EE396: Design Lab Project Report

Design of Laser Self-mixing interferometer for mechatronics applications

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Abstract

The integration of laser technology in mechatronics applications has seen significant advancements in recent years, with the development of novel sensing techniques driving progress. This project report presents the design and implementation of a Laser Self-mixing Interferometer (LSMI) tailored specifically for mechatronics applications. The interferometer utilizes the self-mixing effect within a laser cavity to achieve high-precision distance measurements to sensing of weak optical echoes – for return loss and isolation factor measurements. The system's design emphasizes accuracy and stability through meticulous calibration, rendering it suitable for diverse functions such as position sensing, vibration analysis, and surface profiling. This report details the theoretical foundations, design considerations, experimental setup, and performance evaluation of the LSMI system. The results showcase the effectiveness and versatility of the proposed design, paving the way for enhanced sensing capabilities in mechatronics systems.

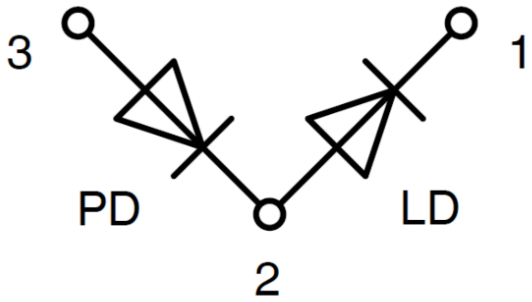
Introduction

The emergence of Laser Self-mixing Interferometry (SMI) in the 1960s represents a pivotal advancement in optical sensing technology, offering a non-contact sensing technique renowned for its intrinsic advantages. SMI's popularity stems from its unique ability to self-align, coupled with high sensitivity, cost-effectiveness, compactness, and compatibility with various laser types. At its core, SMI involves the reflection or back-scattering of a laser beam emitted from a laser cavity by an external surface. This reflected beam then re-enters the cavity, interfering with the existing lasing field, thereby perturbing the output beam's frequency and power. Target information can be extracted from variations in laser frequency or power, making SMI a versatile and powerful sensing technique.

The inception of SMI marked a significant milestone in optical sensing, originating as a method to enhance laser diode stability. Its simplicity and high sensitivity quickly garnered attention, leading to its application in distance measurement and vibration analysis. The groundwork for SMI was laid by pioneering work in the late 1970s, notably by Prof. Erwin K. Reichardt and Prof. C. Zenger, who first described the self-mixing effect in semiconductor lasers. Their research paved the way for subsequent advancements, culminating in practical SMI systems in subsequent decades. Initially conceived for laser stabilization, SMI's versatility soon became apparent as researchers explored its potential across various sensing applications.

Today, SMI stands as a cornerstone of optical sensing technology, offering unmatched precision and versatility within a compact form factor. Its applications span diverse fields, including industrial metrology, robotics, biomedical diagnostics, and environmental monitoring. Of particular interest is its integration into mechatronics systems, where real-time feedback is crucial for precise control and monitoring. In this context, the present project aims to explore SMI's potential for mechatronics applications through the design and implementation of a dedicated Laser Self-mixing Interferometer. Leveraging SMI's inherent advantages such as high sensitivity, compact size, and real-time measurement capabilities, the goal is to develop a versatile sensing platform tailored specifically for mechatronic tasks. This report delves into the theoretical underpinnings, design considerations, experimental setup, and performance evaluation of the proposed LSMI system, highlighting its potential to revolutionize sensing capabilities in mechatronic systems.

Self-Mixing Interferometry Theory

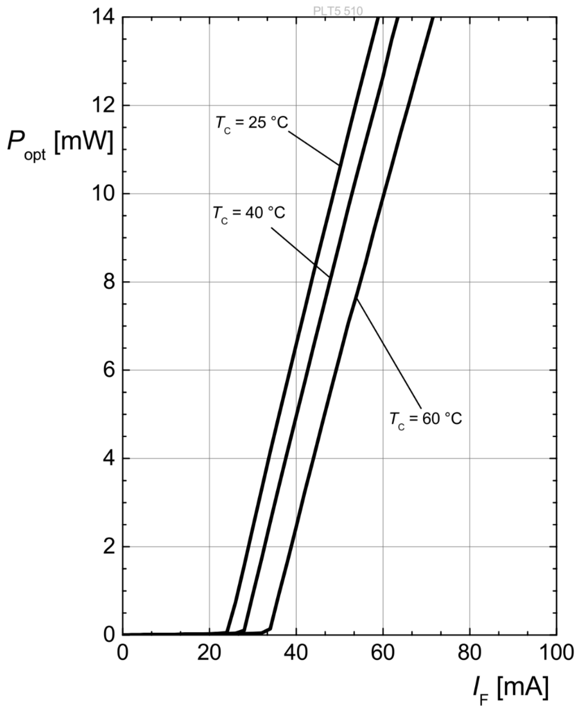


Semiconductor lasers, also known as diode lasers, function on the principle of stimulated emission within a semiconductor material. At the core of these lasers lies a PN junction, where electrons and holes are injected into the active region under forward bias voltage. Here, they recombine, releasing energy in the form of photons through spontaneous emission. Optical feedback, provided by mirrors at each end of the active region, stimulates further emission, leading to population inversion. This state, where more electrons occupy higher energy states than lower ones, is crucial for laser operation. When photons interact with excited electrons, stimulated emission occurs, amplifying light intensity and producing coherent laser light. The threshold current marks the point at which stimulated emission becomes dominant. Temperature influences the bandgap energy and carrier dynamics, affecting laser performance and emitted wavelength. Semiconductor lasers offer precise control and compactness, making them ubiquitous in various applications, including telecommunications, optical storage, and medical devices. Understanding their theoretical functioning is fundamental for optimizing their performance in practical applications.

