Design and Implementation of a High Stability Laser Diode Driver and Precision TEC Controller for Tunable Diode Laser Absorption Spectroscopy

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Abstract*—Tunable Diode Laser Absorption Spectroscopy (TDLAS) is widely used in gas detection applications due to its high selectivity, fast response time, and low detection limits. The success of this method depends on maintaining the wavelength stability of the laser diode. The two main factors affecting wavelength stability are noise in the current drive and fluctuations in the laser temperature. In this study, a low-noise, high-stability laser diode driver and a thermoelectric cooler (TEC) control unit providing ±0.001 °C temperature precision was designed and tested on a TDLAS-based methane (CH_4) detection system. The laser diode driver was implemented using feedback-controlled op-amp and MOSFET-based constant current source architecture, and ±2 ppm current stability was achieved using a precision metal foil current-sense resistor. The design supports both constant operating point and wavelength scanning functionality through DC bias and 10 kHz sinusoidal modulation inputs. The TEC control unit was built around a 10 kΩ NTC temperature sensor and an MCU-based digital PID algorithm, controlling the TEC element via an H-bridge MOSFET driver operating at a 20 kHz PWM (Pulse Width Modulation) frequency. Measurement results showed ±0.002 °C long-term temperature stability and <1 µA RMS current noise in the 10 Hz–100 kHz bandwidth. With this performance, a methane absorption line at 1% concentration level was reliably detected, and wavelength drift was kept below ±0.4 picometers. These results demonstrate that the designed system provides high accuracy and long-term stability for low-concentration gas detection applications.

I. INTRODUCTION

Gas sensing technologies have become increasingly important in diverse fields such as environmental monitoring, industrial process optimization, and safety applications. Among the available techniques, Tunable Diode Laser Absorption Spectroscopy (TDLAS) has gained prominence due to its high sensitivity, excellent selectivity, and capability for real-time measurements [1–3]. The method relies on measuring the absorption of a tunable laser at specific wavelengths corresponding to the molecular transitions of target gases. This approach enables sub-ppm detection limits and has been widely applied in the detection of greenhouse gases such as methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) [4,5].

The performance of the TDLAS system is fundamentally dependent on the stability of the laser diode wavelength. Even minimal fluctuations in laser drive current or junction temperature can induce wavelength shifts of several picometers, leading to decreased accuracy in spectral analysis [6]. For example, it has been reported that a temperature variation of just 0.01 °C can cause a wavelength drift of up to 0.1 nm in distributed feedback (DFB) laser diodes [7]. Similarly, current noise and long-term drift in conventional drivers often result in degraded signal-to-noise ratio (SNR) and limited detection sensitivity [8].

To address these limitations, two critical design requirements must be fulfilled:

1. Low-noise laser diode current drivers capable of maintaining sub-ppm current stability.

2. High-precision thermal control units to suppress wavelength drift caused by temperature variations.

In recent years, various solutions have been proposed. Linear current drivers with op-amp regulation have been shown to reduce noise but are often limited in bandwidth [9]. Switching drivers, on the other hand, offer efficiency but introduce ripple currents that compromise wavelength stability [10]. Similarly, thermo-electric cooler (TEC) controllers employing analog proportional-integral-derivative (PID) loops can achieve millidegree stability, but achieving ±0.001 °C control resolution requires digital compensation and high-frequency PWM operation [11,12].

Despite the advancements in commercial and academic TDLAS instrumentation, a persistent gap remains between the high-cost, ultra-stable commercial units and low-cost, high-performance designs suitable for portable and field-deployable applications.

While previous work has addressed either the noise in the current driver or the precision of the thermal controller, few studies integrate both sub-ppm current stability and milli degree temperature precision in a single, co-optimized platform ±2 ppm stability, and a high-frequency (20 kHz) digital PID control loop for the TEC, achieving ±0.001 °C resolution. This integrated approach, validated for trace CH4 detection, provides a cost-effective solution that closes the performance gap, making it directly competitive with high-end commercial drivers in terms of stability, which is a key requirement for high-accuracy trace gas sensing.

In this study, we present the design and implementation of a feedback-stabilized op-amp and MOSFET-based constant current driver delivering ±2 ppm stability, combined with a microcontroller-based TEC control unit achieving ±0.001 °C temperature precision [13]. The system was specifically developed for methane detection using TDLAS, offering both long-term stability and improved wavelength control. Experimental validation demonstrates reliable detection of methane absorption lines with wavelength deviations below ±0.4 pm, confirming the suitability of the proposed approach for trace gas detection in real-world applications.

