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# Improving the Performance in an Optical feedback Self-mixing Interferometry System using Digital Signal Pre-processing

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## **Abstract**

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filter, signal processing, optical feedback self-mixing interferometry, semiconductor laser, linewidth enhancement factor

## **Disciplines**

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# Improving the Performance in an Optical feedback Self-mixing Interferometry System using Digital Signal Pre-processing

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**Abstract** –This paper considers the issue of noise reduction associated with Optical Feedback Self-mixing Interferometry (OFSMI). The objective is to develop an effective pre-processing filtering solution that can eliminate the inherent noise disturbances. The characteristics of OFSMI signals are described in some detail and two filter solutions are proposed. The latter includes a non-linear median filter and a Kaiser based FIR filter. The performance of the two types of filters are investigated. It is shown that median filters are capable of removing sparkle-like noise while Kaiser based FIR filters are effective in reducing the high frequency noise as well as the slow time-varying signal envelop fluctuation. Interestingly our results show that the best performance is achieved by combining the two filters, that is, a median filter followed by a Kaiser-based FIR filter. In other words, the estimation accuracy of OFSMI parameters such as the line-width enhancement factor (LEF) of semiconductor lasers is significantly improved with the aid of the proposed pre-processing solution.

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## I. INTRODUCTION

The optical feedback self-mixing interferometry (OFSMI) effect occurs when a small fraction of light emitted by a laser is reflected or backscattered by an external target and re-enters the laser active cavity, resulting in variance of both the amplitude and the frequency of the emitted laser power [1-2]. Optical feedback in semiconductor lasers (SLs) is a long-time studied topic which attracted extensive pioneering research work on classifications of different feedback regimes, optical spectrum modification, and RF noise characteristics of back-injected SLs [3-8]. During the early days OFSMI effect was considered a major source of undesired disturbance to the

laser source, but studies on the effect revealed that it can be employed for sensing and measurement of metrological quantities. Experimental set-ups suitably oriented to interferometric sensing have been devised, and theoretical analysis proposed accordingly [9-15].

A typical OFSMI system is depicted in Figure 1. The core part of the system consists of a SL, a lens and an external target. The front facet of the SL and the target forms an external cavity of the SL. When the target moves or the injection current inside the SL changes, the light phase of the external cavity will be modulated, and thus the emitted SL power will vary. The emitted SL power, also called the OFSMI signals, is detected by a monitor photodiode (PD) usually packed in the rear of the SL and then amplified by a trans-impedance amplifier for further processing. The OFSMI signals carry the information associated to the external target as well as the source SL. The commonly-used OFSMI sensing is to firstly obtain OFSMI signals based on the basic system set-up shown in Fig. 1, and then, retrieve the measured information from the OFSMI signals using different algorithms.

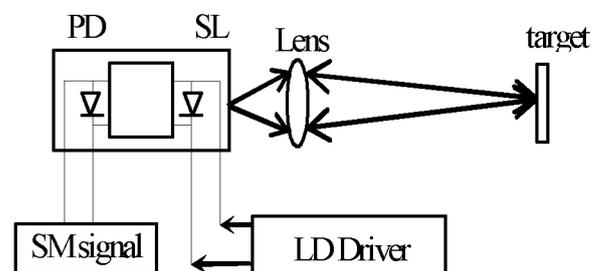


Fig. 1. the experimental set-up based on OFSMI

The quality of signals observed plays a crucial role in the performance of OFSMI based instruments. In practice, due to the influence of many factors, such as temperature variation, fluctuation in the LD driving source and other disturbance associated with the signal acquisition, self-mixing signals observed contain or even are buried into noise. Consequently the actual signals are usually characterized by very low signal-to-noise ratio (SNR).

Based on our observation there are mainly three types of noise or disturbance: additive white-like noise, sparkle-like impulsive disturbance as well as slow time fluctuation in the envelope of an OFSMI signal. Also self-mixing signals exhibit different noise characteristics at different levels of optical feedback. When optical feedback is weak, self-mixing signals are also weak and sometimes they are buried in measurement noise, seen in Fig. 2 (a). When optical feedback becomes stronger, the SNR is higher and signals are easy to be detected. However additive noise becomes stronger and the sparkle-like disturbance interference can be observed, as seen in Fig. 2 (b). Also the signals are always influenced by a multiplicative noise, making the waveform envelop fluctuate with time, as shown in Fig. 2(c).