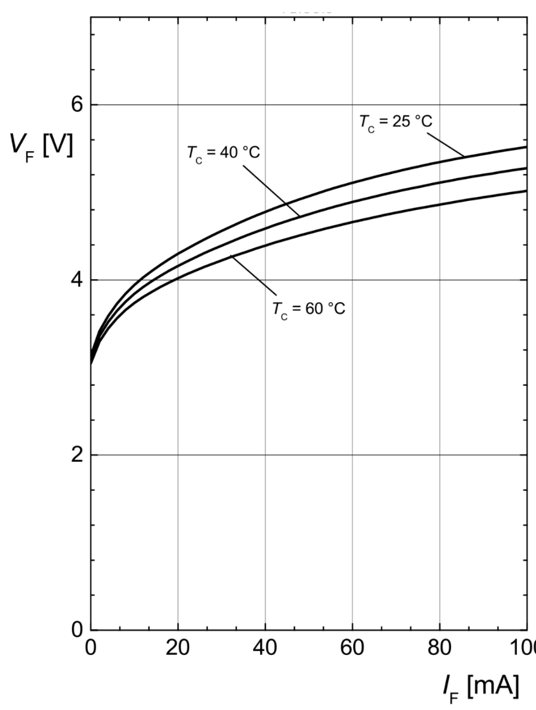
Characteristics of semiconductor lasers:

P–I/V–I characteristics:

The characteristic curve depicts the relationship between the output optical power (P) and the injection current (I) of the laser diode (LD). Initially, as the current increases, the optical power rises gradually. However, upon reaching a specific threshold current, the optical power experiences a sharp increase, indicating the onset of laser emission. This threshold current signifies the minimum current required for laser operation. The laser's working power is directly influenced by the power supply output, with adjustments in the output current allowing for control over the laser's output power within a certain range. Additionally, the V-I characteristic curve illustrates the correspondence between the voltage (V) across the LD and the injection current (I). At low currents, the voltage rises slowly and irregularly, but as the current surpasses a critical value, a linear relationship between current and voltage emerges. This characteristic behavior provides valuable insights into the operational parameters of the laser diode, essential for optimizing its performance in various applications.



Optical Output Power



Forward Voltage

Temperature characteristics:

As a thermal power device, the laser diode (LD) experiences a rise in temperature with prolonged operation. Due to its nature as an electron-photon conversion device, not all electrical energy is converted into light energy, leading to the generation of heat within the LD. This increase in temperature significantly impacts various performance parameters, including output optical power, output wavelength, and threshold current. The temperature characteristic curve illustrates these effects.

- **Threshold Current Shift:** With increasing temperature, the threshold current of the LD gradually rises. This indicates that higher temperatures require a larger injected current to drive the LD successfully.
- **Linear Relationship between Output Power and Injection Current:** At constant temperature and injection current exceeding the threshold, the output optical power (P) exhibits a linear relationship with the injection current (I). However, as temperature rises, the slope of the P-I characteristic curve decreases. This implies that at the same injection current, higher temperatures result in lower output optical power.

Advantage of SMI over Laser:

The advantages of a self-mixing interferometer (SMI) with a laser diode, relevant to various applications are:

- **Simplicity and Cost-effectiveness:** The absence of external optical components required for the source simplifies the setup, rendering it more reliable, compact, and cost-effective. Nevertheless, certain configurations may necessitate the inclusion of lenses or other optical elements for tasks such as beam shaping or enhancing spatial resolution. It's worth noting that these additional components might introduce feedback perturbations, affecting the self-mixing detection process.
- **Alignment-Free Operation:** The inherent spatial filtering property of the laser obviates the need for alignment, as it selectively interacts with the resonator mode. However, challenges may arise in scenarios where surface scattering occurs within a narrow solid angle, potentially leading to alignment issues due to the feedback's sensitivity to the angle between the surface normal and the laser diode axis.
- **Integrated Signal Detection:** The built-in monitor photodiode within the laser diode module eliminates the necessity for an external photodetector. Nevertheless, limitations inherent to the encapsulated photodiode, such as inadequate bandwidth for specific applications, may necessitate the incorporation of additional optical components and an external photodetector.
- **Reduced Stray Light Sensitivity:** Stray-light filtering before the photodetector becomes unnecessary when utilizing an encapsulated photodiode for light sensing.

- **Quantum-Limited Detection:** The detector operates consistently at the quantum regime's achievable signal-to-noise ratio (SNR) quantum limit, provided the noise at the photodetector is disregarded.
- **Versatile Sampling Capabilities:** The beam can be sampled at various points, including multiple locations on the same target, enhancing the instrument's versatility and adaptability to different measurement scenarios.