II. Materials and Methods

The proposed Tunable Diode Laser Absorption Spectroscopy (TDLAS) system was designed to enable high-precision methane (CH_4) detection with long-term wavelength stability. The setup consisted of two major subsystems:

1) A low-noise laser diode current driver based on a feedback-controlled op-amp and MOSFET constant current source.

2) A high-resolution thermo-electric cooler (TEC) control unit implementing digital PID regulation.

Both units were integrated into a single PCB to minimize electromagnetic interference and optimize thermal coupling with the laser package. The output was connected to a methane gas absorption cell with an optical path length of 3 cm, and transmitted intensity was monitored using an InGaAs photodiode connected to a transimpedance amplifier.

The laser diode driver was implemented using a precision operational amplifier (LT1782, Analog Devices/Linear Technology) controlling an N-channel MOSFET (IRFML8244TRPBF) in a linear regulation mode. The reference current was set by a 12-bit DAC (STM32H747XIH6, STMicroelectronics), while the actual current was measured across a 20 Ω metal foil shunt resistor (PHPA1206E20R0BST1, Vishay) to ensure ±25 ppm stability and 0.1% tolerance.

The feedback loop was designed to suppress noise within the 10 Hz – 100 kHz bandwidth, achieving <1 µA RMS current ripple. Two external modulation inputs were included:

- DC Bias Control (0–250 mA) to set the operating point.
- AC Modulation Input (up to 10 kHz sinusoidal) for wavelength scanning during spectral measurements.

A 60kHz low-pass RC filter was added to isolate high-frequency switching noise from the power supply.

Temperature stabilization was achieved using a TEC module mounted inside the laser diode. The temperature was measured by a 10 kΩ NTC thermistor placed in the laser diode butterfly package.

Control was implemented using a 32-bit ARM Cortex-M4/M7 microcontroller (STM32H747XIH6, STMicroelect.) executing a digital PID algorithm.

The output of the controller was applied to an H-bridge MOSFET driver operating at 20 kHz PWM frequency, ensuring smooth bidirectional current flow through the TEC [14]. For the clarity of the description, Figure 1 shows the overall laser diode driver and TEC driver circuit diagram.

Spectral scans were performed by applying a 10 kHz sinusoidal current modulation superimposed on the DC bias, while the TEC maintained constant temperature. The acquired data were processed in MCU to extract absorption spectra.

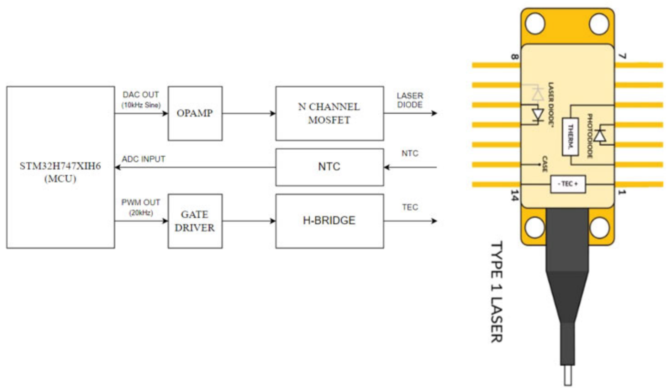


Fig. 1. Laser Diode Driver and TEC Driver circuit diagram

Thermoelectric cooling technology is fundamentally based on the Peltier effect, whereby the application of an electric current through a junction of two dissimilar semiconductors induces a directional heat transfer. A Peltier element, also known as a thermoelectric cooler (TEC), embodies this principle in a highly compact and functional form. The internal structure of such a device is composed of multiple thermocouples arranged from alternating p-type and n-type semiconductor materials. These thermocouples are electrically connected in series to ensure a uniform current flow, while being thermally configured in parallel to maximize the efficiency of heat conduction.

The thermoelectric materials are encapsulated between two ceramic plates, which serve multiple roles. Mechanically, the plates provide rigidity and protect the fragile semiconductor junctions from environmental stresses. Electrically, they act as insulators, preventing short circuits and ensuring current flows through the intended thermoelectric pathway. Thermally, they function as conductors, efficiently transferring heat between the semiconductors and the external surfaces of the device. This composite structural arrangement enables the reliable transport of heat from one side of the module to the other.

