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PHASE DETECTOR FOR LASER PHASE PERTURBATION DEMODULATION

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Abstract: *Laser interferometry is a powerful tool for vibration measurement. It makes it especially suited for measurement of small vibrations which would otherwise be interfered with by contact-based methods.This paper is devoted to the design and implementation of a phase detector for LASER phase perturbation demodulation. Based on self-mixing interferometry, the detector achieves vibrations measurements using the fringe counting method. The paper covers design of a LASER driver, a transimpedance amplifier and an output filter. With a bandwidth of over 200 kHz, the detector is designed to measure vibrations larger than half a wavelength of the lasing frequency. This translates to small vibrations as small as a few micrometers for a red LASER diode for example. In the later part of the report, the detector sub circuits are tested and analysed. The complete detector is however not tested for vibration measurements having failed to acquire the appropriate LASER diode in time. Nevertheless, the vibration testing procedure is presented and ways on automating and improving the sensitivity of the detector discussed.*

Keywords: *Phase detector; LASER, Perturbation Demodulation*

1. INTRODUCTION

Light reflecting off a vibrating surface experiences a change in its phase proportional to the vibrational changes. To recover the vibrations, the reflected signal is usually demodulated by interferometric means. Interferometry started with the first observation of interference by Thomas Young and invention of the first interferometer by Albert Michelson, both in the 19th century. Invention of the laser in the mid 20th century revolutionized interferometry with laser interferometers. Laser interferometers have been applied in vibrometry (vibration measurement), velocimetry (velocity measurement), mechanical metrology, space telemetry, optical fibre sensors among others [1]

The aim of this paper is to develop a phase detector for vibrometry or vibration measurement. The main advantage of LASER vibrometry is that it does not require contact with the vibrating body which makes it suitable for measurement of very small vibrations as well as vibrations in inaccessible areas.

Given a phase-perturbed LASER signal a detector is to be built with the intention of recovering the phase information and subsequently observing the small target vibrations. To generate the appropriate LASER signal, there is a need to reflect off a vibrating surface, then detect the signal and lastly reconstruct the target vibrations from the phase of the back-scattered signal.[2,3]

Phase demodulation in a LASER signal is made possible by the phenomenon of wave interference. Interference is observed when two monochromatic waves from coherent sources interact. Coherence means that the two sources have a constant phase difference between them. A light wave is monochromatic when it is composed of a single wavelength [4].

Wave interference is a simple case of wave superposition. When two or more coherent light waves interact, their amplitudes add or subtract depending on the phase difference between them. Wherever the waves are in phase their amplitudes add leading to constructive interference while the amplitudes cancel out at the points where they are out of phase leading to destructive interference . For any intermediate points, partial addition or subtraction takes occurs[5].

2. METHOLOLOGY

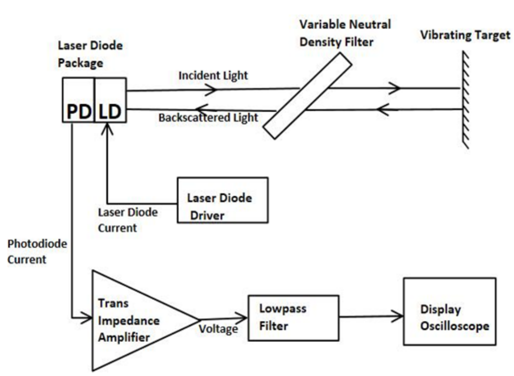
2.1 Choice of Implementation method

In this study, the requirements are clear on demodulation of the phase of the LASER signal, rather than of other LASER parameters such as amplitude, only interferometric methods were considered. Different types of interferometry are studied and evaluated according to two categories: external interferometry and the self-mixing interferometry. External interferometers (such as the Michelson, Twyman-Green and the Mach-Zehnder interferometers) are found to require a large optical equipment part count including beam splitters and Bragg cells, on top of separate LASER and photodiodes which made them bulky and part-count expensive. Moreover, they involve alignment in more than one direction, and hence more cumbersome to set up. On the other hand, a self-mixing interferometer has the following advantages:

1. No beam splitters, mirrors and Bragg cells are required, leading to a setup that is compact, simple and part-count-saving;
2. No extra photo detector is required as detection is done by a monitor photodiode within the LASER package
3. High sensitivity as it can measure vibrations to the order of half a wavelength of the beam (sub-nanometer lengths). Closed loop techniques can however be employed to increase sensitivity beyond half a wavelength.
4. It can successfully operate on rough diffusive surfaces

The biggest limitation of the self-mixing set up is the limited target distance as the LASER regime directly depends on the target distance. To maintain stability, the diode needs to be operated in moderate feedback regime. As a result, the ratio of the maximum to the minimum target distance becomes 4.6 in the absence of any light. However, varying the amount of light fed back (by use of a variable density filter for example), can increase the measurement range further.

The interferometer is thus chosen to be of the self-mixing architecture. To detect vibrations, the simple fringe counting method was adopted. This way, the self-mixing concept could be tested and with the resulting insight help in the design of an automated measurement of the target vibrations. The detector was designed as per the block diagram of Fig.1



Starting with the Fabry-Perot LASER diode package (with a monitor photodiode), a LASER diode driver was designed to provide a stable current to the LASER diode. The work of the variable neutral density filter was to vary the amount of light fed back into the diode to maintain the diode in the moderate feedback regime. The transimpedance amplifier was designed to convert the photodiode current into an amplified voltage with high voltage-to-current ratio and fast response time. A low pass filter was also added to limit the bandwidth of the observed self-mixing signal and in turn limit the system statistical noise.

This section describes the design procedure for the LASER phase detector. The design was split into modules as shown by the block diagram of the figure 9. For every module, description is made of the design considerations and how each consideration is met.
As shown in the block diagram of Fig 1, the overall design involved:

1. Choice of the LASER Diode
2. Design of the LASER diode driver
3. Design of the Trans Impedance Amplifier
4. Design of the output filter

2.2 Choice of the LASER diode

Any single longitudinal mode Fabry-Perot LASER diode with an inbuilt monitor photodiode can be used for self-mixing . Low power is desired to reduce the dangers that come with high power LASERs. Table 1 shows some of the LASER diodes that can be used for self-mixing interferometry. Design of the LASER driver in the next section was based on the Hitachi HL6724MG red LASER diode. However, being that the maximum drive current of the LASER driver is 50 mA, most of the other diodes can still be reliably driven as well.

Table 1. Some LASER diodes suitable for self-mixing interferometer

Laser Diode	Typical Wavelength	Output Power	Typical operating current
HL6724MG	670 nm	5 mW	35 mA
HL6314MG	635 nm	3 mW	30 mA
DL3149-057	670 nm	7 mW	40 mA
HL6722G	670 nm	5mW	32 mA

2.3 Design of the LASER Diode Driver

A LASER diode is basically a current controlled device that emits highly coherent and monochromatic light. However, the diode is very sensitive to current disturbances and can easily get damaged. The LASER driver is thus meant to ensure that:

1. The diode was protected from damage due to excessive transient and sustained currents

2. The LASER current was stable to reduce the noise frequency in the diode output

Different configurations were tested including the Howland current source and simple transistor based current sources. The set up shown in figure 9 was selected for its simple design and ease of control as a voltage controlled current source should feedback control for the LASER diode frequency be implemented. It has an equally stable output current as was determined through the square wave test. The set-up also has a low part count which keeps the cost of implementation low.