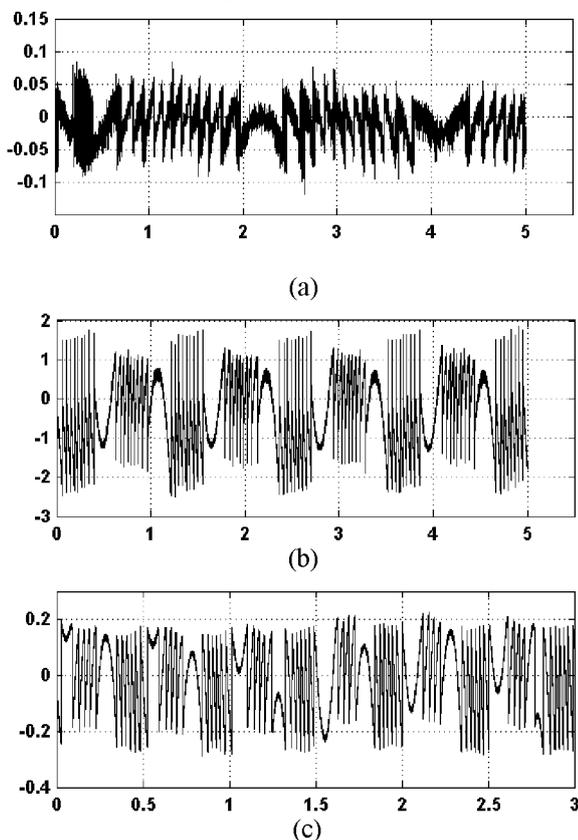


Fig.2 the raw OFSMI signals

The above mentioned noise and disturbance can seriously degrade the performance of sensing and measurement using OFSMI systems. As a result, removal of the noise and disturbance is a significant issue in this area of research. The traditional way to address this issue is to optimize the optical

structure and optical power detection circuits. However, given the work done so far, the noise elimination is still a issue as the signals are far from clean and not much can be done by improving optical system design and implementation. Therefore, in this paper, we try to address this issue by applying digital signal pre-processing to OFSMI signals. In order to achieve this, we will study the self-mixing signal characteristics, based on which we propose to employ digital filters to eliminate these noise and disturbance. Also while trying to eliminate these noises, we should not to introduce distortion to the waveform of the signals. The proposed signal pre-processing methods can be used for different raw OFSMI signals if only choosing suitable filter parameters.

## II. SIGNAL PRE-PROCESSING METHODS

### A. Feature of OFSMI signals

OFSMI signals have been extensively studied [5,9,10,15,16-18], which usually have a fringe structure similar to the traditional interference fringes, and each fringe period corresponds to  $2\pi$  shift in the laser phase, which also corresponds to half wavelength displacement of the external cavity. In case of weak optical feedback, the fringes have sinusoidal-like shape. However, with moderate or high feedback, hysteresis phenomenon occurs which significantly changes the fringes shapes to saw-tooth like [5,17,18]. In this case, OFSMI waveforms are not continuous but containing a sharp jump or drop in every fringe. An example of such kind of OFSMI signals is simulated and plot in Fig. 3.

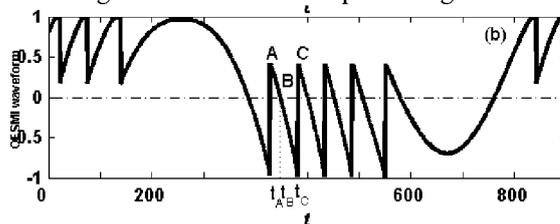


Fig. 3. The simulated OFSMI waveform at moderate feedback. A and C are the jumping points, B is the zero-cross. The time intervals between  $t_A$ ,  $t_B$  and  $t_C$  are measured for estimating the line-width enhancement factor [12].

The locations of the jumping points (such as point A and C) and those zero-cross points (such as point B) on the OFSMI waveform are characteristic points as the time intervals between these points disclose the parameters associated to the SL used in the OFSMI system [12,16], further more, these parameters also reflect the accurate moving information associated to the external target [13,14].

As all the existing theory and measurement algorithms related to OFSMI are based on a normalized signal shown in Fig. 3, it is necessary to accurately measure the peak values on an experimental OFSMI signal in order to normalize the practical signal. Then, those characteristic points can be determined on the experimental signal. So the peaks values are also important characteristic parameters for an OFSMI signal.

### B. Filter design

The above analysis will give a guideline for us to design digital filters. In most cases, people simply use a moving-average filter to remove the additive white-like noise contained in an OFSMI signal. However, for sparkle-like noises and slow-time envelope fluctuation, moving-average filters do not work well.

