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Frequency-Stabilized Laser Utilizing Acetylene Molecular Absorption Lines as Frequency References

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Abstract: Frequency-stabilized lasers, as core components in precision optical systems and communication networks, demonstrate direct correlations between their frequency stability and critical performance metrics such as optical communication capacity and spectral measurement resolution. While conventional ultra-stable optical cavity solutions achieve exceptional stability, their practical implementation faces inherent limitations due to complex temperature control requirements and vibration isolation demands, hindering cost-effective miniaturization for industrial applications. Acetylene molecules, leveraging their intrinsic absorption spectral lines in communication bands, offer novel opportunities for developing compact frequency-stabilized lasers. This paper presents a new stabilization system based on acetylene molecular absorption characteristics. Through optimized optical path design and improved feedback control architecture, effective laser frequency locking in communication bands has been achieved, providing a cost-efficient stabilization solution for applications in fiber-optic communications and quantum sensing technologies.

Keywords: Frequency-stabilized lasers; Acetylene molecules; Absorption lines; Optical communications.

1. Introduction

Frequency-stabilized lasers represent a pivotal technology in modern optics and precision metrology [1, 2]. These systems employ active feedback control mechanisms to lock laser output frequencies to physical reference standards, thereby significantly suppressing random frequency drift and environmental disturbance-induced fluctuations [3]. Since the invention of lasers in the 1960s, frequency stabilization techniques have evolved as foundational components across diverse fields, including high-precision spectroscopy, optical communications, atomic clocks, gravitational wave detection, and quantum information processing [4]. For instance, in fiber-optic communication systems, stable 1550 nm band lasers serve as critical enablers for wavelength-division multiplexing (WDM) technology to achieve high-speed data transmission [5]. In metrology, iodine molecular absorption line-referenced frequency-stabilized lasers have been adopted to define the "meter" standard in the International System of Units (SI). More recently, advancements in cold atom experiments and optical lattice clock research increasingly rely on frequency-stabilized lasers with sub-hertz linewidths to meet extreme precision requirements [6].

The central challenge in laser frequency stabilization lies in establishing high-sensitivity frequency references. Early-stage stabilization schemes primarily relied on Fabry-Pérot interferometric cavities, where laser frequencies were locked to the transmission peaks of optical resonators [7]. However, these methods exhibited extreme sensitivity to thermal expansion coefficients of cavity materials and mechanical vibrations, necessitating sophisticated temperature control and vibration isolation systems. The emergence of saturated absorption spectroscopy in the 1970s introduced a paradigm shift, utilizing natural linewidths of atomic/molecular transitions as frequency references. Recent advancements highlight acetylene (C_2H_2) molecules as an emerging focus for fiber-optic communication and photonic integrated devices, owing to their dense vibrational-rotational absorption lines within telecommunication windows [8]. This molecular feature enables robust frequency references compatible with silicon photonics platforms and wavelength-division multiplexing architectures.

Current mainstream frequency-stabilized laser solutions can be categorized into two types based on application scenarios [9]. The first type employs ultra-stable optical cavities made of ultra-low expansion (ULE) glass or single-crystal silicon, achieving short-term frequency stability up to 10^{-16} level, but these systems have large physical volumes and high costs. The second type is compact frequency-stabilized systems based on molecular/atomic absorption lines, which exhibit slightly lower stability but possess advantages such as small size, low power consumption, and easy integration, making them particularly suitable for industrial sites and space-constrained scenarios [10].

This paper designs and constructs a compact frequency-stabilized laser system based on acetylene molecular absorption lines. Combined with wavelength modulation spectroscopy to extract error signals, and through a proportional-integral-derivative (PID) feedback circuit, the output frequency of a distributed feedback (DFB) laser is locked to the absorption line center, achieving stable 1542 nm laser output and verifying the feasibility of the acetylene-based frequency stabilization scheme. The work presented in this study provides a replicable technical roadmap for small-to-medium-sized laboratories to develop self-controlled frequency-stabilized lasers, while also laying the foundation for future development of low-cost frequency-stabilized modules targeting fiber-optic sensing networks.