Components used

The components used to design laser self-mixing interferometry are:

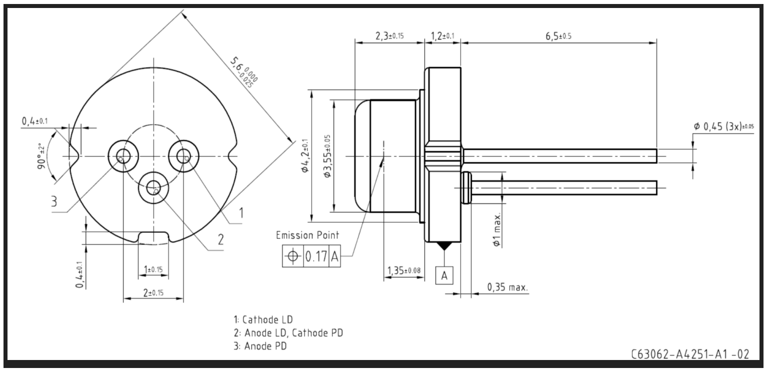
- Laser self-mixing interferometry with emission wavelength= 515 nm
- Arduino UNO
- LM317 regulators
- Operational amplifier- LM324
- Liquid-crystal display
- DC power supply- 9V
- Convex lens- Focal length- 15cm
- Potentiometer
- Capacitors
- Resistors

Laser self-mixing interferometry:

Laser self-mixing interferometry (SMI) is a versatile optical measurement technique employed in various scientific and industrial applications. Key features include:

- **Interference Principle:** SMI capitalizes on interference patterns generated within a laser cavity when light emitted by a laser diode interacts with a target and reflects back into the cavity.
- **Precise Measurements:** SMI offers high precision in distance, velocity, and vibration measurements due to its ability to detect minute changes in interference patterns.
- **Non-Contact Operation:** As a non-contact measurement method, SMI is ideal for applications where direct contact with the target is undesirable or impractical.
- **Compact Setup:** SMI systems typically consist of a compact arrangement of laser diode, optics, and photodetectors, facilitating ease of setup and integration into experimental setups or industrial machinery.

In conclusion, Laser self-mixing interferometry stands as a powerful and flexible tool for precise optical measurements, offering numerous advantages for scientific research, industrial processes, and medical diagnostics.



Arduino UNO:

Arduino UNO is a programmable microcontroller board. It can be erased, and reprogrammed, very easily. It is based on the ATmega328P microcontroller, which is a low-power, high-performance 8-bit AVR microcontroller with 32KB of in-system programmable flash memory and IKB of EEPROM.

Some of its features are:

- USB port for programming and serial communication
- 14 digital input/output pins
- 16 MHz quartz crystal oscillator
- Power jack for external power supply
- 6 analog input pins
- Reset button

LM317 regulators:

The LM317 voltage regulator is a compact and versatile integrated circuit renowned for its adjustable output voltage capability. With built-in current limiting and thermal shutdown protection, it ensures safe and reliable operation. Its simple circuit design and minimal external components make it easy to integrate into a wide range of electronic projects. Commonly used in power supplies and voltage regulation applications, the LM317 offers a cost-effective solution for achieving stable and adjustable voltage outputs in diverse electrical systems.

Operational amplifier- LM324:

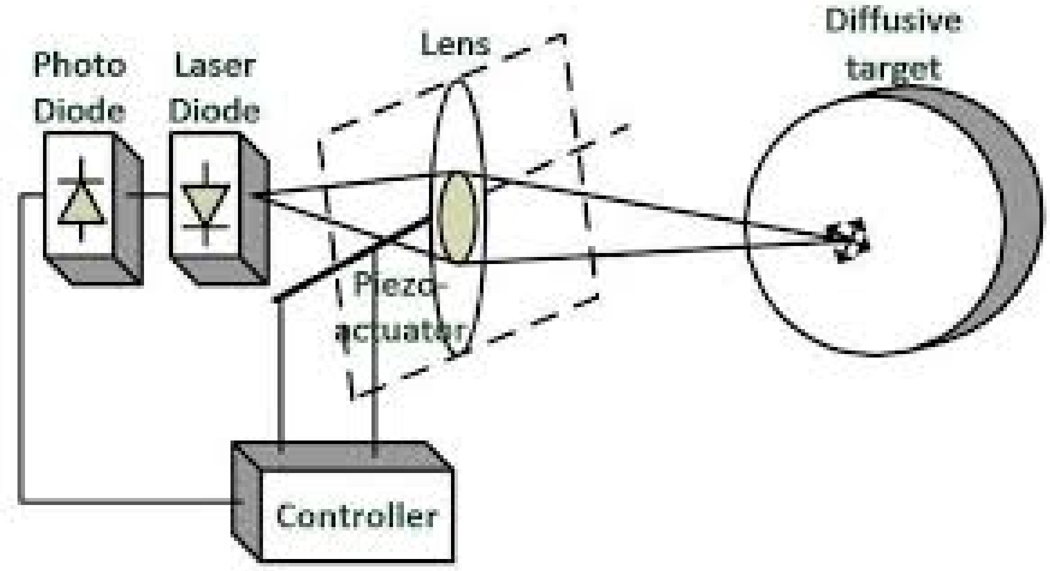
The LM324 is a quad op-amp IC prized for its versatility and reliability in analog circuits. With four independent op-amps in one package, it offers compactness and flexibility in design. Operating over a wide voltage range (3V to 32V), it suits diverse power supplies. Its low input bias current ensures accurate signal processing, while built-in protection features enhance durability.

