The Effect of Multiple Transverse Modes in Self-Mixing Sensors Based on Vertical-Cavity Surface-Emitting Lasers

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***Abstract* — In this work we investigate the effect of multiple transverse modes, such as those found in Vertical-Cavity Surface-Emitting Lasers, in self-mixing sensors. We show that the sensitivity of the system and the accuracy of the measurement changes periodically with target distance.**

Keywords - self-mixing; VCSEL; multiple transverse modes; optical feedback; backscatter modulation

I. INTRODUCTION

External optical feedback in semiconductor lasers has been studied by many researchers [1-3]. In many cases this feedback is undesirable [4] as it can increase the intensity noise of the laser. However, this feedback has also been used for many constructive purposes including measurement of displacement, distance and velocity [5], target angle [6], 3-dimensional object imaging [7, 8]; applications in optical microscopy [9], various medical applications [10, 11], laser line width [12] and laser line width enhancement factor [13] measurements.

These measurements are based on the self-mixing interference which takes place inside a laser diode and the assumption that there is only a single longitudinal mode in the laser cavity. To account for the presence of multiple longitudinal modes in in-plane lasers other researchers have assumed that the modes only interfere with themselves and add together in power [14, 15]. The optical power is maximum at external cavity lengths where all modes have the same round trip phase shifts which corresponds to an integer multiple of the effective laser cavity length, *nL*.

In this work we analyse the influence of multiple transverse modes on the accuracy and sensitivity of a self-mixing sensor based on a Vertical-Cavity Surface-Emitting Laser (VCSEL). We show that the modes add constructively in power at target distances where the modes have the same round-trip phase shift in the external cavity. Experimental results confirm that the sensitivity of the self-mixing system exhibits periodic variations with target distance and that multimode operation can affect the accuracy of the measurement.

II. SELF-MIXING THEORY

The self-mixing effect occurs when the light emitted from a laser is reflected back from the target into the laser cavity. The light emitted from the laser has a controllable frequency and phase so the reflected light will add constructively or destructively with the light inside the laser cavity depending on the position of the target. The phase shift introduced by the round trip travel to and from the target effectively causes a phase change in the reflectivity of the laser mirror and produces changes to the output frequency, the line width, the threshold gain and the output power of the laser. In practice, the output of the laser is measured in terms of its optical power and has a sinusoidal relationship with target distance as indicated in the equation below [7]

$$P = \eta\left(I_{op} + \frac{\kappa_{ext} q V}{L T_s a \Gamma} \cos(2\pi \nu \tau_{ext}) - I_{th} \right). \quad (1)$$

III. EFFECT OF MULTIPLE LASING MODES

The theory in the previous section assumes that there is only a single longitudinal mode in the laser cavity. However, other researchers have shown how the presence of additional longitudinal modes can affect the operation of the laser with feedback [14, 15]. The modes are assumed to be independent of each other and interfere only with themselves and there is no mode competition. The total output power of the laser is determined by the incoherent superposition of the power variations for each mode wavelength.

The total output power will be at a maximum when the powers of each mode are simultaneously at a maximum. The emission frequency of each longitudinal mode with feedback at these points is assumed to be a resonant frequency of the laser cavity which is equal to an integer multiple of the effective cavity length, *nL*. This means that the maximum power will occur simultaneously for adjacent longitudinal modes at integral multiples of the effective cavity length, *nL*.

In this paper we investigate the effect of multiple transverse modes such as those found in Vertical-Cavity Surface-Emitting Lasers (VCSELs). Due to the very short cavity in this type of laser there is always only one longitudinal mode present in the emission spectrum but there can be several coexisting transverse modes. We still assume that the modes interfere only with themselves and exhibit no mode competition. This leads to periodic maxima and minima of the output power that are not dependent on the effective laser cavity length. Instead, we show that the output power is periodic with target distance where the round trip phase shifts of the two mode wavelengths without feedback are both equal.

When the round trip phase shifts of both modes are an integer multiple of 2π then the output power is periodic at distances equal to half the lowest common multiple (LCM) of the mode wavelengths. When the round trip phase shifts are a similar fractions of 2π, but not an integer multiple, then the output power is periodic at distances equal to the lowest common fraction (LCF) of the mode wavelengths.

