A Massively Parallel Imaging System Based on the Self-Mixing Effect in a Vertical-Cavity Surface-Emitting Laser Array

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***Abstract*— In this work we propose a massively parallel self-mixing imaging system, based on an array of VCSELs, to measure surface profiles of displacement, distance, velocity and liquid flow rate. The feasibility of this concept is demonstrated by the successful operation of a small scale prototype consisting of eight individual commercial VCSELs with integrated photodetectors. The system is used to accurately measure the velocity at different radial points on a rotating disk. The results show no influence of crosstalk. A massive version of the system will be useful in many industrial and biomedical applications where real-time surface profiling, vibrometry and velocimetry will be very beneficial.**

***Index Terms*—optical feedback, parallel imaging, self-mixing, vertical-cavity surface-emitting laser**

I. INTRODUCTION

THE behavior of a semiconductor laser diode with external optical feedback is a complex but well researched phenomenon [1], [2]. It is often seen as a hindrance in many applications since it can increase the intensity noise of the laser [3], but it is also the enabling process behind many applications [4], [5].

The optical feedback is a result of the laser beam being partially reflected from an object back into the laser cavity. The reflected light interferes or 'mixes' with the light inside the laser cavity and produces variations to the operating frequency and output power of the laser. This process is commonly referred to as the 'self-mixing' effect and the resulting output power variations can be monitored as photocurrent fluctuations of the photodiode integrated with the laser package or by the change in the junction voltage across the laser diode [6]. This phenomenon allows the laser to be used as both a source and detector and significantly reduces the cost and complexity of the interferometric sensing system. The self-mixing phenomenon has been used for many constructive purposes that include linewidth reduction [7], measurement of target displacement [8], distance [9], velocity [10], angle [11] and liquid flow rate [12], [13]. It has also recently found application in measurements of the laser linewidth [14] and laser linewidth enhancement factor [15]. The self-mixing effect has also been used to create 3D surface profiles of an object. Most of these demonstrations have employed scanning techniques where the laser beam is mechanically shifted across the surface of the object [16]-[21].

However, there are surprisingly few reports on parallel imaging systems using the self-mixing effect. The advantages of parallel detection over scanning methods are well known: higher frame rates or a higher signal-to-noise ratio (SNR). So far, only a rudimentary parallel self-mixing imaging system has been constructed with three individual commercial semiconductor lasers to measure the speed and distance of different parts of a rotating disk [22], [23]. While the number of points in the image can be increased by using an array of lasers and detectors, preceding technology has hampered the development of a massively parallel self-mixing imaging system.

With the advent of Vertical-Cavity Surface-Emitting Lasers (VCSELs) it is now possible to cost effectively manufacture a two-dimensional monolithic array of lasers. In this article, we propose a massively parallel self-mixing imaging system based on an array of VCSELs. We demonstrate, for the first time, the feasibility and the advantages of the system by the successful operation of a small scale prototype consisting of eight individual commercial TO-46 packaged VCSELs with integrated photodetectors. The prototype is used to accurately measure the velocity profile of a rotating disk with no indication of crosstalk between neighbouring channels. The proposed system will be useful in many industrial, biomedical and micro fluidic applications where real-time surface profiling and velocimetry will be very beneficial.

The paper is organized as follows: Sec. 2 describes how target velocity can be measured with the self-mixing effect. In Sec. 3 we describe in detail the proposed massively parallel imaging system. The feasibility of the system is demonstrated with the experimental setup described in Sec. 4 with the results presented in Sec. 5. Finally, a short discussion of the

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experimental results and the future work planned for a massive version of the system is presented in Sec. 6 and conclusions are drawn in Sec. 7.

II. SELF-MIXING THEORY

The self-mixing effect occurs when the light emitted from a laser reflects from a target and is injected back into the laser. To measure the velocity of a target, the output power waveform can be considered to be the result of coherent mixing inside the laser cavity of the lasing field and the Doppler-shifted light back-scattered from the target. For the self-mixing configuration, the frequency shift of the incident light due to the Doppler effect is given by [12],

$$f_{\text{Doppler}} = \frac{2v_{\text{target}} n \cos\theta}{\lambda} \tag{1}$$

where, v_{target} is the magnitude of the target velocity, n is the refractive index of the surrounding medium, θ is the angle the target makes with respect to the longitudinal axis of the laser and λ is the wavelength of the laser.