Design

Optical distance sensors, owing to their high resolution and non-invasive nature, are widely employed for accurately estimating the absolute distance of remote targets. These sensors encompass various techniques, including laser triangulation, Time-of-Flight (ToF), absolute interferometry, and the self-mixing interference effect in laser diodes. Among these, Laser Self-mixing Interferometry (SMI) has emerged as a particularly advantageous technique due to its high resolution, compact size, and cost-effectiveness. SMI leverages the optical back-injection phenomenon within a laser cavity, where a fraction of light emitted by the laser diode is reflected back by an external target, subsequently mixing with the internal lasing field. This interaction modulates both the laser frequency and emitted power, providing valuable information about the target's position.

The standard setup for SMI typically includes :

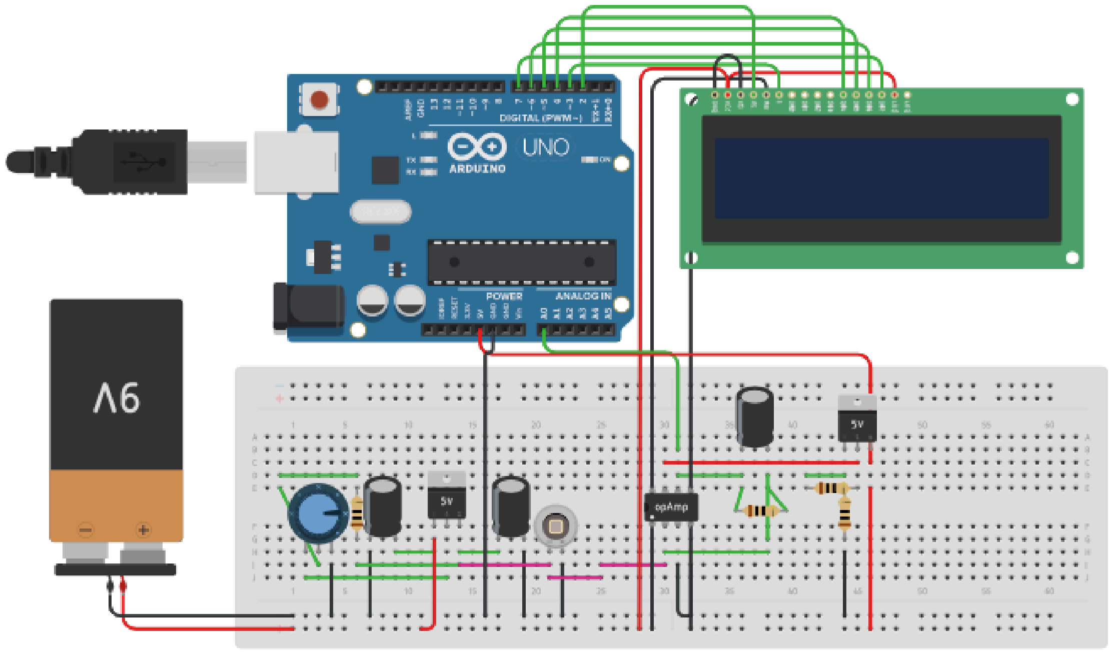
- Laser diode
- Monitor photodiode
- Collimating lens
- Target



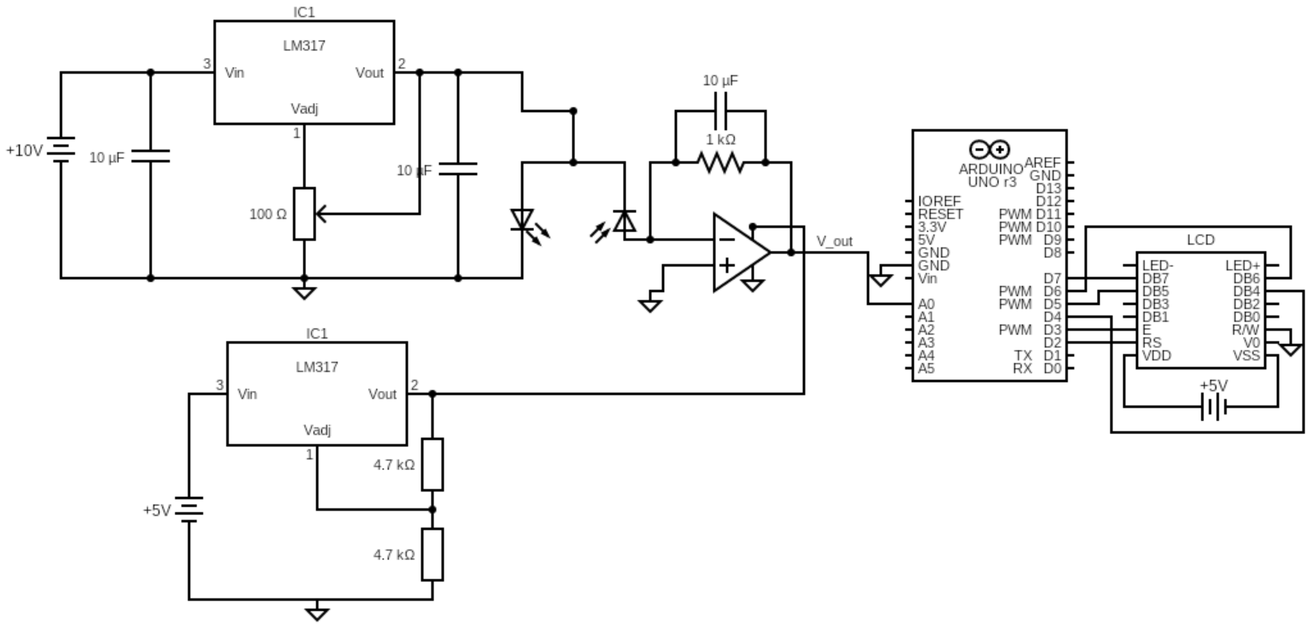
The monitor photodiode directly measures the power emitted by the laser diode, which exhibits a periodic function in relation to the back-injected phase, where the distance between the laser and the target is a critical parameter.

