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# Design of an FPGA-Based Acetylene Laser Frequency Stabilization System

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**Abstract:** Laser frequency stability is a core performance metric in precision optical measurement and optical communication systems. This paper presents the design and implementation of an active frequency stabilization system for a 1542 nm laser based on the absorption spectrum of acetylene molecules. With a field-programmable gate array (FPGA) as the core control unit, the system integrates the optical module, signal conditioning and conversion circuits, and a low-noise laser driving and temperature control circuit, enabling the integrated operation of modulation, phase detection, and feedback control. At the hardware level, a differential signal architecture and low-noise filtering design are adopted to effectively suppress environmental noise and electromagnetic interference.

**Keywords:** Laser frequency stabilization; FPGA; Digital lock-in amplification; PID control.

## 1. Introduction

Since the invention of the laser in the 1960s, laser technology, with its excellent directionality, monochromaticity, and coherence, has been widely applied in fields such as precision metrology, optical communications, spectroscopy, and defense. In precision interferometric measurement, the laser wavelength serves as the length standard, and its frequency stability directly determines the measurement accuracy; in coherent optical communication systems, laser frequency drift severely degrades receiver sensitivity and signal quality. With the continuous advancement of cutting-edge technologies such as optical frequency standards and high-resolution spectroscopy, increasingly stringent requirements have been placed on laser frequency stability. The linewidth and frequency drift of conventional free-running lasers can no longer meet the needs of the above research fields, and laser frequency stabilization has therefore become an indispensable technique in modern precision measurement [1].

The output frequency of a free-running semiconductor laser drifts significantly under the influence of temperature fluctuations, mechanical vibrations, power supply noise, and device aging, making it unsuitable for direct use as a precision measurement light source. Active frequency stabilization, which introduces a highly stable reference frequency and constructs a feedback control loop to compensate the laser frequency in real time, is an effective means of achieving long-term laser frequency stability [2]. Among various reference frequency sources, the energy-level transition frequencies of atoms or molecules exhibit inherent stability and are immune to external disturbances. In particular, stabilization schemes based on molecular saturated absorption spectroscopy, owing to their high stability, reproducibility, and low sensitivity to the environment, have become one of the mainstream approaches to high-precision laser frequency control [3, 4]. The acetylene molecule exhibits strong absorption lines near the 1542 nm band, which effectively eliminate Doppler broadening and yield reference spectral lines with narrow linewidth and stable frequency, making it an ideal reference source for laser frequency stabilization in the optical communication band [5, 6]. This paper presents a digital laser frequency stabilization system with an FPGA as the core control unit. By optimizing the hardware circuit architecture and embedded control algorithms, automatic locking and stable control of the laser frequency are realized.

## 2. System scheme

The overall architecture of the system consists of four parts: the optical path and wavelength monitoring subsystem, the FPGA control and hardware platform, the host computer software, and the low-noise laser driving circuit. In the optical path, an acetylene gas cell is used to produce the saturated absorption effect, and a photodetector converts the optical signal into an electrical signal, which is then sent to the back-end processing circuit, as shown in Fig 1. As the core of the system, the FPGA hardware platform performs analog-to-digital conversion of the saturated absorption signal through an ADC circuit. Inside the FPGA, modules including the lock-in amplifier, PID controller, locking logic, and data communication work in coordination to process the digital signals and generate the frequency correction control signal [6]. This signal is converted into an analog voltage by a DAC circuit and then sent to the low-noise laser driving circuit to adjust the operating current of the semiconductor laser, forming a closed-loop feedback loop that ultimately achieves stable locking of the laser frequency. The low-noise laser driving section comprises a current driving module and a temperature control module. The current driving module provides a low-noise bias current for the laser. The temperature control module monitors the laser temperature using an NTC thermistor and actively regulates it through a thermoelectric cooler (TEC), thereby suppressing frequency fluctuations caused by temperature drift. The entire driving circuit is powered by a low-noise supply to reduce power supply ripple interference with the laser output.