The schematic of the current source was as shown in Fig.2

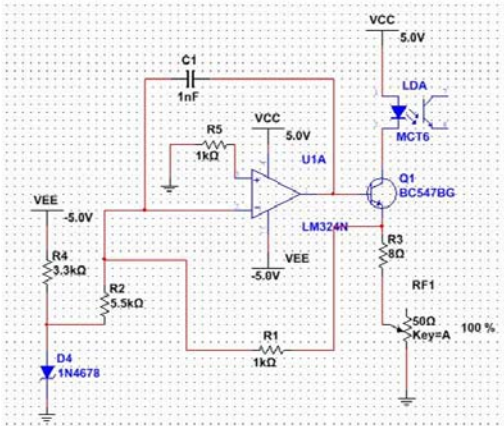


Figure 2. Circuit of the Laser Diode Current Source (Driver)

Resistor R3 acts as the limit resistor for the maximum current through the diode. To ensure this driver could work with all of the aforementioned diodes, a maximum drive current of 50 mA was chosen. A trimmer pot resistor P1 is added so that the current could be varied to suit the requirements of the particular diode. Together, potentiometer P1 and resistor R3 act as output current sensors. Capacitor C1 was to stabilize the output current by shunting out high frequency components and therefore eliminate ringing in the LASER diode current. The Zener diode D1 is used as a voltage reference while resistors R1 through R3 determined the output current per unit of reference voltage.

2.4 Design of the Trans Impedance Amplifier

The work of the trans-impedance amplifier is to convert the small photocurrent from the photodiode into an amplified voltage with minimal noise addition. The trans-impedance amplifier was thus designed with the following considerations:

1. Stability with regard to temperature and drift noise
2. Large volts/ampere conversion ratio
3. Fast speed of response.

The transimpedance amplifier set up is as shown in Fig 3

A fast speed of response was ensured by operating the photodiode in photoconductive mode achieved through reverse biasing the photodiode by 5 V. This bias condition is also chosen to simplify the design so that the common mode voltage appearing at the input of the transimpedance Op Amp was zero. Current from the photodiode sees a large impedance on the non-inverting input of the Op Amp, and is thus forced through resistor RF. Because the non-inverting input is at virtual ground, a negative voltage proportional to the current is registered at the Op Amp output.

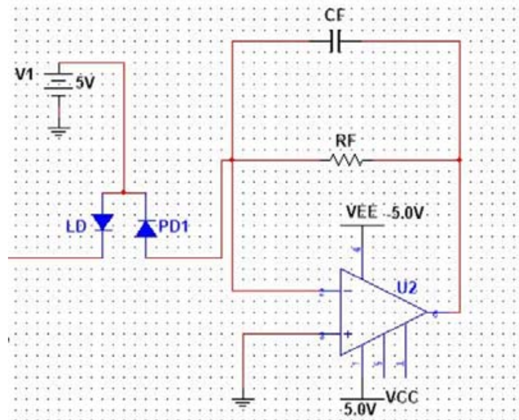


Figure 3: Circuit of the Transimpedance Amplifier

2.5 Design of the Low Pass Filter

Typical spectral responses of some silicon photodiodes are as shown in Fig 4. Sensitivity of a photodiode is significant in the visible light range with peak response in the infrared region (about 900 nm to 1000 nm). In figure 12, QE is the photodiode quantum efficiency, which is the number of electrons or holes that can contribute to the photodiode current as a fraction of the number of incident photons.

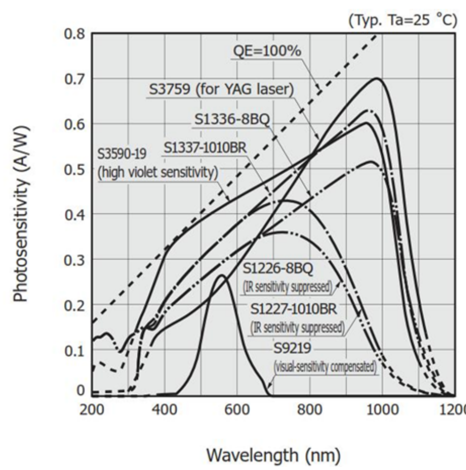


Figure 4. Spectral Response of Various Silicon Photodiodes

As a result, it is anticipated that there would be noise especially from the ambient light from the sun (which is essentially DC), and from the electrical lighting (50 Hz). The DC noise is easy to eliminate with a coupling capacitor. However, a high pass filter to limit the electrical lighting frequencies was not designed as significant vibrations occur at these low frequencies to have them filtered out. Instead, noise at such frequencies could be minimized by modulating the LASER diode current by closed loop (feedback) means, which would be appropriately designed once the detector was tested and its behavior characterized.