To estimate the absolute distance, the laser wavelength is modulated, and the fringes period is measured. Initially, signal processing involved simple fringes counting, but more effective approaches have been developed. Techniques such as interpolated Fast Fourier Transform (FFT) provide accurate beat frequency calculation and distance estimation. However, challenges such as signal non-sinusoidally and speckle effect-induced errors have prompted the development of advanced signal processing algorithms. These include approaches like all-phase FFT, MUltiple SIgnal Classification (MUSIC), and Genetic Algorithm (GA), each aiming to improve accuracy and robustness in SMI-based distance sensing systems. Despite the challenges, SMI remains a powerful tool with applications not limited to absolute distance measurement, including displacement, speed, vibration sensing, imaging, liquid flow, biomedical applications, and laser parameters measurements, showcasing its versatility and potential for various scientific and industrial endeavors.

Circuit Diagram



Schematics of the circuit diagram:

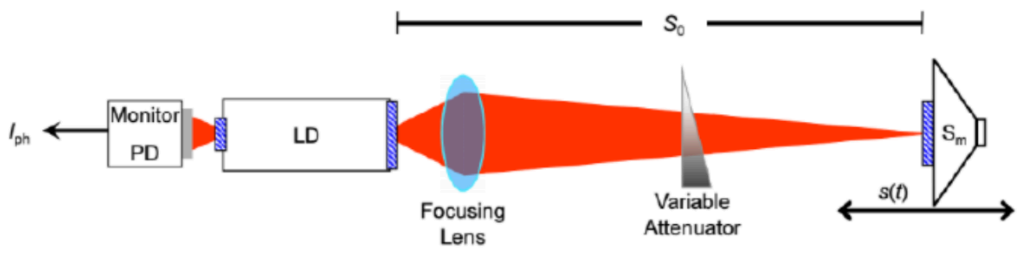


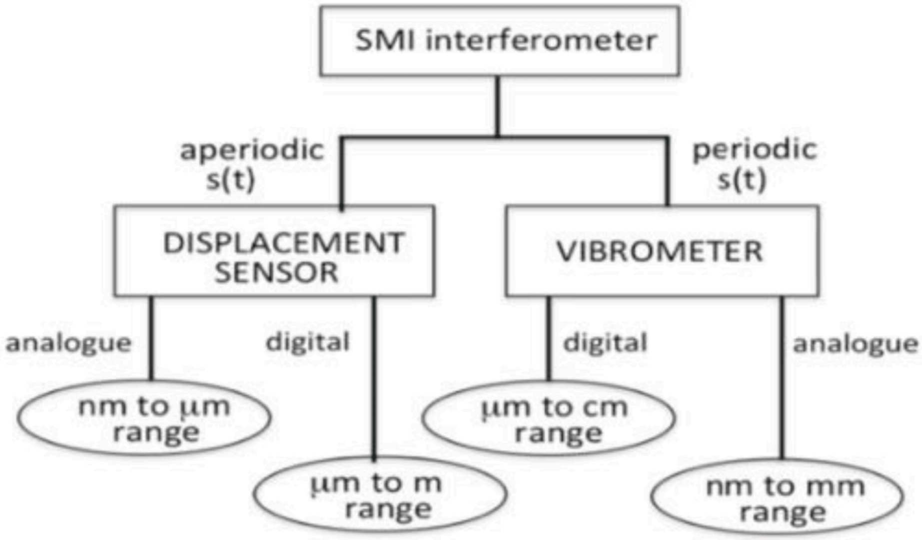
Arduino code

```
#include <LiquidCrystal.h>
#include "fft.h"

#define SAMPLE_RATE 20000 // Sampling frequency (greater than the frequency of audible sound)
#define NUM_SAMPLES 256   // Number of samples for FFT (should be power of 2)
#define VOLTAGE_PIN A0    // Analog pin for voltage input
#define LCD_RS 12         // LCD RS pin
#define LCD_EN 11         // LCD enable pin
#define LCD_D4 5          // LCD data pin 4
#define LCD_D5 4          // LCD data pin 5
#define LCD_D6 3          // LCD data pin 6
#define LCD_D7 2          // LCD data pin 7
#define LCD_COLS 16       // Number of LCD columns
#define LCD_ROWS 2        // Number of LCD rows

LiquidCrystal lcd(LCD_RS, LCD_EN, LCD_D4, LCD_D5, LCD_D6, LCD_D7);
double vReal[NUM_SAMPLES];
double vImag[NUM_SAMPLES];

void setup() {
  Serial.begin(9600);
  lcd.begin(LCD_COLS, LCD_ROWS);
  analogReference(DEFAULT);
  fft_windowing();
}

void loop() {
  for (int i = 0; i < NUM_SAMPLES; i++) {
    // Read voltage input from A0
    vReal[i] = analogRead(VOLTAGE_PIN);
    delayMicroseconds(1000000 / SAMPLE_RATE); // Sampling delay
  }

  fft_windowing();
  fft_reorder();
  fft_run();

  int peak = 0;
  double max = 0;
  for (int i = 0; i < (NUM_SAMPLES / 2); i++) {
    double mag = sqrt(vReal[i] * vReal[i] + vImag[i] * vImag[i]);
    if (mag > max) {
      max = mag;
      peak = i;
    }
  }

  // Calculate the corresponding frequency
  float frequency = peak * (SAMPLE_RATE / NUM_SAMPLES);

  // Display the frequency on LCD
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("Frequency:");
  lcd.setCursor(0, 1);
  lcd.print(frequency);
  lcd.print(" Hz");

  delay(1000);
}
```