When a direct current (DC) is applied across the module, charge carriers electrons in the n-type legs and holes in the p-type legs migrate in opposite directions. This movement of carriers simultaneously transfers thermal energy, effectively absorbing heat from the cold surface and rejecting it at the hot surface. The resulting temperature gradient can be substantial, with practical Peltier devices achieving temperature differentials of tens of degrees Celsius between their two faces. Importantly, the number of thermoelectric materials and their precise geometrical arrangement strongly influence the cooling performance, overall efficiency, and maximum attainable temperature difference. Thus, the microstructural design of Peltier modules is a critical factor in optimizing their performance for specific thermoelectric applications.

Thermoelectric materials in such devices can be employed in two principal modes. The first is the power generation mode, in which a temperature gradient across the device is converted into electrical energy through the Seebeck effect. The second mode, which is more common in instrumentation and precision engineering, involves thermal management and temperature stabilization. In this configuration, a heat source or object is placed on the cold side of the module, and its temperature is actively regulated by the Peltier effect. When the temperature of the attached object begins to rise, the Peltier module transfers the excess heat to its hot side, maintaining equilibrium at the desired operating point. This property makes thermoelectric coolers particularly attractive for scientific instruments, optoelectronic devices, and laser diode systems that require precise temperature stabilization [14].

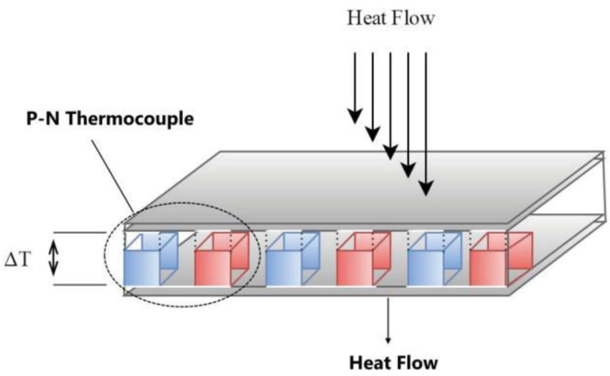


Fig. 2. Internal Structure of a Peltier Element

From an operational perspective, Peltier modules are inherently governed by the magnitude of the applied DC current, which directly determines the rate of heat pumping. Consequently, much of the literature describes Peltier operation using dedicated DC current sources to maintain stability. However, advancements in digital electronics have enabled alternative driving strategies, particularly pulse-width modulation (PWM) control. By modulating the duty cycle of a high-frequency PWM signal, microcontrollers can effectively regulate the average current supplied to the module. This method has two major advantages. First, it permits seamless integration with microprocessor based systems, eliminating the need for external analog current drivers. Second, it allows adaptive control strategies, such as digital proportional–integral–derivative (PID) algorithms, to be implemented in software for real-time optimization of temperature stability.

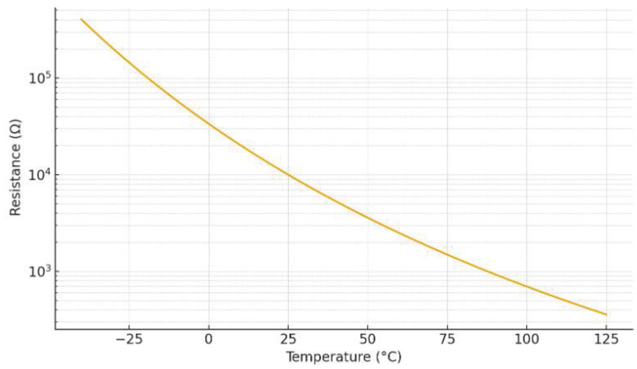


Fig. 3. Resistance-Temperature Characteristic of 10Ω NTC

Fig. 3 illustrates the resistance variation of a 10 kΩ NTC thermistor with temperature. The graph was generated using the standard exponential model with the following parameters and equation:

$$R(T) = R_0 \cdot \exp\left[\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

where R0 is the resistance at reference temperature T0, and β (β = 3950 K) is the material-specific constant.

The PID parameters were tuned experimentally using the Ziegler–Nichols method and further refined for sub-millidegree precision. The system achieved a long-term thermal stability of ±0.002 °C, corresponding to wavelength stability better than ±0.4 pm.