2. Theory

2.1. Laser frequency stabilization methods

The core of laser frequency stabilization lies in establishing a precise correlation between the laser frequency and a reference standard, coupled with real-time correction of frequency deviations through feedback systems. Current mainstream technologies can be divided into two categories. The first is the Pound-Drever-Hall (PDH) method. This approach utilizes the resonant characteristics of an optical resonator to generate error signals. By modulating the laser frequency near cavity modes and detecting phase variations in the reflected optical field, an error voltage proportional to the frequency deviation is extracted. The PDH method achieves extremely high frequency stability. However, its sensitivity to thermal expansion of cavities, mechanical vibrations, and mirror losses necessitates reliance on ultra-low expansion materials and multi-stage vibration isolation systems, leading to significantly increased system complexity and cost. The second is absorption spectroscopy. This technique employs intrinsic transition frequencies of atoms/molecules as natural frequency references, achieving stabilization by detecting spectral absorption features. Compared to the PDH method, absorption spectroscopy eliminates the need for complex resonator structures. It directly acquires error signals using compact gas absorption cells, offering advantages such as low cost, ease of integration, and environmental interference resistance. Notably, acetylene (C_2H_2) molecules have emerged as highly promising reference sources in communication bands due to their abundant vibrational-rotational absorption lines.

2.2. Frequency stabilization via acetylene absorption spectroscopy

Acetylene molecules exhibit a linear symmetric structure, with vibrational modes including stretching vibrations and bending vibrations. In the 1550 nm band, absorption primarily originates from vibrational-rotational transitions in the ν_3 fundamental band. The actual line shape of acetylene absorption lines is formed by the combined effects of multiple physical mechanisms, primarily including the following aspects. The first is Doppler broadening. Gas molecules have velocity distributions due to thermal motion, causing laser frequency shifts perceived by molecules with different velocities. The second is collisional broadening. Frequent collisions between molecules shorten the lifetime of energy levels, leading to homogeneous broadening. The signal-to-noise ratio and linewidth can be balanced by adjusting the gas pressure. This work constructed a compact frequency-stabilized laser system based on the vibrational-rotational absorption lines of acetylene (C_2H_2) molecules at 1542 nm. The frequency of a distributed feedback (DFB) laser was locked to the absorption line center using PID feedback control.

3. Experiment

3.1. Optical system

The experimental optical path comprises three parts: laser emission, absorption detection, and feedback control (schematic diagram shown in Fig. 1). Light emitted from the laser first passes through an optical isolator to suppress back-reflection-induced destabilization. Subsequently, the beam enters an acetylene-filled gas cell incorporating a specially designed retro-reflective mirror configuration, enabling double-pass propagation through the gas medium to enhance absorption effects. Transmitted light is collected by a high-sensitivity photodetector, with its output signal routed to signal processing circuitry. This dual-pass optical architecture effectively increases the absorption path length, thereby significantly improving the signal-to-noise ratio.

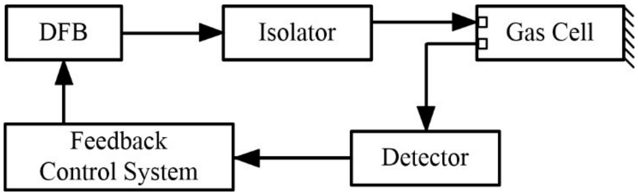

Fig. 1 Laser frequency stabilization system

3.2. Feedback control system

The frequency locking control system generates error signals through wavelength modulation spectroscopy: after applying frequency modulation to the laser, the harmonic components of the absorption signal are extracted using a lock-in amplifier. This harmonic exhibits a characteristic zero-crossing point at the absorption line center frequency, where the slope direction directly reflects the frequency deviation. The error signal is processed by a PID control circuit to generate a correction signal for the laser driver current. In the PID controller, the proportional unit rapidly responds to instantaneous deviations, the integral unit eliminates long-term drift, and the derivative unit suppresses high-frequency noise. The coordinated action of the three ensures the system's fast convergence and stable maintenance. The optical path provides a high-sensitivity frequency discrimination reference, while the circuit achieves rapid dynamic response. Their collaboration maintains the laser frequency stably locked at the center of the acetylene absorption line over extended periods.