Given the feature of the OFSMI waveforms and their noise types, and in order to accurately pick up the useful information, we should choose digital filters with the following characteristics:

- The locations of the jumping or dropping points and edges should be kept, which then requires minimum phase shift for the characteristic points.
- The sparkles should be removed while keeping the waveform nearby unchanged.
- The filters should have flat band-pass response

Based on the above requirements, we propose that, for the 'sparkle like' noise some non-linear filtering techniques should be used, such as median-filtering. High frequency noise and slow time fluctuation can be combated with a band-pass filter based on the Kaiser window after carefully choosing the window parameters. By combining these two types of filters, clean self-mixing signals can be obtained.

### C. The median filter

Median filter is a nonlinear filter with unique characteristics in that its unit-impulse response is zero and unit-step response is still a unit-step. Median filters are proven to be a powerful tool for combating impulsive noises. Consider a case where an external target vibrates at a frequency of 70Hz and about 2μm amplitude, the wavelength of the SL is 780nm, the self-mixing signal frequency should fall within the range from 70Hz to 40KHz. We acquired an OFSMI data flow with  $2 \times 10^5$  samples from the OFSMI system shown in Figure 1 for this particular situation. There are 4210 samples in the shortest fringe. Fig. 4 shows the data in one period of the vibration.

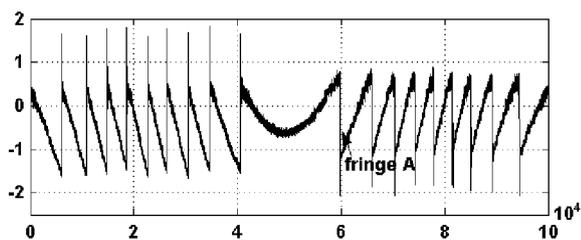


Fig. 4. A typical OFSMI signal

As the span of a sparkle-like impulse is less than 19 points in most cases, we may use a 19 points median filter to remove the sparkle parts. The filtering result is shown on Fig. 5. A raw OFSMI signal is displayed on the top and its filtered one using a 19 points median filter is on the bottom on Fig. 5 (a). The enlarged view for one fringe after filter is shown on Fig. 5 (b). Obviously, this median filter is able to greatly reduce the amplitudes of impulsive noise, and also its jumping locations

are well kept. However, there are still some residual sparkles, as can be seen clearly from the enlarged view. These residual sparkles will still affect the normalization for the OFSMI data as it might be taken as the peak value of the signals. This will degrade the parameters estimation accuracy using the approach proposed in [12].

In order to gain the best performance, we tried median filters with different widths and the results are shown in Fig.6. It is seen that longer median filters are able to completely remove the sparkles, but they will also somehow reduce the values of the true signal peaks.

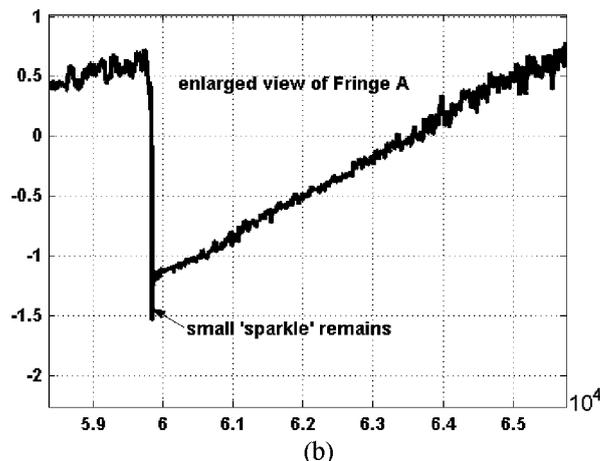
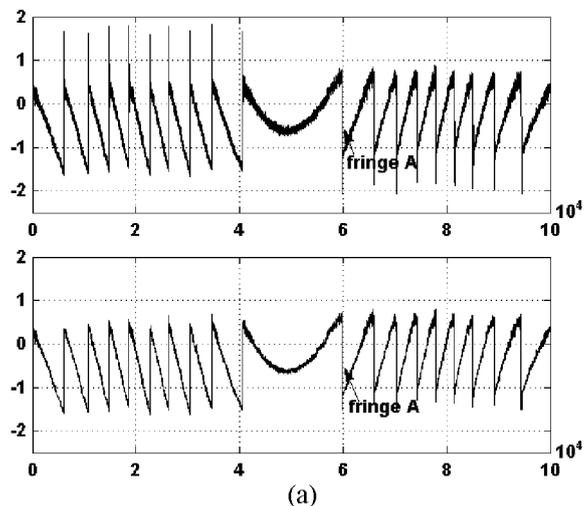


Fig. 5. The median filter result for the experimental data. (a) a raw OFSMI signal on the top and its filtered one using a 19 points median filter on the bottom. (b) the enlarged view of fringe A after filter

From Fig 6, the dotted curve with 19 point median filter is considered as a good choice. Besides, as seen in Fig. 5 and Fig. 6, high frequency noise and the slow-time fluctuation still exist after the 19-points median filter. Hence the data should be further processed.