A fourth order low pass filter was designed to limit the bandwidth of measurement. This was necessary so as to limit the system statistical noise such as shot and

Johnson noise in the output of the detector. A fourth order filter was chosen because of its better attenuation in the stopband (-80 dB per decade) as compared to lower order filters. The filter was designed as Bessel type filter to ensure a maximally flat response in the passband. Moreover, the Sallen-Key topology was selected for its simplicity. A 3 dB cut-off frequency for the low pass filter was set at 250 kHz to just cater for the bandwidth of the transimpedance of the amplifier. The filter is designed as a cascade of two second order Sallen-Key filters as shown in Fig 5.

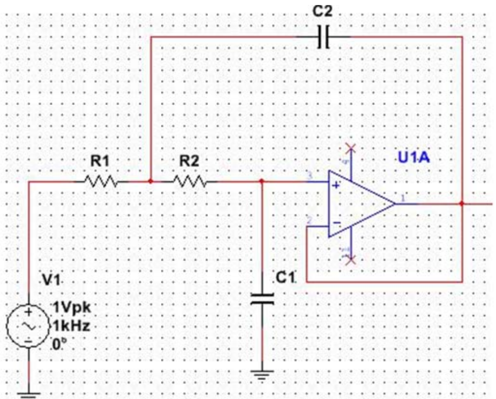


Figure 5. Second order Sallen-Key topology

3. IMPLEMENTATION AND TESTING

The complete designed circuit is built on a printed circuit board of dimensions 8.5 cm × 6.7 cm using the Eagle PCB software. The schematic and board layout of the complete detector are as shown in figures 6 and 7 respectively.

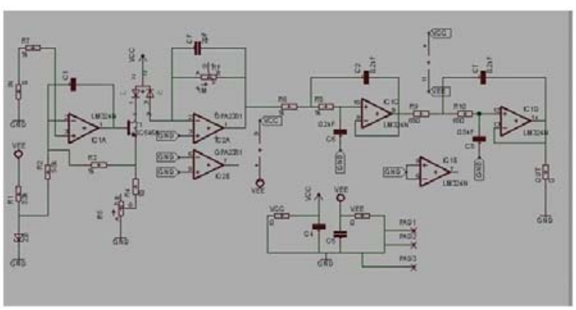


Figure.6 Schematic capture of the complete detector

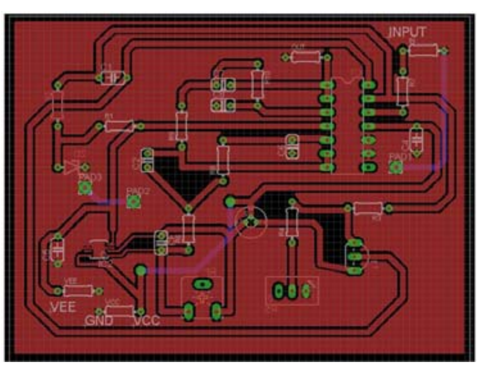


Figure.7 Board Layout of the Phase detector

3.1. Testing of the Complete Detector

In the event of testing, the following procedure is followed. The set up for testing of the detector is shown in Fig.8. The sound speaker is driven by a function generator as shown. A resistance of 8.2 Ω is incorporated to match the output impedance of the generator and that of an 8 Ω speaker, eliminating reflections in the speaker sub circuit. The vibrating speaker causes vibrations on the target surface which are picked up by the detector. The detector's output is then observed on the oscilloscope. The target distance from the LASER diode is varied to determine the range within which the diode interferometric signal is stable. A variable neutral density filter is then placed between the target and the LASER diode and varied to determine the increase in the stable target range.