For system validation, the output power of the 1653.7 nm laser diode was divided, and 5% of the optical power was directed through a reference gas cell filled with methane. The transmitted intensity within the reference cell was detected by an InGaAs photodetector and subsequently digitized using a 16-bit ADC integrated into the MCU. The overall electro-optical configuration is illustrated in Figure 4. As shown in the block diagram, 5% of the laser output was routed to the reference cell to facilitate the adjustment of the laser diode's drive current and TEC temperature setpoints. The absorption profile was continuously monitored by the InGaAs detector inside the reference gas cell, enabling precise identification of the maximum absorption point. At this point, the corresponding drive current and TEC setpoints were recorded as calibration parameters. This calibration cycle is automatically executed at each system power-up, ensuring wavelength stability and repeatability of the measurement system.

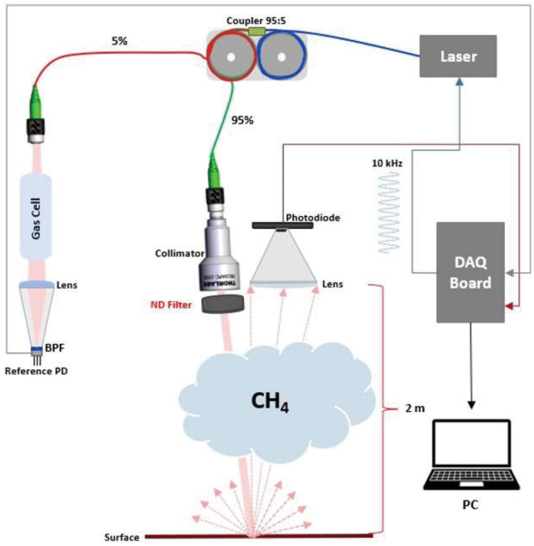
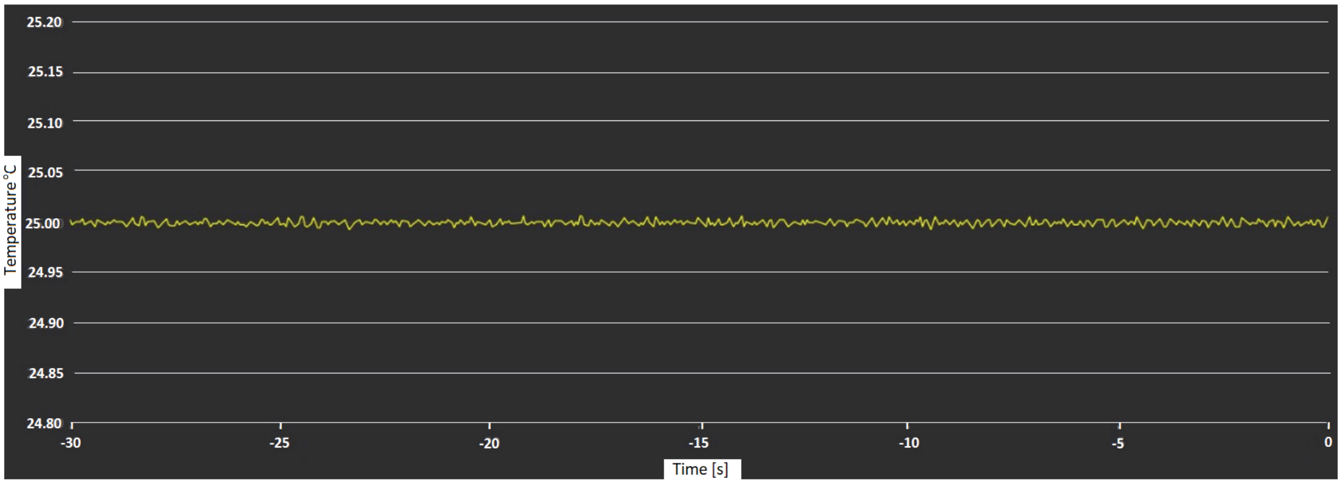