IV. Application To Self-Mixing Measurements

To illustrate the effect of multiple transverse modes we performed a simulation of the output power for two different transverse modes with equal intensity over a wide range of target distances. The results in Fig. 1 show the simulation for two typical transverse modes of a VCSEL at wavelengths 875 nm and 874.5 nm. With these two wavelengths we obtain a LCM of 1.530375mm.

Fig. 1 shows the results for targets a few wavelengths around 100 times the LCM of the two modes while Fig. 2 shows the results for targets a few wavelengths around 100.25 times the LCM. In Fig. 1 we can see that the two modes are in phase and produce maximum modulation of the total output power while in Fig. 2 we can see that the modes are out of phase and produce almost no output power modulation. These results can be shown to be periodic with the LCM as predicted in the theory in the previous section.

With single mode operation, the output power is periodic and peak counting methods can be used to determine the displacement of a target with a resolution of half a wavelength. From the results in Fig. 2 we can see that with multimode operation there can be more than one peak within half a wavelength of target displacement which leads to errors in the accuracy of the measurement.

We can also see the effect of the multimode operation on a self-mixing sensor by measuring the distance to a target. In this case, the frequency of the laser is modulated to produce a multiple number of resonant modes with phase differences of 2π. The distance is proportional to the frequency separation between successive resonant modes. The resulting output power is a triangle wave with small steps that correspond to the resonant modes in the cavity. These power fluctuations can be made more distinct by differentiating the power waveform to produce a series of sharp peaks that are spaced at a frequency that is proportional to the distance.

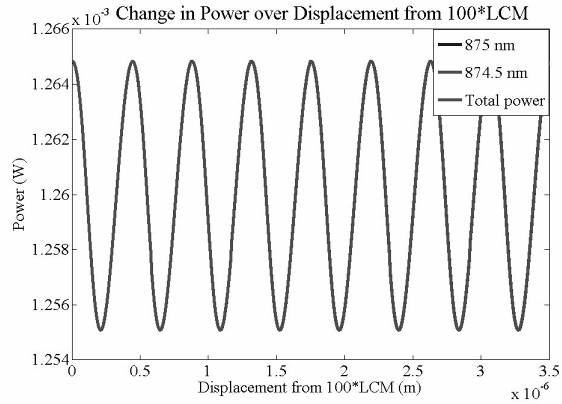

Figure 1. Output power versus displacement from 100*LCM

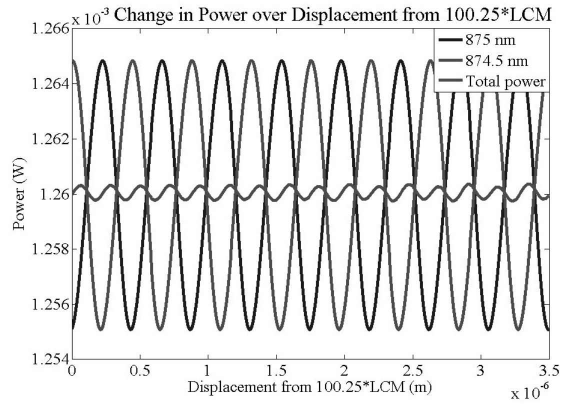

Figure 2. Output power versus displacement from 100.25*LCM

A simulation was performed with the same two transverse modes used in the displacement simulations at different target distances. In this simulation we assumed that the modes have an equal intensity with the 875 nm mode having a frequency modulation coefficient of 10 GHz/mA and the 874.5 nm mode having a frequency modulation coefficient of 11 GHz/mA. Fig. 3 shows the differentiated output power waveform for a target at a distance that is 100 times the LCM of the two transverse mode wavelengths while Fig. 4 is the same waveform for a target at 100.25 times the LCM.

These simulations tell us that the maximum of the resulting envelope occurs in the middle of the waveform with the peaks if the target is at an integer multiple of half the LCM of the two wavelengths. Similarly, the minimum of the envelope occurs in the middle of the wave at distances halfway between the maximum points.

The period of the envelope is proportional to the difference between the frequency modulation coefficients of the two modes and the length of the frequency sweep induced by the frequency modulation. The modulation depth of the envelope can also be shown to be dependent on the mode suppression ratio and the shape can become more complicated when there are more than two modes.