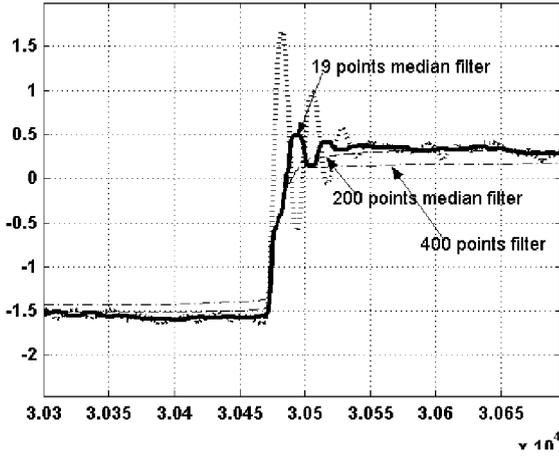


Fig. 6 The enlarged view for one jumping part using different filters. The dotted line:raw data; the solid one: 19 points median filter; the dashed one: 200 points median filter; dashed dot: 400 points median filter

#### D. Filtering based on Kaiser window

An alternative way for noise removal is to use linear filters. In this section we investigate the performance of FIR band-pass filters by the Window method, based on the Kaiser window function. The impulse response of the filter is given as following:

$$h[n] = w[n]h_d[n] \cos \omega_c n \quad (1)$$

where  $h_d[n] = \frac{\sin \omega_c n}{\pi n}$ ,  $\omega_c = \omega_{c2} - \omega_{c1}$  is the pass-band

width and  $\omega_0 = \frac{\omega_{c2} + \omega_{c1}}{2}$  being the central frequency. Note

that  $\omega_{c1}$  and  $\omega_{c2}$  are the two stop band frequencies. The Kaiser window function  $w[n]$  is defined as follows:

$$w[n] = \begin{cases} I_0[\beta \sqrt{1 - [(n - \alpha) / \alpha]^2}], & 0 \leq n \leq M \\ 0, & \text{else} \end{cases} \quad (2)$$

where  $I_0(\cdot)$  is the zero-th order modified Bessel function of the first type,  $\beta$  is a parameter that determines the shape of the window.  $\alpha = M/2$  where  $M$  is the length of the window. The Kaiser window function is advantageous in that its shape is continuously variable to provide essentially any required amount of stop band attenuation.

The frequency band of OFSMI signals can be roughly estimated based on the feature of its waveform. For the signals given above, we found that the Kaiser window width with 1023 points can achieve a good filtering result. By taking the DFT of the signals, we found that the frequency spectrum falls within the range of 70Hz and 40KHz. Therefore we set  $\omega_{c1}$  to be 20Hz in order to eliminate the slow time-varying fluctuation. However, the cut-off frequency  $\omega_{c2}$  should be chosen with much more care as it a significant impact on the jumping edge

of the waveform. In order to look at the influence of, we studied the cases where  $\omega_{c2}$  is 80KHz, 160KHz and 240KHz respectively and the filtering results are shown in Fig. 7. Obviously,  $\omega_{c2}$  does influence the shape of the jumping edge.

It is seen that  $\omega_{c2} = 240\text{KHz}$  yields the best result. In fact we

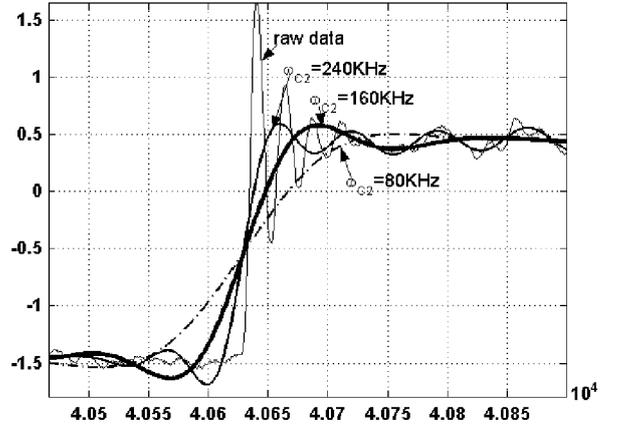


Fig.7 The filter results using different stop bands. The solid line is the filter with  $\omega_{c2} = 240\text{KHz}$ ; The thick solid is with  $\omega_{c2} = 160\text{KHz}$  and the dash-dot line is with  $\omega_{c2} = 80\text{KHz}$ .