The superposition of two waves of different frequency leads to a waveform with a beat frequency that is equal to the difference between the two frequencies. Therefore, the output power of the laser varies periodically in time at a rate that is equal to the Doppler frequency calculated using Eq. (1). However, the Doppler signal from a rotating target is randomly amplitude modulated by speckle effects, since the part of the rotating target that is illuminated by the laser light continuously changes [24]. This makes it difficult to employ peak counting techniques to determine the Doppler frequency. However, the beat frequency of the output power waveform can be easily determined by detecting the peak frequency in the fast Fourier transform (FFT) spectrum, which is linearly proportional to the velocity of the target as will be shown later in this paper.

III. PROPOSED IMAGING SYSTEM

The previous section shows how the self-mixing effect can be used to take a measurement from a single point on an object. This can be extended to acquire an image of the surface profile by mechanically scanning the laser beam across different points of the object. However, the acquisition time for each pixel in the image must be long enough to achieve the desired SNR, which is directly proportional to the acquisition time for a shot-noise limited detection scheme. If a large number of pixels are required for the image then the scanning operation precludes real-time image acquisition and measurement of rapid variations in the surface profile of the object.

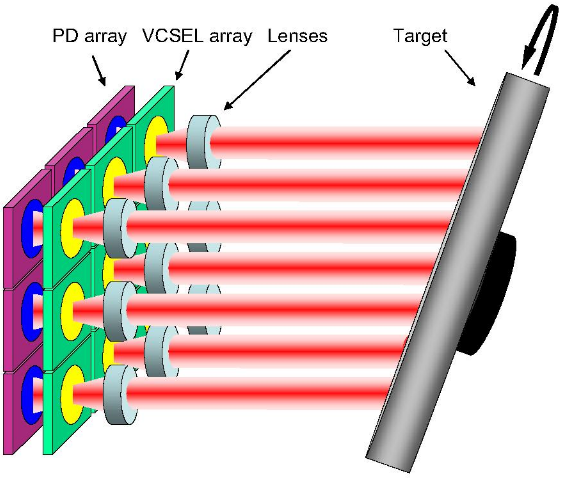

Fig. 1. Illustration of the proposed imaging system

This limitation can be overcome with the use of ‘full-field’ or ‘parallel’ imaging techniques. In these systems, the whole measurement area is illuminated and scattered light is detected with an array of photodetectors. This allows measurements to be taken from a number of different points simultaneously and reduces the image acquisition time.

Another important advantage of parallel detection is a higher SNR. Given that many applications require the image to be captured within a certain time frame then parallel detection will give a higher SNR. This is a result of a longer allowable acquisition time for each pixel in the image compared to the scanning operation.

In this paper, we propose a massively parallel self-mixing imaging system based on an array of VCSELs. A diagram of the proposed imaging system is shown in Fig. 1. This system is more compact and robust compared to other parallel imaging systems since each VCSEL is used as both a source and detector. This will be extremely useful in obtrusive and remote environments that are commonly encountered in many industrial and biomedical applications where the measurement of the surface profile at real-time frame rates will be beneficial and provide vital diagnostic information.

IV. EXPERIMENTAL SETUP

To demonstrate the viability of the imaging system proposed in Sec. 3 we constructed a small scale prototype using eight individual TO-46 packaged single mode Lasermate VCT-F85A32-OS VCSELs with integrated photodetectors arranged in a linear array. The VCSELs were mounted in a custom made aluminium block with a pitch of 5.8 mm. A separate block was constructed to mount eight plastic aspheric Konika T544C DVD objective lenses at the same pitch as that of the VCSELs. The lens block was attached to the VCSEL block so that the lenses were aligned with the VCSELs in all directions except the longitudinal and lateral axes. The VCSEL block was also attached to a translation stage to align the VCSEL beams in the longitudinal and lateral directions. This setup was then used to measure the velocity profile of a rotating disk.

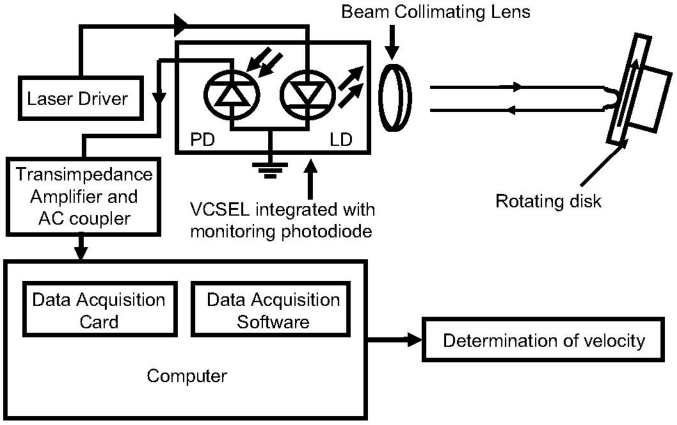

Fig. 2. Block diagram for a single channel of the experimental setup

A block diagram for a single channel of the imaging system is shown in Fig. 2. Each VCSEL has an individual driver circuit so that the current injected into each laser can be individually controlled. The backscattered light from the target is collected by the collimating lenses and mixed with the light inside the corresponding VCSEL cavities. The resultant fluctuations in the output power are detected by the integrated photodiodes, followed by a transimpedance amplifier and AC-coupler circuit for each channel to produce a high contrast self-mixing signal for each measurement point. The output of each channel is sampled simultaneously by a National Instruments 16-bit data acquisition card and sent to a PC for processing and display in LabView.

