Effects of the Programmable Real-Time White Gaussian Noise Generated by FPGA on the Laser Linewidth Spectrum

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***Abstract*—This study investigates the effects of various parameters of real-time white Gaussian noise on the laser linewidth spectrum using a field-programmable gate array with digital-to-analog converters.**

Keywords—various parameters white Gaussian noise, real-time, laser linewidth spectrum, FPGA implementation.

I. Introduction

Laser linewidth is a crucial parameter for various applications, such as optical coherent systems [1] and coherent frequency-modulated continuous-wave (FMCW) Light Detection and Ranging (LiDAR) [2]. To explore laser linewidth tolerance in these systems, a variable-linewidth laser is required. However, traditional methods involve replacing different laser diodes to achieve varying linewidths [3], leading to errors in the optical power and wavelength. To overcome these problems, an external lithium niobite (LN) phase modulator modulates the random walk noise with a limited wall to achieve variable linewidths [1,2]. The mirror method employed for controlling the laser linewidth has the drawback of a lack of low-frequency components, resulting in a lack of modulation in the central part of the laser linewidth spectrum [1,2]. To mitigate this problem, a low-frequency compensation method using white Gaussian noise from a function generator (FG) was introduced [2]. However, a limitation of the function generator method is that the noise is read from memory rather than being generated in real time. This lack of real-time noise generation makes it difficult to accurately simulate the actual laser noise resulting from thermal fluctuations within the laser diode [4], thereby reducing the effectiveness of the method. To overcome this limitation, we suggest the generation of real-time white Gaussian noise instead of relying on the FG-generated noise and investigate the impact of the new noise on the laser linewidth spectrum. In addition to the limitations of the mirror method and the use of FG-generated noise, another concern is the high sensitivity of the laser linewidth to the cut-off frequency of the white Gaussian noise. Even a slight change in the cut-off frequency can result in a significant increase in the laser linewidth [2], making it difficult to perform precise control. To address this, a potential approach involves investigating the effects of varying the parameters of white Gaussian noise, such as the standard deviation (STD) and mean. This approach presents a novel approach for investigation as it has not been previously explored. It holds the potential to shed new light on the impact of different noise characteristics on the laser linewidth spectrum and could offer a promising method for the precise control of the laser linewidth. Unfortunately, current devices such as FG and analog noise sources make it difficult to easily change these parameters. Therefore, new methods and equipment are required to generate real-time white Gaussian noise with varying parameters. To achieve this, a programmable device that can produce real-time noise with variable white Gaussian noise parameters is required. Field Programmable Gate Arrays (FPGAs) equipped with digital-to-analog converters (DACs) present a potential solution to overcome the limitations of current devices, such as FG or analog noise sources. The proposed method using FPGA and DACs presents an efficient and flexible approach for generating real-time noise with variable parameters by generating white Gaussian noise with varying mean and STD and feeding it into the phase modulator. This enables more accurate investigations into the effects of different white Gaussian noise features on the laser linewidth spectrum, facilitating more precise control over lasers with variable linewidths. The obtained results could identify a suitable laser that closely approximates the actual laser, reducing the cost of such systems while making them more accessible for widespread use.

II. Work Principle and Experiment Set up

A. The Principle of FPGA the White Gaussian Noise

Fig. 1 depicts the principle of generating white Gaussian noise using the look-up table (LUT) method. The first step involves generating a pseudo-random number using the linear feedback shift register (LFSR) method [5], which quickly produces nonsequential lists of numbers via right-shift and exclusive-OR gate (XOR) operations. This method enables the easy generation of 16-bit pseudo-random numbers, which act as memory addresses to be read in the double-data-rate3 (DDR3) dual inline memory module (DIMM). To ensure real-time performance, the limitations of the LFSR method must be addressed, including the requirement for a time interval to complete one period and repeat, and the fact that the bit numbers of the Gaussian number must be less than those of the LFSR. Additionally, generating high bits of pseudo-random numbers is time consuming, which can affect real-time system performance. To overcome these problems, a truncation method was employed, whereby the highest two bits of the pseudorandom numbers generated by the LFSR were cut. This eliminated the effects of the time interval. To ensure real-time system performance, a 16-bit LFSR was deemed suitable for generating pseudo-random numbers considering the required creation time. The following step involved the quantization of standard deviation Gaussian distribution numbers with varying means of 1 V and 0.9 V into 14-bit numbers using MATLAB (R2022a). Subsequently, the numbers were matched to the pseudo-random numbers of the LFSR and saved in the DIMM of the FPGA. This allowed for changeable parameters, such as standard deviations and means, resulting in variable random white Gaussian distribution numbers. Real-time variable random white Gaussian distribution numbers were produced by reading the DIMM via the memory address generated from the LFSR. The FPGA board (Xilinx Artix 7 evaluation board AC 701) was connected to a 600-MSamples/s DACs (Analog Device AD 9736) using a 14-bit double data rate (DDR) low-voltage differential signaling (LVDR) interface to ensure real-time