3.3. Results

Fig. 2 demonstrates the locking characteristics based on acetylene absorption lines. When the laser frequency deviates from the central position, the frequency discrimination signal reflects the direction of frequency offset, providing a high-sensitivity discrimination reference for closed-loop feedback. After locking, continuous monitoring of the output laser using a high-resolution wavelength meter confirms that stable 1542 nm laser output is obtained (shown in Fig. 3).

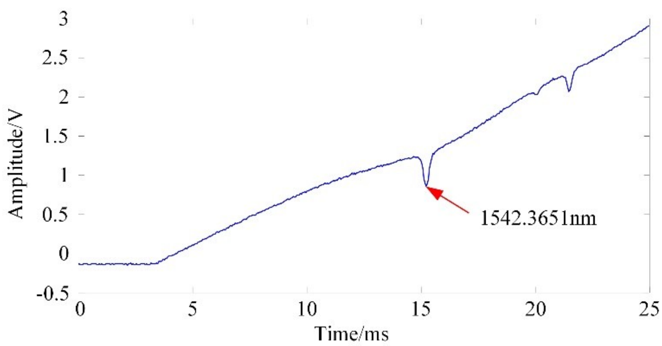

Fig. 2 Locking characteristics based on acetylene absorption lines

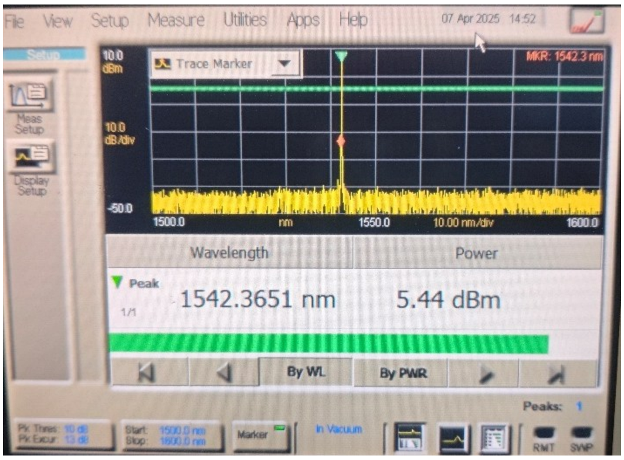

Fig. 3 Stable wavelength laser generation

The experimental results confirm that the frequency stabilization scheme based on acetylene absorption lines can effectively stabilize laser frequencies in communication bands at low cost. The dual-pass absorption structure and mirror spacing optimization in the optical design significantly enhance the signal-to-noise ratio, while PID control parameter tuning ensures rapid convergence and anti-interference capability of the closed-loop system. This provides a reliable technical pathway for developing industrial-grade frequency-stabilized lasers.

4. Conclusion

This work proposes a laser frequency stabilization method based on acetylene molecular absorption spectroscopy. By integrating a dual-pass absorption optical path design with closed-loop feedback control technology, the system complexity and cost are significantly reduced. Experimental validation confirms the feasibility of this method in communication bands, demonstrating the practical value of acetylene molecules as natural frequency references. Compared with conventional approaches, this system eliminates the need for precision temperature control or vibration isolation apparatus, maintaining reasonable stability while better suiting industrial field deployments and space-constrained scenarios. Future research may focus on optimizing absorption cell packaging processes and modular integration to advance the large-scale application of this technology in fiber-optic networks, lidar systems, and related fields.

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