LabView was also used to perform additional signal conditioning to the frequency domain signals including the use of a 7-term Blackmann-Harris window. The frequency spectrum for each channel was averaged 50 times and subsequently saved into a text file. A total of 50 averaged frequency spectra were recorded for further processing in Matlab to calculate the velocity measured at different points on the rotating disk. The velocities for the rotating disk were calculated using the peak frequency of the signal in the FFT spectrum and Eq. (1).

V. EXPERIMENTAL RESULTS

In the experiment we measured the velocity at different radial distances on the surface of a rotating disk. Each VCSEL is operated at the same bias current of 3.5 mA with the disk 60 mm away and the surface tilted at an angle of 79 degrees with respect to the optical axes of the VCSELs. The beams were aligned so that there were four beams on each half of the surface of the disk. The FFT spectrum for a single point on the disk rotating at different speeds is shown in Fig. 3. Ignoring the strong peak at zero due to the DC offset of the signal, the peak frequency in the spectrum increases as the speed of the disk increases. By blocking the light from different channels we also observed that there was no change in the FFT spectrum, which indicates that there was no noticeable crosstalk.

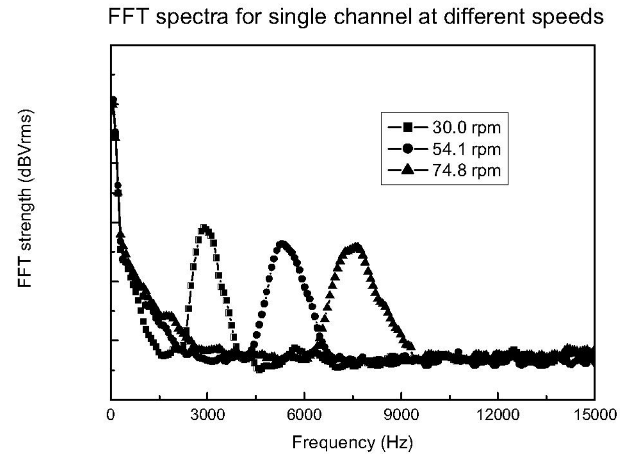

Fig. 3. Output power frequency spectra for a single channel at different disk speeds

The results in Fig. 4 show the actual velocity versus the measured velocity while Fig. 5 shows the accuracy of the measurement for different radial points of the disk. In these diagrams the negative sign for the radial distance indicates that the laser beam is from one half of the disk while a positive sign indicates the velocity is measured on the other half of the disk. The velocity at the centre of the disk was not measured but the theoretical value of zero has been included to illustrate the correct velocity profile of the disk. From this we can see that the measured profile corresponds closely to the calculated velocity profile of the rotating disk and a high level of accuracy is obtained. We also include the results obtained for individual operation of each channel in these diagrams, which show that there is no noticeable change due to crosstalk.