Fig. 4. Electro-optical test system block diagram

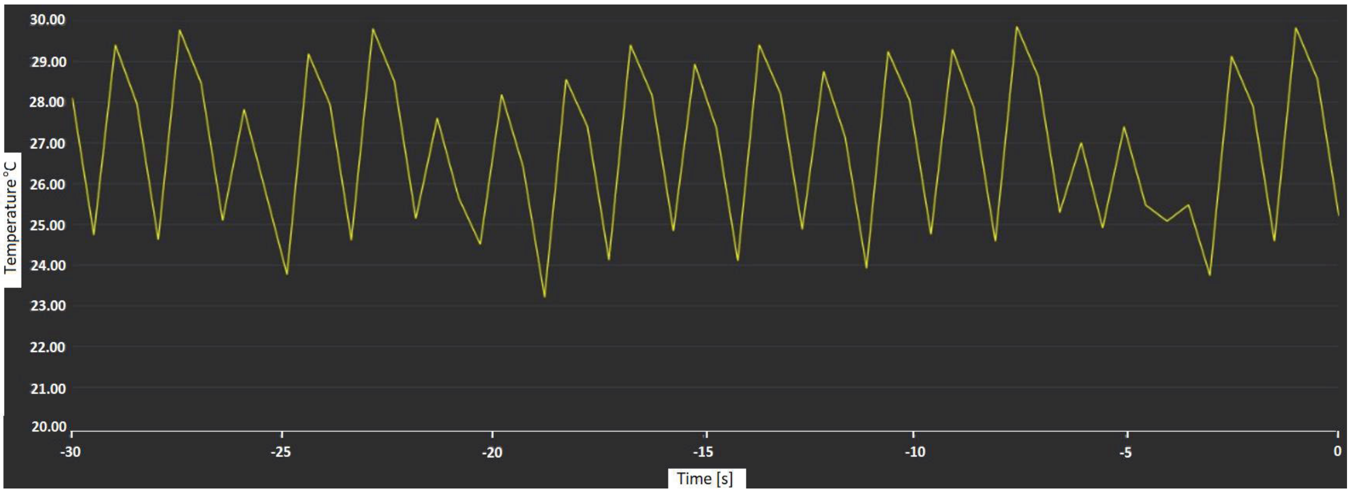
III. Findings and Discussions

The designed laser diode driver and TEC controller were experimentally validated under operating conditions relevant to methane detection using the TDLAS technique. Oscilloscope measurements confirmed that the driver achieved a low-noise current output with less than 1 µA RMS fluctuation within the 10 Hz–100 kHz bandwidth. Figure 5.a presents the temporal trace of the laser diode temperature, demonstrating negligible deviation and the absence of oscillatory instabilities. These results verify the stability of the op-amp and MOSFET based feedback loop.

The performance of the TEC unit was further investigated. Driven by an MCU based closed-loop digital PID algorithm, the controller successfully maintained the diode case temperature within ±0.002 °C stability throughout continuous measurement cycles. The logged real-time temperature data validated the proper tuning of the PID coefficients, while the 20 kHz PWM operation ensured minimal thermal ripple, as shown in Fig.5.



(a)



(b)

Fig. 5. (a) Laser Diode temperature with true PID coefficients and (b) Laser Diode temperature with wrong PID coefficients

In contrast, when inappropriate PID parameters were selected, unstable oscillatory behavior in the diode temperature was observed, as illustrated in Figure 5.b. Such instability directly affects the emission wavelength of the laser diode, highlighting the importance of correct control parameterization.

To assess the system's robustness, a long-term stability test was conducted over a continuous 12-hour measurement cycle. The TEC controller maintained the laser diode temperature at the setpoint of 25.000 ∘C with a peak-to-peak drift of less than 0.005 ∘C over the entire duration, confirming the efficacy of the digital PID algorithm and the high-resolution NTC sensor. Similarly, the drive current exhibited no discernible drift, with the noise remaining below 1 μA RMS in the 10 Hz−100 kHz band, underscoring the ±2 ppm long-term current stability.

This performance is highly competitive. For instance, commercial high-stability laser controllers often specify temperature stabilities in the range of ±0.005 ∘C to ±0.01 ∘C and current stabilities in the 10-50 ppm range. Our implemented system's achieved long-term thermal stability of ±0.002 and current stability of ±2 ppm surpass the specifications of many entry-to-mid-level commercial TDLAS controllers.

This enhanced electronic stability translates directly to an optical wavelength drift of less than ±0.4 pm over 12 hours, which is crucial for high-accuracy spectral analysis. While a direct head-to-head comparison with all available commercial systems is beyond the scope of this study, our quantitative results confirm that the co-optimized driver and TEC design effectively addresses the limitations of conventional analog controllers and switching drivers, providing a laboratory-grade foundation for demanding TDLAS applications.