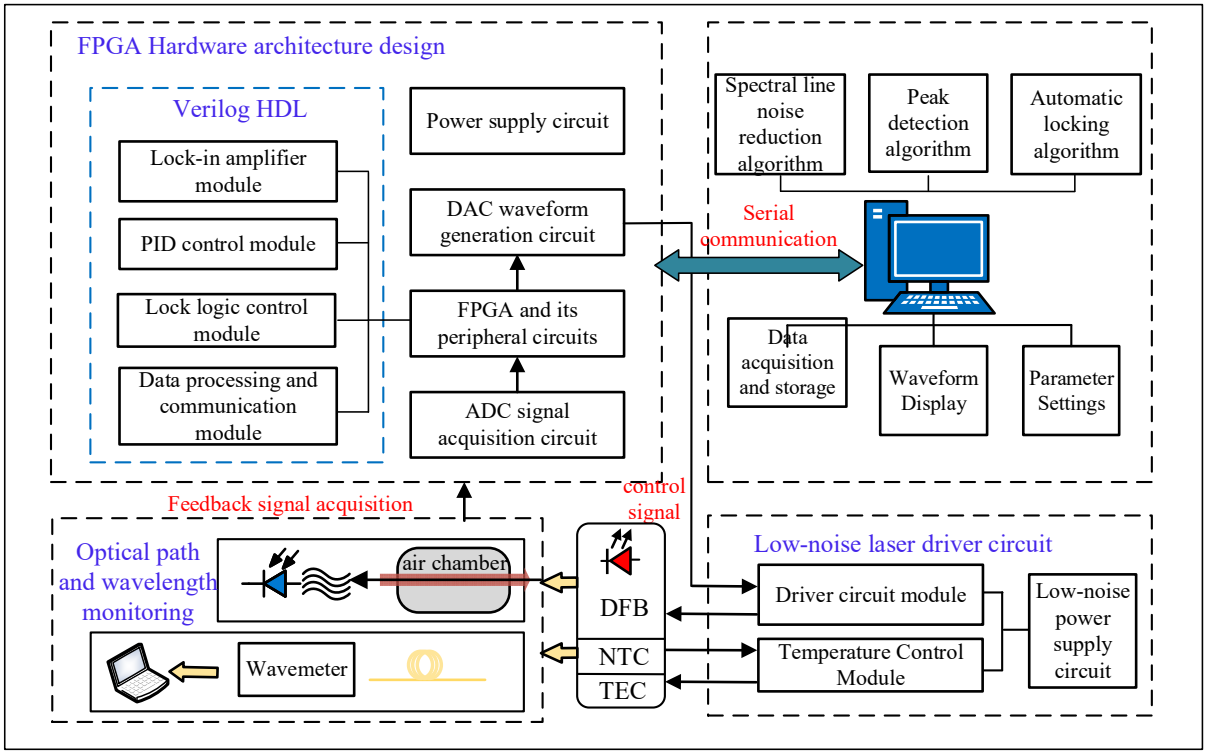



**Fig. 1** System hardware block diagram

## 3. Circuit design

The FPGA and its peripheral circuits undertake key tasks such as instruction parsing, data computation, and peripheral coordination. The power supply circuit adopts a multi-channel voltage regulator tree to provide stable, low-ripple operating voltages for the FPGA core and I/O interfaces. The configuration circuit uses an SPI Flash as non-volatile storage to hold the FPGA configuration program, enabling automatic loading at power-on. The clock circuit employs a temperature-compensated active crystal oscillator to provide a high-precision reference clock for the internal timing logic, meeting the timing requirements of high-speed signal processing. In the signal chain, the FPGA communicates with the ADC acquisition circuit and the DAC output circuit through a high-speed parallel interface to ensure the real-time performance of data transmission.

After photoelectric conversion by the photodetector, the absorption spectrum signal has a small amplitude and is susceptible to environmental noise and electromagnetic interference. To improve signal acquisition accuracy, the system employs a high-speed ADC chip with a differential input architecture, which offers strong common-mode interference rejection, high input impedance, and a large dynamic range, and can effectively suppress noise coupling during transmission. Since the output of the front-end conditioning circuit is a single-ended signal, a single-ended-to-differential amplifier circuit is added at the front end of the ADC. This circuit not only completes the signal topology conversion but also provides moderate amplification of the weak spectral signal so that its amplitude matches the optimal input range of the ADC. A precision resistor network ensures the symmetry of the differential signal, reducing conversion distortion and improving acquisition accuracy. The digital control signal generated by the FPGA undergoes digital-to-analog conversion by a DAC chip. Since the selected DAC operates in differential output mode while the subsequent laser driving circuit typically requires a single-ended control signal, a single-ended-to-differential conversion circuit is used to complete the signal topology conversion. The converted single-ended signal may still contain high-frequency spurious components and digital noise from the DAC output; if fed directly into the driving circuit, it would degrade the stability of the control signal. To this end, a sixth-order elliptic low-pass filter is designed in the signal path to remove high-frequency noise and smooth the output signal. The filtered signal is then amplified by a low-noise operational amplifier to adjust its gain, ensuring that the signal amplitude meets the requirements of the driving circuit and finally producing an accurate and stable analog control signal.