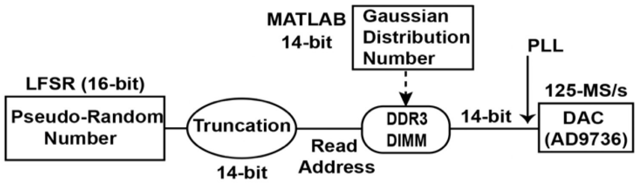

Fig. 1. Principle of the programmable white Gaussian noise using the FPGA with DACs.

analog noise generation. The DACs were configured to output a 1 Vpp (V) signal, resulting in the analog white Gaussian noise output changing to varying mean values of 0.125 V and 0.113 V STD. The phase-locked loop (PLL) method was utilized to convert the DACs to 125-MSamples/s, optimizing the low-frequency performance. An analog noise filter was used instead of a digital filter in the FPGA to ensure stability and precise control over the bandwidth of white Gaussian noise.

B. *The Experimental Set Up*

The experimental setup for controlling and measuring the laser linewidth spectrum, as illustrated in Fig. 2, utilizes the coherent interference method with two narrow fiber laser diodes (LD, NKT photonics Koheras BASIK) with wavelengths of 1550.075 nm and 1550.090 nm. Optical attenuators (att., Anritsu MN 935A2) were employed to control the power in each path, with one path serving as the reference and the other as the laser linewidth control path. The polarization controller (PCs, Alnair Labs MLC15 QHN SMFS) controlled the polarization of the light in the control path, which was then modulated by an LN phase modulator (PM, Sumitomo Osaka Cement T.PMH1.55 S) with a half-wave

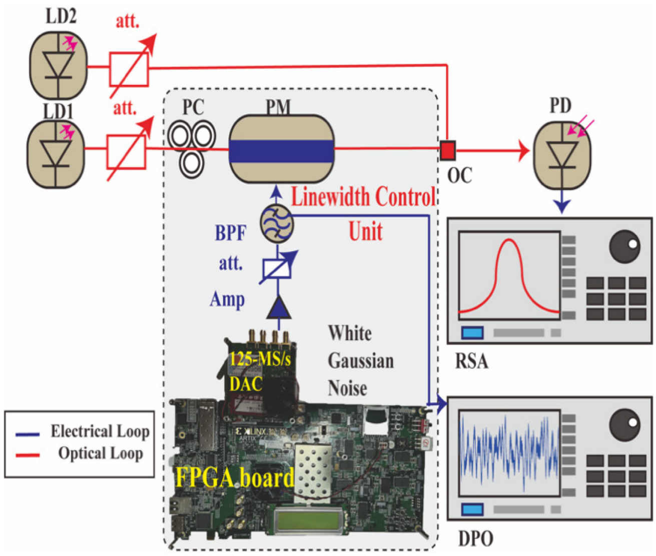

Fig. 2. Experimental scheme of the variable linewidth laser and laser linewidth measurement.