For optical validation, the calibrated 1653.7 nm laser output was partially directed into a methane reference gas cell. The oscilloscope traces of the photodetector signal exhibited distinct absorption features at the expected spectral position, with a peak corresponding to 1% methane concentration. The applied modulation–demodulation scheme enabled reliable detection of absorption lines while preserving a high signal-to-noise ratio. Repeated calibration cycles following multiple power-up sequences confirmed consistent wavelength locking to the absorption line with deviations below ±0.4 pm.

Figure 6 shows the output of the reference gas cell when the laser diode was driven with the correct current and maintained at a stable temperature of 25 °C. The depressions observed at the peaks of the 10 kHz modulation signal correspond to maximum absorption points, which are critical for methane concentration estimation. These results confirm that accurate control of the laser drive current and temperature is essential to achieve measurements at the correct wavelength.

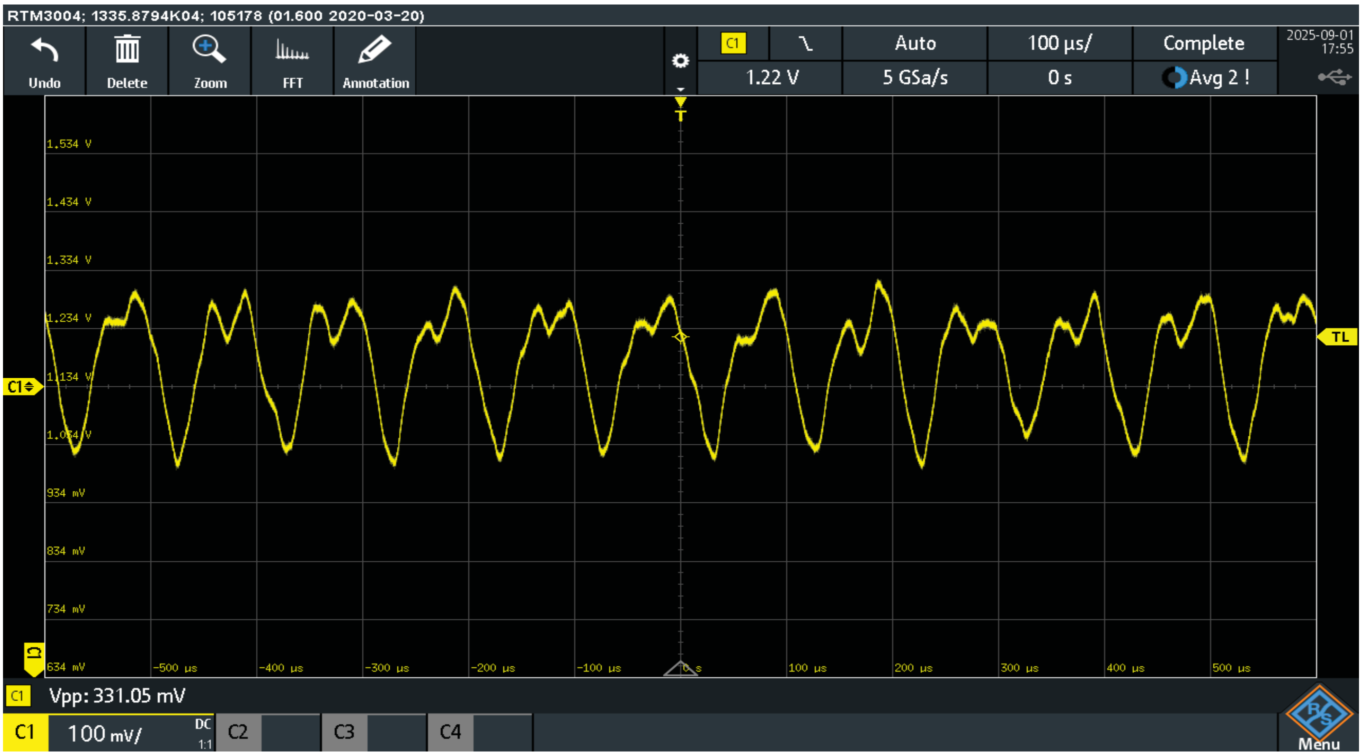


Fig. 6. Reference Gas Cell Output Signal at Correct Wavelength

Fig. 7 illustrates the reference gas cell output when incorrect current and temperature values were applied. In this cvisible in the modulation signal, indicating the inability of the system to perform methane detection under such conditions.