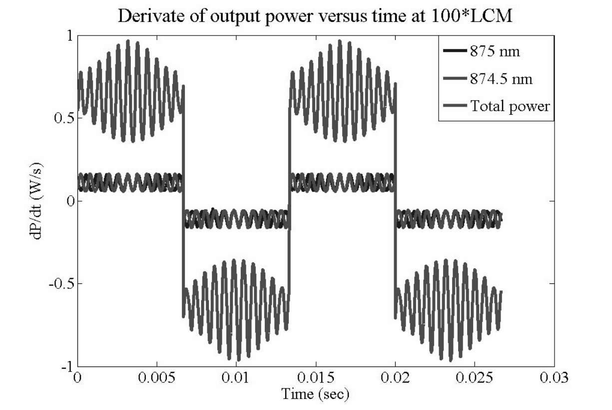

Figure 3. Derivative of output power versus time at 100*LCM

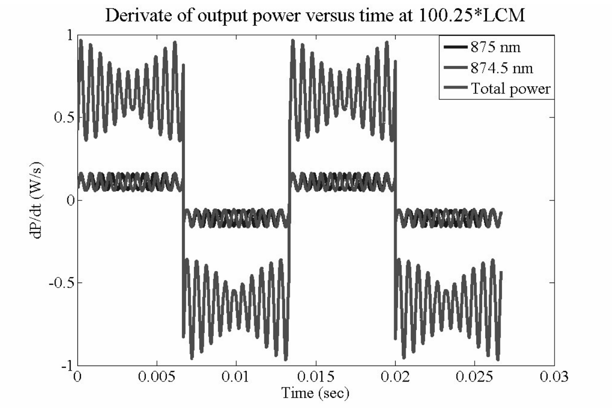

Figure 4. Derivative of output power versus time at 100.25*LCM

The distance to the target can still be accurately determined in this case. For the superposition of two waves of slightly different frequency we obtain two peaks in the FFT spectrum separated by the difference in the frequencies of the two waves. The peaks in the FFT spectrum represent the frequencies of the peaks in the differentiated waveform for each mode which can be used to find the distance to the target.

As the length of the frequency sweep becomes very small or the difference between the frequency modulation coefficients approaches zero the two modes have the same peak frequencies and there is no envelope in the differentiated waveform. Instead, the peaks of the two modes add constructively or destructively at different target distances. This leads to the amplitude of the peaks in the total differentiated waveform, which are an indication of the sensitivity of the system, to be periodic with target distance at half the LCM of the two mode wavelengths. There are also target distances where there are extra peaks in the differentiated waveform which also results in errors in the accuracy of the measurement.

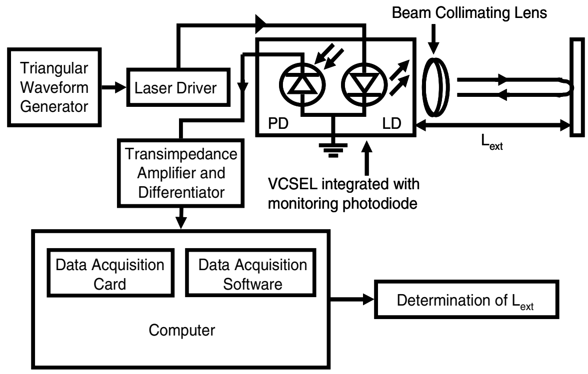

Figure 5. Block diagram of experimental setup

V. Experimental Setup

To verify the theory and simulation results presented in the previous sections we used a single mode VCT-F85A42-S VCSEL and a multi mode VCT-F85A42 VCSEL, sold by Lasermate, in a self-mixing system to measure the distance to a target.

A block diagram of the system is shown in Fig. 5. A waveform generator is used to supply a triangle waveform voltage. This signal is sent to the laser driver circuit which modulates the current of the laser. The desired VCSEL is placed in a mount which is fixed to an optical rail and a lens is used to collimate the beam. The target is made from a circular piece of sandblasted aluminum and mounted on an adjustable XYZ platform. The light from the laser is reflected back from the target into the laser cavity where the internal monitor photodiode is used to detect the fluctuations in the power of the light. The photocurrent is then converted into a voltage with a transimpedance amplifier and used by a differentiator circuit to obtain the waveform with the sharp peaks. The output of the differentiator is sampled with a National Instruments 12-bit data acquisition card in a PC. LabView was then used to view the time domain signal of the differentiated waveform which can be processed to calculate the distance to the target.