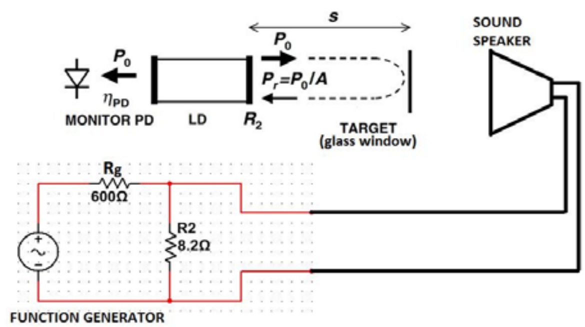


Figure 8. Phase detector testing set up

3.2. Testing of the LASER driver

The LASER driver is tested through simulation and by building its circuit on the Breadboard. The testing is set up as shown in Fig.9. With the signal generator V1 set to 0 V, the emitter voltage of transistor Q1 is read on a multimeter as the 50 Ω trimmer is varied from maximum to minimum. The emitter voltage remained constant at 0.39 V even as the trimmer resistance is varied.

A square wave test is then performed on the LASER driver. The signal generator was set to a square wave amplitude of 65 mV. The driver current output was observed on the oscilloscope as the voltage drop across the 8Ω resistor R3 and the trimmer RF1. The input voltage and output current waveforms are shown in Fig. 10.

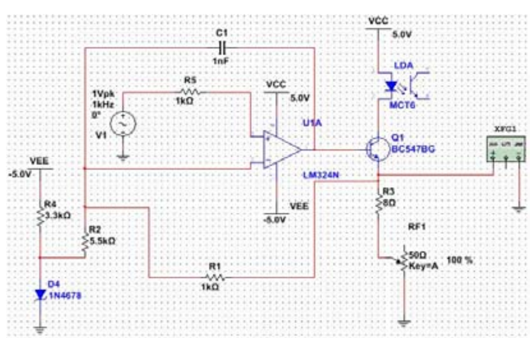


Figure 9. Testing circuit of the LASER driver

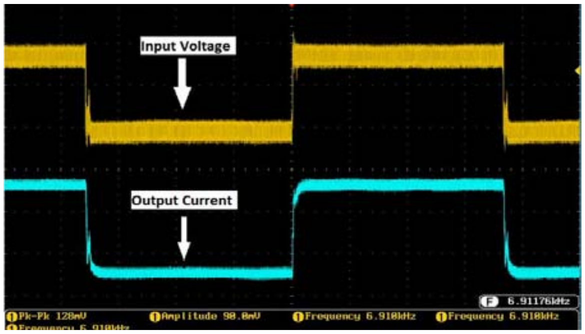


Figure 10. Input Voltage and Output Current Waveforms

The output current waveform in Fig.10 shows no ringing or oscillations. Instead, the smoothing at the voltage transitions shows that very high frequency components are filtered out. Again, the rise time of the output current waveform is less than a microsecond, showing that the LASER driver can handle feedback signals of over 1 MHz. Being that the bandwidth of the system is 250 kHz, the LASER driver has enough bandwidth for the design of a feedback controller based on the detector output.