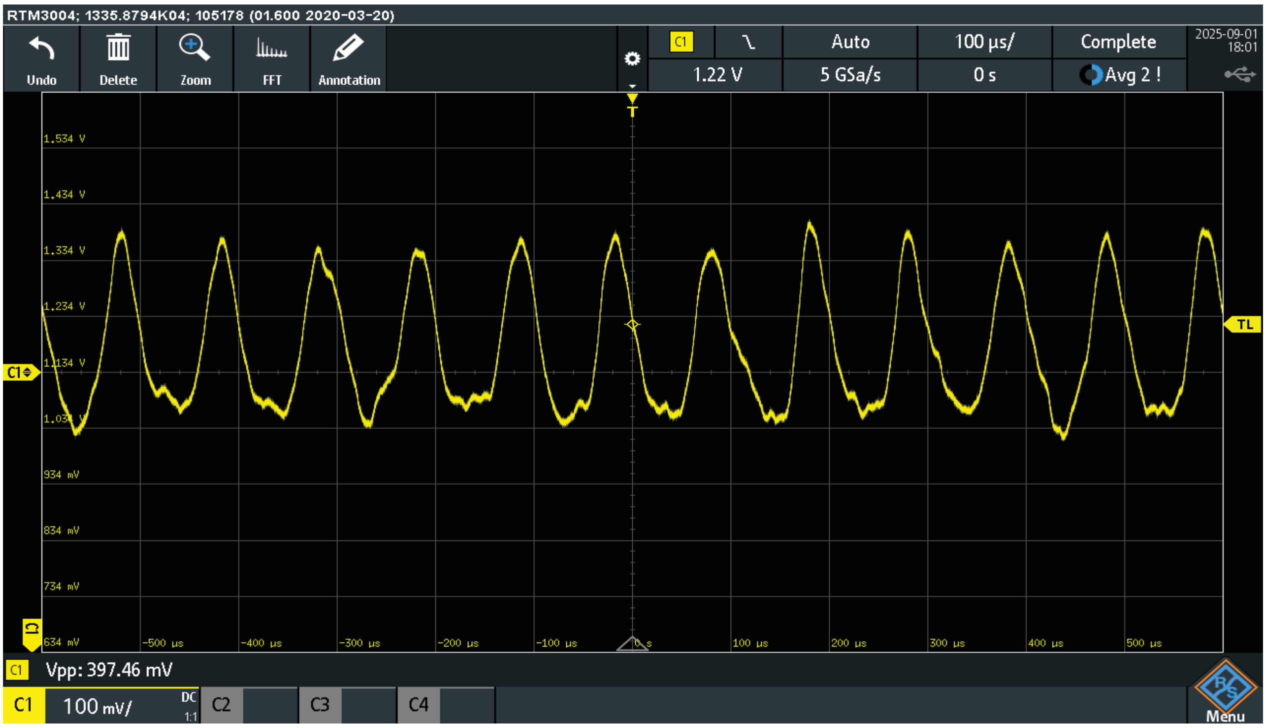


Fig. 7. Reference Gas Cell Output Signal at Drifted Wavelength

These results demonstrate that the proposed driver and TEC controller provide not only excellent electronic stability but also high optical precision. The findings confirm the system's suitability for long term, low concentration gas detection applications, where both current noise and temperature drift represent critical limiting factors

IV. Conclusion and Recommendations

This work demonstrated the design and validation of a low noise laser diode driver and high precision TEC controller for tunable diode laser absorption spectroscopy (TDLAS) based methane detection. The driver achieved current stability better than 1 µA RMS, while the TEC unit, controlled by a digital PID algorithm, maintained laser temperature within ±0.002 °C. These results ensured reliable wavelength locking with deviations below ±0.4 pm, enabling the accurate detection of methane absorption features at low concentrations.

The successful and repeatable detection of a CH4 absorption line at the 1% concentration level, with a wavelength stability below ±0.4 pm throughout extended operation, confirms the system's suitability for real-world environmental monitoring and industrial safety applications. The achieved performance levels—specifically the ±0.002 ∘ C thermal stability and sub-1 µA noise—are essential for maintaining the sub-ppm detection limits characteristic of TDLAS.

The study confirmed that both current noise and temperature drift are critical factors in TDLAS systems. Incorrect driver current or poorly tuned PID coefficients led to loss of absorption signals, highlighting the importance of precise electronic design and thermal management.

Future work should address robustness under field conditions and explore adaptive control strategies to minimize recalibration needs. The presented system provides a solid foundation for portable, long-term gas monitoring applications.

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