VI. Results

The results in Fig. 6 and Fig. 7 illustrate the response of the system at different target distances with the single mode VCSEL. Here we can see that the heights of each peak in the waveform are approximately the same and the shape of the waveform does not vary with distance.

The results in Fig. 8 and Fig. 9 show the effect of the multiple transverse modes with the multimode VCSEL at different target distances. Here we can see that the height of the peaks in the differentiated waveforms vary due to the different frequency modulation coefficients of the two transverse modes of the VCSEL. The maximum and minimum points in the envelope of the differentiated waveform vary with target distance with a periodicity of approximately 1.25 mm which corresponds to a LCM or LCF of 2.5 mm.

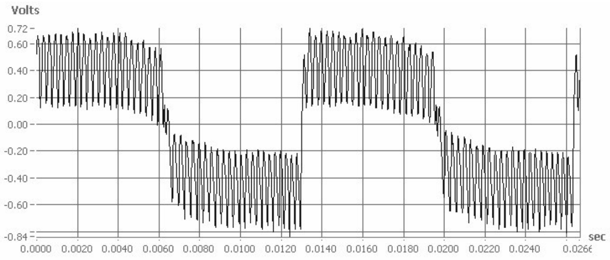

Figure 6. Derivative of output power with single mode VCSEL at 19.87cm

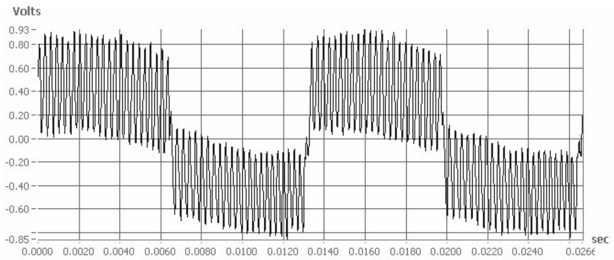

Figure 7. Derivative of output power with single mode VCSEL at 20.02cm

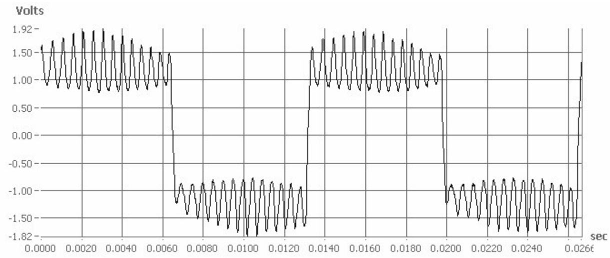

Figure 8. Derivative of output power with multimode VCSEL at 19.87cm

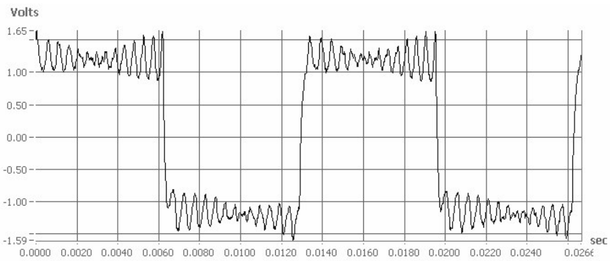

Figure 9. Derivative of output power with multimode VCSEL at 19.995cm

VII. CONCLUSIONS

In this paper we have investigated the effect of multiple transverse modes, such as those found in a VCSEL, on the accuracy and sensitivity of a self-mixing sensor. We have shown that the output power of the VCSEL is at a maximum when the transverse modes have the same round trip phase shift in the external cavity, which is equivalent to half the LCM or LCF of the mode wavelengths. For displacement measurements this results in periodic accuracy and sensitivity. The distance to the target can still be accurately determined but the sensitivity and accuracy of the system become periodic as the envelope in the resulting signal disappears. These results tend to suggest that multimode VCSELs should not be used as self-mixing sensors but the resulting problems can be minimized if the mode suppression ratio is adequate or the modes can be independently monitored.

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