found that, in order to keep the jumping locations and edge,  $\omega_{c2}$  should be chosen to be at least 6 times as the highest frequency of the signal. However high  $\omega_{c2}$  will result in large ripples in the waveform, which then requires us to choose suitable values for  $\beta$ . Fig. 8 presents that how the parameter  $\beta$  amends the ripple. It is seen that Fig. 8 a large  $\beta$  may decrease ripple height.

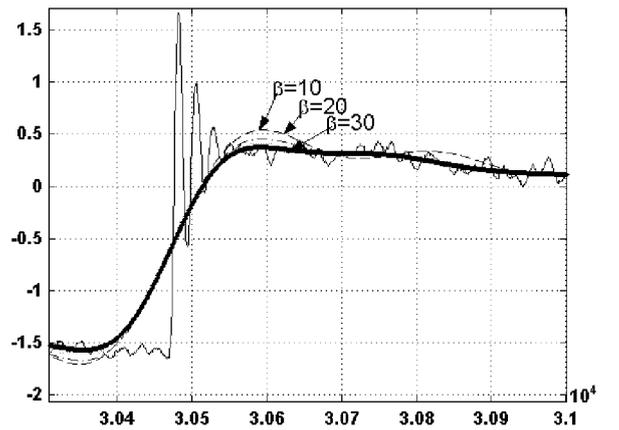


Fig. 8. The filtered results using different  $\beta$  in Kaiser window. The dash line is with  $\beta = 10$ ; The dash-dot line is with  $\beta = 20$ ; The thick solid line is with  $\beta = 30$ .

The above results show that Kaiser based band pass filters are able to combat the high frequency noise and slow-time varying fluctuations. However they also introduce some distortion at the locations of the jumping points. Also the peak values are increased if we only use Kaiser based filters. In other words, respond of the Kaiser based filter to the jumping waveform and sparkles is not as good as that of the median. In order to achieve the best performance, we propose to employ median filters followed by Kaiser based filters and the performance is shown in Fig. 9.

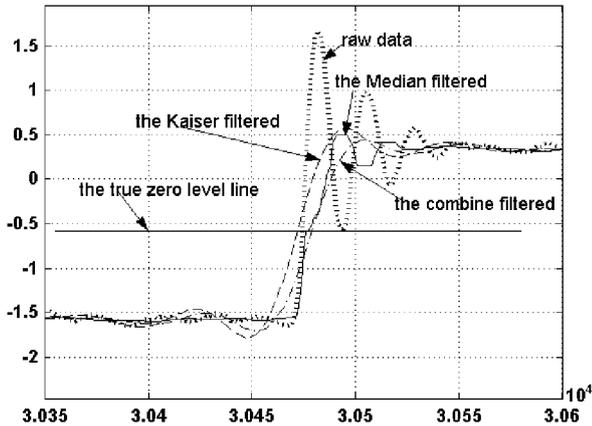


Fig. 9 The enlarged view for one jumping part on the OFSMI signal using different filters. The dotted line: raw data; the dashed one: Kaiser window based filter; the solid one: 19 points median filter; the dash-dotted one: the combined filter.

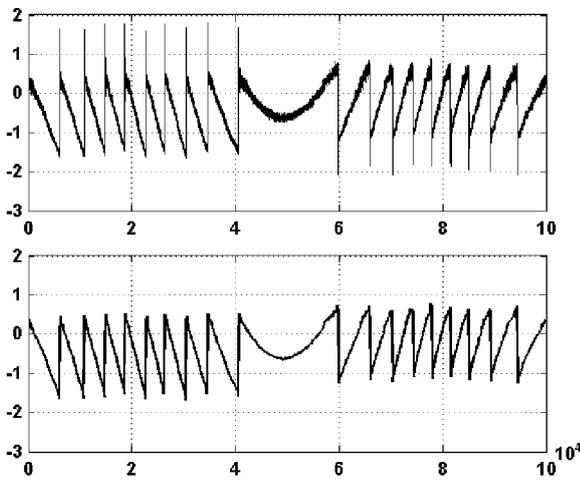


Fig. 10. The filtering result using the combined filter. The raw data is plot on top figure. The filtered data is on the bottom.

