope spectra with different delay lengths. (b) Fourier transform spectra of the partial coherent envelope with different delay lengths. (c) Coherence coefficient under different delay length. (d) Integrated linewidth measurement with the DSHI method. (e) Integrated linewidth measurement with the frequency noise and β-separation line.

4. Conclusion

In summary, we propose the concept of coherence linewidth from the coherent envelope in delayed self-heterodyne detection. The coherence linewidth can be obtained when the coherence coefficient degenerates to 1/e. Using the coherence linewidth, we can get the coherence of the laser. In the proof-of-concept experiment, the measured coherence linewidth of kHz orders is smaller than the traditional integrated linewidth by the long-delayed self-heterodyne detection method and frequency noise method with β-separation line, indicating that the coherence linewidth is less affected by the low-frequency $1/f$ noise. In the current work, the required delay fiber is still relatively long, which should cover the coherent length of the laser. The concept of coherence linewidth proposed in this work provides a candidate method of laser coherence characterization, which is especially beneficial for the parameter evaluation of narrow linewidth laser in the field of laser precision measurement.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Geng, Y., Zhou, H., Han, X., *et al.* (2022) Coherent Optical Communications Using Coherence-Cloned Kerr Soliton Microcombs. *Nature Communications*, **13**, 1070-1078. https://doi.org/10.1038/s41467-022-28712-y

[2] Khonina, S.N., Kazanskiy, N.L., Butt, M.A. and Karpeev, S.V. (2022) Optical Multiplexing Techniques and Their Marriage for On-Chip and Optical Fiber Communication: A Review. *Opto-Electronic Advances*, **5**, Article 210127. https://doi.org/10.29026/oea.2022.210127

[3] Cheng, C.H., Shen, C.C., Kao, H.Y., Hsieh, D.H., Wang, H.Y., *et al.* (2018) 850/940-nm VCSEL for Optical Communication and 3D Sensing. *Opto-Electronic Advances*, **1**, Article 180005. https://doi.org/10.29026/oea.2018.180005

[4] Wang, Y., *et al.* (2023) Laser Feedback Frequency-Modulated Continuous-Wave LiDAR and 3-D Imaging. *IEEE Transactions on Instrumentation and Measurement*, **72**, 1-9. https://doi.org/10.1109/TIM.2023.3249246

[5] Zhao, Z.Y., Tang, M. and Lu, C. (2020) Distributed Multicore Fiber Sensors. *Opto-Electronic Advances*, **3**, Article 190024. https://doi.org/10.29026/oea.2020.190024

[6] Yang, X., Liu, Y., Sun, X., Yang, X. and Yao, J. (2021) Strain- and Temperature-Sensing Characteristics of Fiber Ring Laser Sensor with Cascaded Fabry-Perot Interferometer and FBG. *IEEE Transactions on Instrumentation and Measurement*, **70**, 1-7. https://doi.org/10.1109/TIM.2021.3105266

[7] Yin, G., Jiang, R. and Zhu, T. (2022) In-Fiber Auxiliary Interferometer to Compensate Laser Nonlinear Tuning in Simplified OFDR. *Journal of Lightwave Technology*, **40**, 837-843. https://doi.org/10.1109/JLT.2021.3123725

[8] Harris, M., Pearson, G.N., Vaughan, J.M., Letalick, D. and Karlsson, C. (1998) The Role of Laser Coherence Length in Continuous-Wave Coherent Laser Radar. *Journal of Modern Optics*, **45**, 1567-1581. https://doi.org/10.1080/09500349808230653

[9] Letalick, D., Renhorn, I., Steinvall, O. and Shapiro, J.H. (1989) Noise Sources in La-

ser Radar Systems. *Applied Optics*, **28**, 2657-2665. https://doi.org/10.1364/AO.28.002657

[10] Li, M., Guo, Y., Wang, X., Fu, W., Zhang, Y. and Wang, Y. (2022) Researching Pointing Error Effect on Laser Linewidth Tolerance in Space Coherent Optical Communication Systems. *Optics Express*, **30**, 5769-5787. https://doi.org/10.1364/OE.447408

[11] Schawlow, A.L. and Townes, C.H. (1958) Infrared and Optical Masers. *Physical Review*, **112**, 1940-1949. https://doi.org/10.1103/PhysRev.112.1940

[12] Dang, L., Huang, L., Shi, L., Li, F., Yin, G., *et al.* (2023) Ultra-High Spectral Purity Laser Derived from Weak External Distributed Perturbation. *Opto-Electronic Advances*, **6**, Article 210149. https://doi.org/10.29026/oea.2023.210149

[13] Bai, Z., *et al.* (2021) Narrow-Linewidth Laser Linewidth Measurement Technology. *Frontiers in Physics*, **9**, Article 768165. https://doi.org/10.3389/fphy.2021.768165

[14] Okoshi, T., Kikuchi, K. and Nakayama, A. (1980) Novel Method for High-Resolution Measurement of Laser Output Spectrum. *Electronics Letters*, **16**, 630-631. https://doi.org/10.1049/el:19800437

[15] Domenico, G.D., Schilt, S. and Thomann, P. (2010) Simple Approach to the Relation between Laser Frequency Noise and Laser Line Shape. *Applied Optics*, **49**, 4801-4807. https://doi.org/10.1364/AO.49.004801

[16] Zhou, Q., Qin, J., Xie, W., Liu, Z., Tong, Y., Dong, Y. and Hu, W. (2015) Power-Area Method to Precisely Estimate Laser Linewidth from Its Frequency-Noise Spectrum. *Applied Optics*, **54**, 8282-8289. https://doi.org/10.1364/AO.54.008282

[17] Huang, S., *et al.* (2016) Laser Linewidth Measurement Based on Amplitude Difference Comparison of Coherent Envelope. *IEEE Photonics Technology Letters*, **28**, 759-762. https://doi.org/10.1109/LPT.2015.2513098

[18] Wang, Z., Ke, C., Zhong, Y., Xing, C., Wang, H., Yang, K., Cui, S. and Liu, D. (2020) Ultra-Narrow-Linewidth Measurement Utilizing Dual-Parameter Acquisition through a Partially Coherent Light Interference. *Optics Express*, **28**, 8484-8493. https://doi.org/10.1364/OE.387398

[19] Xue, M. and Zhao, J. (2021) Laser Linewidth Measurement Based on Long and Short Delay Fiber Combination. *Optics Express*, **29**, 27118-27126. https://doi.org/10.1364/OE.428787

[20] Chen, M., Meng, Z., Wang, J. and Chen, W. (2015) Ultra-Narrow Linewidth Measurement Based on Voigt Profile Fitting. *Optics Express*, **23**, 6803-6808. https://doi.org/10.1364/OE.23.006803