voltage of 2.7 V at a frequency of 1 MHz. To generate noise, the FPGA board and DACs (125-MS/s) were utilized, with the power and bandwidth of the noise managed by electrical amplifiers (Amp, NF BA4805, and FEMTO DHPVA-101), electrical attenuators (att., Fairview microwave SA 4090), and a low-frequency variable bandpass filter (BPF, NF 3628). Following filtering, the white Gaussian noise was monitored using a digital phosphor oscilloscope (DPO, Agilent DSO81204B). Once the phase noise in the optical path was controlled using various white Gaussian noise parameters generated by the FPGA, the PM impacted the laser linewidth spectrum in the linewidth control part. The two optical paths were combined using an optical coupler (OC), with coherent interference resulting in the detection of a 0.015 nm wavelength by the PD (Sevensix Inc 12.5Gb/s Optical Receiver). A real-time spectrum analyzer (RSA, Tektronix RSA 3308A) was used to detect the electrical signal from the PD and obtain the laser linewidth spectrum. Once the phase noise in the optical path was controlled using various white Gaussian noise parameters generated by the FPGA, the PM impacted the laser linewidth spectrum in the linewidth control part. The two optical paths were combined using an optical coupler (OC), with coherent interference resulting in the detection of a 0.015 nm wavelength by the PD (Sevensix Inc 12.5 Gb/s Optical Receiver). A real-time spectrum analyzer (RSA, Tektronix RSA 3308A) was used to detect the electrical signal from the PD and obtain the laser linewidth spectrum.

III. Results and Discussion

The DPO detected low-frequency white Gaussian noise with a bandwidth of 200 kHz and standard deviations of 0.125 V and 0.113 V, respectively. A fast Fourier transform (FFT) was performed, and the spectrum results are displayed in Fig. 3(a) with a resolution bandwidth (RBW) of 250 Hz. The blue and red lines represent the 0.125 V and 0.113 V standard deviation noise spectra, respectively. The mean of the noise was set to 0 V. Both spectra show a clear 200 kHz cut-off frequency, and the white Gaussian noise displayed equal intensity at different frequencies under 200 kHz. The noise power was approximately -20 dBm, with slight power differences owing to signal voltage fluctuations. These results demonstrate the successful generation of STD 0.125 V and STD 0.113 V 200 kHz white Gaussian noise. Subsequently, the impact of varying the standard deviations of the white Gaussian noise on the laser linewidth spectrum is investigated using the results obtained. The laser linewidth spectrum results of the two standard deviations are compared and presented in Fig. 3(b). The red line represents the laser linewidth spectrum results obtained using 0.113 V STD white Gaussian noise. In a 4 MHz span and 20 kHz RBW, the linewidth of the laser was determined to be 659 kHz. A Gaussian model was used to fit the laser linewidth spectrum, and the black line represents the fitting line for the laser linewidth. The results demonstrate that the laser linewidth spectrum overlapped with the Gaussian fit line, indicating a good Gaussian shape. The peak power of the laser linewidth was -30 dBm. Meanwhile, the laser linewidth spectrum using the 0.125 V STD white Gaussian noise is shown as a blue line. In a 4 MHz span with a 20 kHz RBW, the linewidth of the laser was 743 kHz, and the Gaussian fit model was used for this laser linewidth spectrum. The yellow line represents the Gaussian fit line for the laser spectrum, which overlaps the laser linewidth spectrum. The bell-shaped laser linewidth spectrum generated by the 0.125 V STD white Gaussian noise is flatter than that of the 0.113 V STD white Gaussian noise. Additionally, the peak power of the 0.125 V STD white Gaussian noise laser linewidth spectrum is -36 dBm. The linewidth of the 0.125 V STD white Gaussian noise laser is 84 kHz larger than that of the 0.113 V STD white Gaussian noise laser. To analyze the difference in the laser linewidth spectrum resulting from the two different standard deviation white Gaussian noises, their characteristics must be examined.