The laser driving circuit adopts a low-noise constant-current source design, providing a stable bias current for the semiconductor laser to suppress frequency noise caused by current fluctuations. The temperature control circuit uses an NTC thermistor to monitor the laser operating temperature in real time. Based on the temperature deviation, the TEC cools or heats the laser, and combined with a closed-loop control algorithm, stabilizes the laser temperature at the set point, thereby reducing the influence of temperature drift on the output frequency.

## 4. System implementation

A 1542 nm semiconductor laser is used as the light source [8]. A triangular-wave scanning modulation is applied to the driving current of the laser so that the laser frequency sweeps across the vicinity of the acetylene absorption line. After passing through the acetylene gas cell, the laser beam is converted into an electrical signal by the photodetector. Since the absorption spectrum signal has a small amplitude and is easily overwhelmed by circuit noise, the performance of the signal conditioning circuit becomes a critical factor determining system stability. If the front-end circuit noise is too high, thermal noise, shot noise, and low-frequency noise will be superimposed on the weak signal, causing distortion

of the error signal demodulated by the lock-in amplifier and leading to laser frequency jitter or even loss of lock. Therefore, the system adopts a differential transmission architecture and a low-noise pre-amplifier design in the signal acquisition path, and a sixth-order elliptic low-pass filter is configured at the DAC output to effectively suppress high-frequency noise and power supply ripple, thereby providing a high signal-to-noise ratio input for the subsequent digital signal processing. Inside the FPGA, a quadrature lock-in amplifier performs phase-sensitive detection on the sampled signal [9] and successfully demodulates the error signal that reflects the deviation of the laser frequency from the center of the absorption line. After computation by the PID controller, this error signal generates a correction voltage, which is output through the DAC to the laser driving end to form a closed-loop feedback. Experiments show that the FPGA modules work in coordination to complete the entire process from signal acquisition and demodulation to feedback control, realizing automatic locking of the laser frequency. In terms of hardware implementation, the FPGA core control board, ADC acquisition circuit, DAC output circuit, laser driving circuit, TEC temperature control circuit, and related auxiliary circuits were designed, fabricated, and assembled. The feedback signal acquired by the FPGA signal processing system, constructed with an FPGA chip as its core and complemented by a complete set of peripheral support circuits, is shown in Fig 2. All modules are connected through standard interfaces. After power-on, the system automatically loads the FPGA configuration program, completes initialization and parameter setting, and enters the scanning or locking operating state.

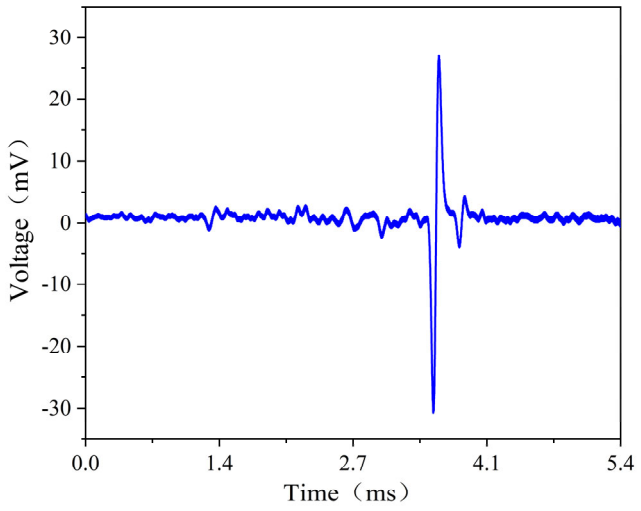



**Fig. 2** Feedback signal collected by acetylene laser frequency stabilization circuit

# 5. Conclusion

This paper has presented the design and implementation of an FPGA-based laser frequency stabilization system for a 1542 nm laser. Using the absorption spectrum of acetylene molecules as the frequency reference, the system employs an FPGA to implement digital lock-in amplification and PID closed-loop control. Through low-noise signal conditioning circuits and an integrated temperature-controlled driving design, the influence of environmental disturbances and circuit noise on the laser frequency is effectively suppressed. This study provides a feasible technical solution for the integration and domestication (localization) of laser frequency stabilization systems, and has certain application value in the fields of precision optical measurement and optical communications.

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