Vibration Measurement

Self-mixing interferometry (SMI) stands as a versatile and powerful method for sensing and measuring vibrations across a vast range of amplitudes, from picometers to millimeters, and frequencies spanning from sub-Hertz to megahertz. As an optical probe, SMI offers the distinct advantage of being non-invasive, capable of measuring without perturbing the target surface, and operating from a significant standoff distance. Furthermore, the configuration simplicity of SMI sets it apart from conventional interferometers, as it eliminates the need for external optical components beyond the laser source.





Principles of Interferometry applied for vibration Measurement

Interferometry operates on the principles of coherence, interference, and wavefront analysis. Coherence refers to the temporal and spatial correlation between different parts of a wavefront, ensuring a stable interference pattern. Interference arises from the superposition of waves, resulting in amplitude and phase modulation. Wavefront analysis involves characterizing the spatial distribution of light waves, crucial for understanding interference phenomena.

The Interference Dynamics:

The interference pattern in self-mixing interferometry undergoes complex dynamics due to the interplay between multiple factors. These include the optical path length variation induced by the vibrating surface, the phase modulation caused by the Doppler effect, and the feedback mechanism within the laser cavity. Understanding these dynamics requires a deep grasp of optical wave propagation, laser physics, and feedback control theory.

Explanation of Phase and Amplitude Modulation in Retro-Injection Interferometry:

When light emitted by a laser falls upon a vibrating surface, a fraction of this light is reflected back into the laser cavity. This reflected light reintegrates with the outgoing beam within the cavity, leading to interference patterns known as fringes. These fringes exhibit modulation in both phase and amplitude due to the movement of the vibrating surface.

Mathematical Representation:

The phase modulation (Φ) observed in the interferometric signal is directly proportional to the distance (s) between the laser source and the vibrating target, as described by the equation $\Phi = 2ks_0$, where k is the wave number and s_0 is the physical distance. Consequently, a change in distance (Δs) results in a corresponding phase shift ($\Delta\Phi$) in the interferometric signal.

Phase Shift Calculation:

By imposing a phase shift of an entire period ($\Delta\Phi = 2\pi$), which corresponds to a displacement of half the wavelength ($\Delta s = \lambda/2$), it becomes possible to discern an entire fringe on the oscilloscope screen. Thus, by counting the number of visible fringes, one can infer both the magnitude and direction of the displacement with a resolution of half the wavelength.

Amplitude Modulation:

In addition to phase modulation, the interference pattern also exhibits amplitude modulation. This modulation arises from variations in the intensity of the reflected light due to the movement of the vibrating surface. The amplitude modulation manifests as fluctuations in the intensity of the interferometric signal.

Frequency Calculation using FFT with Arduino:

Once the interferometric signal is captured by the photodiode and amplified, it can be fed into the Arduino microcontroller for further processing. To calculate the frequency of the vibrations, the Arduino can perform a Fast Fourier Transform (FFT) analysis on the signal. The FFT algorithm decomposes the signal into its frequency components, revealing the dominant frequencies present.

Arduino FFT Implementation:

1. **Signal Acquisition:** Read the analog signal from the photodiode using an analog input pin on the Arduino.

2**. FFT Processing**: Implement an FFT algorithm to transform the time-domain signal into the frequency domain.

3. **Frequency Extraction**: Identify the dominant frequency component in the FFT output corresponding to the vibration frequency.

4. **Display or Output:** Display the calculated frequency on an LCD screen, serial monitor, or any other output device.

By leveraging the power of FFT analysis with Arduino, it becomes feasible to accurately determine the frequency of vibrations detected by the retro-injection interferometry setup, facilitating a wide array of applications ranging from acoustic analysis to structural health monitoring.

Problems Encountered and Scope for Further Improvement

Nonlinear Effects and Chaos:

Under certain conditions, self-mixing interferometry exhibits nonlinear behavior, characterized by complex phenomena such as chaos and bifurcations. Nonlinear effects arise from the interaction between the laser field and the external environment, leading to deterministic yet unpredictable behavior. Understanding nonlinear dynamics requires advanced mathematical tools such as chaos theory and nonlinear dynamics. Advanced algorithms such as wavelet transforms and Hilbert-Huang transforms further enhance the analysis of non-stationary and non-linear signals.