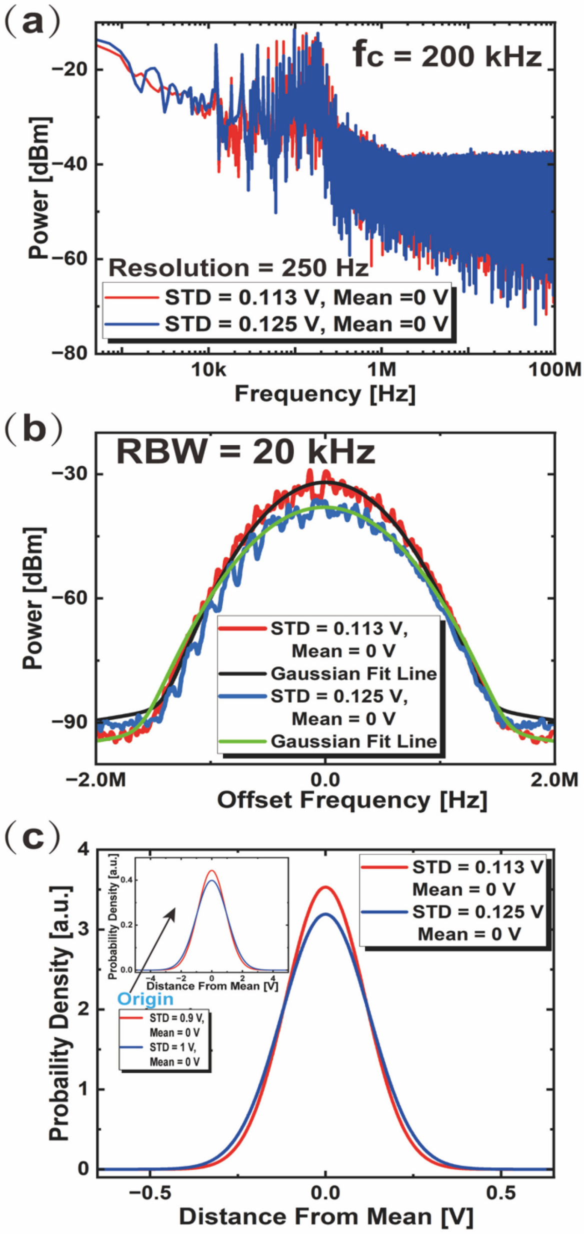

Fig. 3. Spectrum of (a) white Gaussian noise with a 200 kHz cut-off frequency and varying standard deviations, (b) laser linewidth under different standard deviations of white Gaussian noise, and (c) normal distribution of white Gaussian noise with different standard deviations.

A normal distribution graph is used to visualize the features of each distribution, as shown in Fig. 3(c). The blue line represents the 0.125 V STD characteristics, whereas the red line represents the 0.113 V STD characteristics. The graph shows the probability density of the two white Gaussian noises plotted against their distance from the mean on the x-axis. The mean of both distributions was set to 0 V, resulting in the center of the x-axis being 0. The peak of the blue line is 3.6 a.u., while the peak of the red line is 3.2 a.u. It is evident that the bell curve of the 0.125 V STD is flatter than that of the 0.113 V STD, and as a result, the linewidth of the 0.125 V STD is larger than that of the 0.113 V STD. The Gaussian distribution number that was originally quantized is depicted in the top-left corner of the figure. The results demonstrate that the characteristics of white Gaussian noise with different standard deviations had a considerable impact on the laser linewidth spectrum, primarily owing to the linearity of the LN modulator in the low-frequency range. This linearity allowed for the linear modulation of low-frequency signals, resulting in a variable laser linewidth. The resulting laser linewidth spectrum displays a Gaussian distribution owing to this modulation. Furthermore, a larger standard deviation of white Gaussian noise results in a greater modulation of the laser linewidth spectrum, leading to a flatter bell curve, lower peak power, and larger linewidth. Thus, the proposed method provides a means of achieving more precise control over the laser linewidth spectrum. In this experiment, the effects of the mean of the white Gaussian noise were investigated. Specifically, the mean value of the white Gaussian noise was varied at -1 V, 0 V, and 1 V, while the STD values were maintained at 0.125 V and 0.113 V. Interestingly, the results indicate that changing these parameters did not affect the laser linewidth spectrum. This finding provides evidence that these adjustable parameters are not significant in determining the laser linewidth spectrum.

IV. Conclusion

In conclusion, an FPGA board with 125-Ms/s DACs and an analog filter was used to successfully generated low-frequency programmable real-time white Gaussian noise. The results reveal that the standard deviation of the white Gaussian noise had a significant impact on the laser linewidth spectrum. Specifically, larger STD resulted in a wider and flatter bell-curve Gaussian shape for the laser linewidth. However, the mean of the white Gaussian noise did not affect the laser linewidth spectrum. Therefore, it can be concluded that precise control of the laser linewidth requires careful consideration of the standard deviation of white Gaussian noise.

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