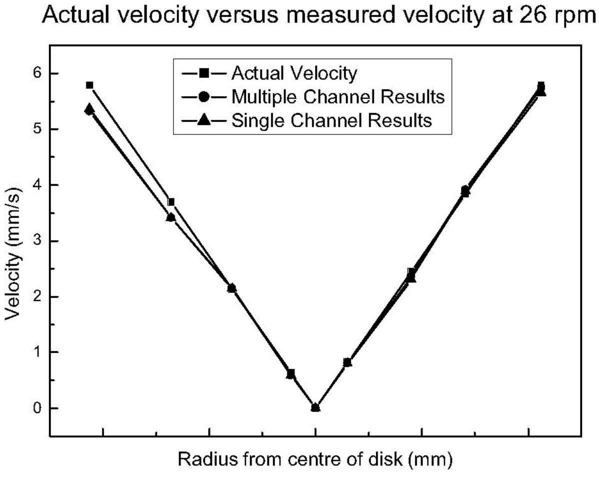

Fig. 4. Actual versus measured velocity profile for rotating disk

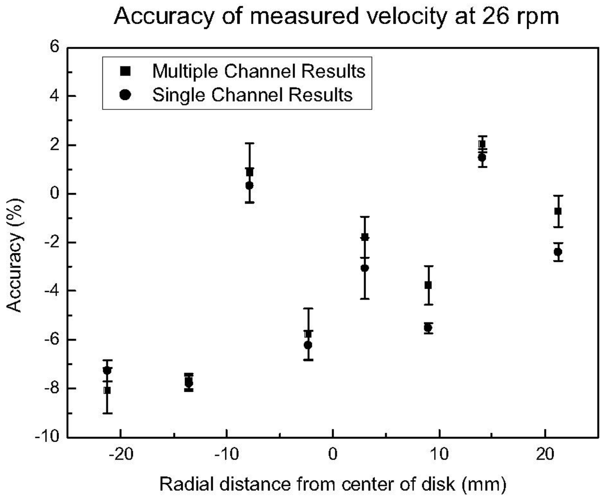

Fig. 5. Accuracy of velocity for different channels for rotating disk

VI. DISCUSSION AND FUTURE WORK

While the results from the small scale prototype demonstrate the usefulness of the proposed imaging system there are a number of issues which should be considered for the construction of a massive version of the system. Firstly, the diameters of the TO-46 packages used in the experimental setup are 5.4 mm, which makes the size of the optical system very large. However, this issue will be of less importance with a monolithically integrated VCSEL array since the spacing between the devices is typically 250 μm.

Another issue that will require further experimental investigation with the monolithically integrated VCSEL array is the effect of optical crosstalk between the channels. While some of the earlier self-mixing papers dismiss the possibility of interference between the channels due to coherent nature of the detection scheme [23], [25] there is a weight of evidence that injection locking in VCSELs can occur even for injection levels as low as 10^{-3} of the affected (slave) VCSEL power [26]-[28]. The frequency detuning under which locking has been observed is typically limited to a range between 2 GHz and 90 GHz and depends on the injected signal level [28], [29]. As the locking occurs only for very limited range of phase differences and wavelength detuning, requires mode and waist size matching and particular polarization conditions [30]-[33], further study is needed to make any predictions related to the immunity of this sensing scheme to inter channel crosstalk and the feedback levels at which it may occur. The issue could not be addressed with the experimental setup used in this work due to the large spacing between the TO-46 packaged VCSELs. Also, the potential effects of optical crosstalk with the integrated VCSEL array can be minimized by an optimized design of the optical system using an array of micro lenses. Similar approach has been successfully implemented earlier for minimizing the crosstalk between channels in VCSEL based free-space optical-interconnects [34], [35].

Although it is possible to integrate a photodetector with a VCSEL there is only one report of such a device fabricated in an array form [36]. Instead, the photodetector array can be discarded by monitoring the self-mixing signal with the change in junction voltage of each element in a VCSEL array. This makes a voltage based VCSEL array self-mixing imaging system very attractive as it reduces the component size and cost and eliminates any misalignment or back reflections from the photodiode array.

There are also other important issues which will have an impact on the overall performance of the system including signal processing and the design of the electronic circuit layout. In most small scale systems a single processor is used to analyze the signals from all channels. However, with a large number of channels the number of operations per second required for real time frame rates can become extremely large.

To counter this problem a number of parallel processors can be implemented with electronic circuits, although this would come at the expense of an increased circuit size and complex layout. However, the physical size of the circuit and layout can be reduced with the use of Very Large Scale Integration (VLSI) or Ultra Large Scale Integration (ULSI) technology.

An alternative solution to reduce the circuit size is to employ multiplexing in the system so that only a small number of channels are read in at the same time. This would not only reduce the circuit size, since fewer drivers and receivers would be needed, but would also reduce the signal processing requirements and minimize the thermal problems within the system. However, this method is another form of scanning. Instead of the laser beam being mechanically guided towards different parts of the object it is electrically guided by the switching circuit or multiplexing operation. The maximum frame rate and SNR will be reduced compared to a massively parallel system but will still be greater than that achievable with single point scanning. Although multiplexing will reduce the overall size of the circuit it is desirable to have individual driving, receiving and processing circuits for each channel to obtain the maximum frame rate and SNR for the imaging system.

VII. CONCLUSIONS

In this paper we have proposed a massively parallel imaging system using the self-mixing effect in an array of VCSELs. The system can be used to accurately monitor rapid variations in the surface profiles of displacement, distance, velocity and liquid flow rate. The feasibility of the system was demonstrated by a small scale prototype, which accurately measured the velocity profiles of a rotating disk. Potential problems in the construction and performance of a massive version of the system have been discussed and adequately addressed. The proposed imaging system presented in this paper will be very useful in many industrial and biomedical applications where real-time surface profiling, vibrometry and velocimetry will be very beneficial and provide vital diagnostic information.

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