3.3. Testing of the Transimpedance Amplifier

The testing of the transimpedance amplifier requires a small current comparable to the small current expected from the LASER package monitor diode. Testing of the amplifier was accomplished through simulation. A hardware testing could not be accomplished without the LASER diode. The simulation set up is as shown in Fig.11

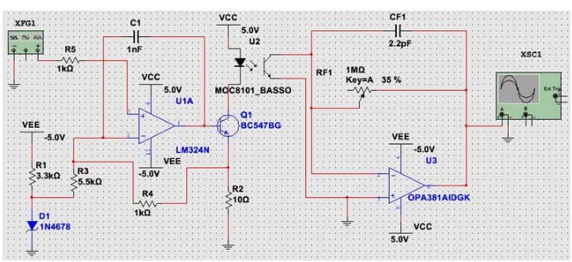


Figure 11. Multisim simulation set up for the transimpedance amplifier

A sinusoidal signal of 5 mV amplitude is input on the non-inverting input of the LASER driver op amp through the signal generator XFG1. The MOC8101 optocoupler is used to simulate the LASER and photodiode package system. A voltage waveform output of 23 mV amplitude is observed on the oscilloscope at the output of the transimpedance amplifier. The output as shown in Fig.12 confirmed that the transimpedance amplifier stable.

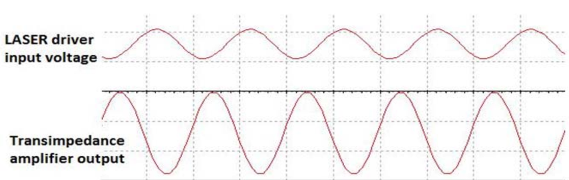


Figure 12. Transimpedance amplifier output waveform

3.4. Testing of the Lowpass Filter

The fourth order Sallen-Key Bessel filter is implemented and tested by building it on the Breadboard and its frequency response determined. Frequency response of the filter is determined by feeding 40 mV at its input and the output voltage is recorded for frequencies from 100 Hz to 600 kHz as shown in table 2. The frequency response is plotted as shown in Fig 13. The filter has a bandwidth of about 200 kHz.

Table 2. Frequency response data for the lowpass filter

Frequency (kHz)	0.1	0.5	1	2	30	65	96
Output Voltage (mV)	40	40	40	40	40	39	38
Frequency (kHz)	156	206	225	300	400	627	
Output Voltage (mV)	36	30	26	22	16	8	

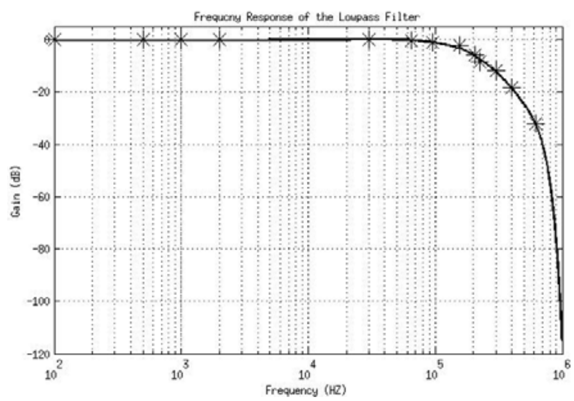


Figure 13. Frequency Response of the lowpass filter

4. DISCUSSION

A 200 kHz bandwidth LASER phase perturbation demodulator was designed and built. The detector was based on self-mixing interferometry and achieved phase demodulation by the fringe counting method. Its component circuits namely the LASER driver, the transimpedance amplifier and the output lowpass filter were tested and verified to meet their design specifications. Although a single longitudinal mode LASER diode appropriate for self-mixing could not be acquired in time to test the detector for its phase demodulation characteristics, the testing procedure was presented.

The detector is still far from automated, requiring manual counting to convert fringes into the equivalent vibration amplitude and frequency. Moreover, its sensitivity is based on the lasing wavelength and can only be used for measurement of vibration amplitudes greater than half the lasing wavelength.

5. CONCLUSION

The main objective of the paper was to build a phase detector for demodulation of the LASER signal phase perturbations and use the phase detector to observe small vibrations on a glass window. Theoretical background was developed and the detector designed and implemented. The detector is however not a finished product. Instead, it forms the basis upon which more control and automation of the phase demodulation mechanism can be built. The use of a self-mixing interferometer which is suited for closed loop feedback control further adds to the reasons to not only fully test this detector but also improve upon it.

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