Advantages of SMI for Vibration Measurements:

The non-invasive nature of SMI makes it particularly suitable for a wide array of vibration measurement applications. Unlike traditional methods that may require physical contact or surface treatment, SMI can analyze vibrations from a distance, preserving the integrity of the target surface. Moreover, its simplicity of setup and operation streamlines the measurement process, facilitating rapid deployment and experimentation.

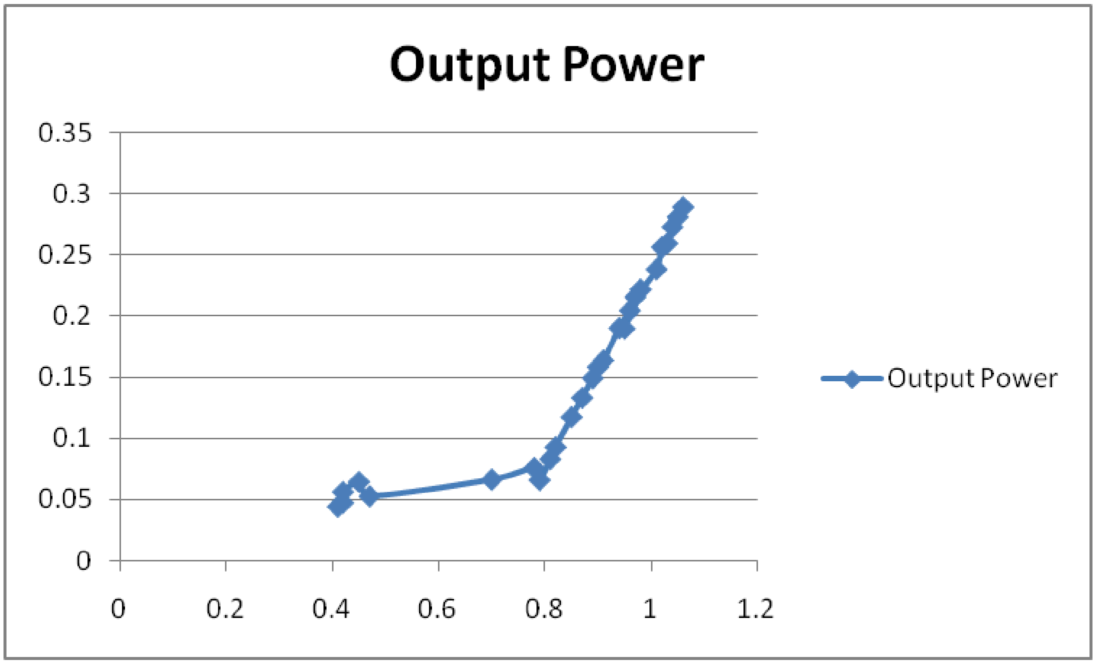
The performance capabilities exhibited by these SMI instruments set a benchmark unparalleled by other reported approaches in the literature. Their ability to operate across such a broad spectrum of parameters signifies a significant advancement in vibration sensing technology. As we explore the intricacies of SMI configurations and processing methods, we gain insights into the unparalleled precision and versatility offered by this innovative technique.

Data Recorded

Experimental Measurements P_ld vs V_out:

Resistance	V_out	Output Power
20	1.06	0.2887
21.4	1.05	0.2805
21.9	1.04	0.2724
22.1	1.03	0.2591
22.5	1.02	0.2561
25.7	1.01	0.2378
26.2	0.97	0.2153
27.3	0.98	0.2215
27.1	0.95	0.1894
27.4	0.96	0.2042
27.8	0.94	0.1899
28.1	0.91	0.1636
29.3	0.9	0.1581
29.9	0.89	0.1491

Resistance	V_out	Output Power
30.4	0.87	0.1331
31.3	0.85	0.1174
32.1	0.82	0.0928
32.9	0.81	0.0831
33.1	0.79	0.0665
34.9	0.78	0.0758
36.2	0.7	0.0664
40.7	0.47	0.0528
69.4	0.45	0.0645
89.5	0.42	0.0562
105.2	0.42	0.0475
110.6	0.41	0.0444



Output Power versus V_out

Further Improvements

In our exploration of Laser Self-Mixing Interferometry (SMI), we've observed the output power of the laser diode and the current supplied to it showcase a distinct linearity. Leveraging this, we can enhance our measurement capabilities beyond traditional displacement. By implementing Pulse Width Modulation (PWM) to modulate the current supplied to the laser diode, we effectively control its output power. This modulation technique allows us to vary the duty cycle of the signal, thereby adjusting the average power delivered to the laser diode. Integrating PWM control mechanisms into our laser diode driver circuitry, we can precisely regulate the current supplied, resulting in controlled variations in output power. This controlled modulation of output power enables us to extend our measurement capabilities to absolute distance estimation. By correlating the controlled current or PWM duty cycle with known distances through a calibration process, we establish a calibration curve that facilitates accurate inference of absolute distances based on observed laser intensity during measurements. This advancement holds significant promise across diverse industries, enabling precise positioning, navigation, surveying, and monitoring applications, and underscores the transformative potential of integrating PWM and current control with Laser SMI.

Absolute Distance Measurement

In self-mixing interferometry, absolute distance measurement often involves employing wavelength modulation. When the target remains stationary, modulation of the laser wavelength leads to a proportional shift in the interferometric phase ϕ = 4π·s/λ, where s represents the distance between laser and object.

$$\frac{\partial \varphi}{\partial \lambda} = -4\pi \frac{s}{\lambda^2}$$

The simplest method for modulating the laser wavelength involves adjusting the pump current I. Assessing the fringe frequency f_tone during this modulation allows for the measurement of the target distance.

$$s = -\frac{\lambda^2}{2 \cdot \left(\frac{\partial \lambda}{\partial I}\right) \cdot \left(\frac{\partial I}{\partial t}\right)} f_{tone}$$

The typical modulation profile follows a triangular shape, and the distance measurement is derived by averaging the frequencies observed during both the ascending and descending phases of this triangular waveform. This averaging enhances accuracy and mitigates the impact of potential target movements. However, s exhibits linearity with f_tone solely under conditions of small modulation amplitude and low-frequency modulation. This is due to the factor (∂λ/∂I), which is not consistent with I and requires compensation.

We observed the instrument's standard deviation and non-linearity. To determine the absolute target distance, a linear combination of measurements from the modulating waves is utilized. Regression curves are calculated for the curve and the final distance results are obtained by averaging the measurements. Additionally, individual data points are discarded based on specific criteria to enhance accuracy. These criteria include low tone amplitude near the noise floor and inadequate amplitude of the second highest bin in the interpolated FFT, which can lead to errors in frequency estimation.

To assess accuracy, the absolute error of the mean distance is evaluated as the difference from the grating ruler measurement, serving as an estimation of the optical sensor's nonlinearity.

One key enhancement involves implementing pulse-width modulation (PWM) signal control to regulate the injection current of the laser diode. By utilizing PWM control, we can achieve a more precise and linear relationship between the injection current and the absolute distance being measured.

PWM control allows for the modulation of the average power delivered to the laser diode by rapidly switching the current on and off at a fixed frequency. By adjusting the duty cycle of the PWM signal, we can effectively control the average current supplied to the laser diode. This finer control over the current can help optimize the laser output and improve the linearity of the distance measurement.

By incorporating PWM signal control into the laser vibrometer design, we can achieve greater accuracy and stability in distance measurements. This enhancement will enable more reliable and precise vibration analysis, making the vibrometer even more suitable for a wide range of applications in research, industrial monitoring, and biomedical diagnostics. Additionally, it opens up opportunities for advanced signal processing techniques and further optimization of the measurement system for enhanced performance.

Applications

Laser Self-Mixing Interferometry (SMI) is a versatile technique with various applications across different fields. Here are some notable applications:

- **Vibration and Motion Sensing**: Laser SMI can detect small vibrations and motions in structures or objects. It finds applications in structural health monitoring, machine condition monitoring, and inertial navigation systems.
- **Displacement Measurement:** Laser SMI can be used for precise distance and displacement measurements. It offers high resolution and accuracy, making it suitable for applications such as industrial metrology, semiconductor manufacturing, and nanotechnology.
- **Surface Roughness and Topography Measurement:** By analyzing the interference patterns generated by the laser beam reflected from a surface, Laser SMI can characterize surface roughness and topography. This is useful in industries like automotive, aerospace, and materials science.
- **Biomedical Sensing:** Laser SMI has applications in biomedical sensing, such as measuring blood flow velocity, detecting microvibrations in tissues, and monitoring physiological parameters like pulse rate and respiration rate, where they are still in their infancy but may lead soon to important breakthroughs, an important event for all researchers interested in the field. In all the techniques described, the SMI configuration

demonstrates itself as particularly simple and low-cost, while supplying a high sensitivity of detection and fast response.

- **Quantum Optics and Quantum Interference:** At the quantum level, self-mixing interferometry exhibits fascinating phenomena rooted in quantum optics. Quantum interference effects, such as Hong-Ou-Mandel interference and photon antibunching, can manifest in self-mixing setups under certain conditions. Exploring the quantum aspects of interferometry opens up new avenues for ultra-sensitive measurements and quantum-enhanced sensing technologies.

Conclusion

In conclusion, our demonstration of a laser vibrometer utilizing the self-mixing effect in a laser diode represents a significant advancement in non-contact vibration measurement technology. Through the design, construction, and testing of the circuit, we have validated its effectiveness in accurately measuring vibrations, particularly in professional loudspeakers. Additionally, our exploration of a variant of the peak counting method for amplitude measurement enhances the versatility and applicability of the vibrometer.

The potential applications of this laser vibrometer are diverse and impactful, ranging from monitoring soft or lightweight structures to delicate biological objects like the tympanic membrane. Its intrinsic low cost, achieved through the use of simple off-the-shelf optical components and straightforward signal processing, makes it accessible for various research and industrial purposes.

Looking ahead, future endeavors will focus on further enhancing the technical characteristics of the prototype to increase its sensitivity and accuracy. By continuing to refine and optimize the design, we aim to unlock even greater potential for this laser vibrometer in a wide range of real-world applications.