Fig. 9 shows the resulted waveforms when the median filter and Kaiser based filters are employed respectively, as well as the waveform when applying a median filter followed by a Kaiser based filters. It is seen the combination of the two filters gives the best performance. In order to test the performance, we applied this approach to the same signal described in Section II C and the results are given in Fig. 10,

which shows that very clean OFSMI signal waveform can be obtained.

### III. THE MEASUREMENT RESULTS

In order to test the performance of the proposed approach, we firstly employed the proposed filtering technique to the data described in Section II C, and then fed the pre-processed data into the algorithm presented in [12] on the measurement of the linewidth enhancement factor (LEF). Table I give the results of LEF measurement when different filtering techniques are applied. It is seen that pre-processing using an median filter followed by a Kaiser based filter gives the best LEF estimation, which is closest to the true LEF value 4.0. Also it is seen that the measurement of LEF is very sensitive to the filters used, which implies that pre-processing must be done with care.

TABLE I.

THE ESTIMATING RESULTS FOR LEF FOR THE SIGNAL WITH ACTUL LEF=4

Filter types	LEF
Median	3.6±21.6%
Kaiser	5.4±7.6%
combine	4.1±7.2%

### IV. CONCLUSION

The paper studied the issue of pre-processing OFSMI signals with the purpose of removing the noise and disturbance. Based on OFSMI signal characteristics, we proposed to use median filters to remove sparkle-like noise, and to employ Kaiser-based FIR filter to combat the high frequency noise as well as the slow time-varying signal envelop fluctuation. Performance analysis shows that a median filter followed by a Kaiser based FIR filter will give the best result for noise removal and thus yield more accurate results for parameter estimations, such as the LEF.

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### REFERENCES

- [1] M. B. Spencer and W. E. Lamb, Jr. "Laser with a transmitting window," *Phys. Rev. A* vol. 5, pp. 884-897, 1972
- [2] M. B. Spencer and W. E. Lamb, Jr. "Laser with an external injected signal," *Phys. Rev. A* vol. 5, pp. 898-912, 1972.
- [3] R. Lang and K. Kobayashi, "External optical feedback effects on semiconductor injection laser properties," *IEEE Journal of Quantum Electronics*, vol.16, pp.347-355, March 1980.
- [4] G. A. Acket, D. Lenstra, A. J. D. Boef and B. H. Verbeek, "The influence of feedback intensity on longitudinal mode properties and optical noise in index-guided semiconductor lasers", *IEEE J. Quantum Electron.*, vol. 20, pp.1163-1169, Oct. 1984

- [5] K. Peterman, Laser diode modulation and noise, *Dordrecht, The Netherlands: Kluwer*, 1988
- [6] H. Olesen, J. H. Osmundsen and B. Tromborg, "Nonlinear dynamics and spectral behavior for an external cavity laser", *IEEE J. Quantum Electron.*, vol. 22, pp. 762-773, June.1986
- [7] N.Schunk, K. Pertermann, "Numerical analysis of the feedback regimes for a single-mode semiconductor laser with external feedback", *IEEE J. Quantum Electron.*, vol. 24, pp. 1242-1247, July, 1988
- [8] K. Peterman, "External optical feedback phenomena in semiconductor lasers," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 1, No.2, pp.480-489, June 1995
- [9] G. Giuliani, M. Norgia, S. Donati, T. Bosch "Laser diode self-mixing technique for sensing applications," *J. Opt. A: Pure Appl. Opt.*, vol. 4, No. 6, pp. S283-S294, 2002.
- [10] S. Donati, G. Giuliani, and S. Merlo, "Laser diode feedback interferometer for measurement of displacements without ambiguity," *IEEE Journal of Quantum Electronics*, vol.31, pp.113-119, Jan.1995
- [11] L. Scalise, Y. Yu, G. Giuliani, G. Plantier and T. Bosch, "Self-mixing laser diode velocimetry: application to vibration and velocity measurement," *IEEE Trans. on Instrumentation and Measurement*, vol. 53, No.1, pp. 223-232, 2004.
- [12] Y. Yu, G. Giuliani and S. Donati, "Measurement of the linewidth enhancement factor of semiconductor lasers based on the optical feedback self-mixing effect," *IEEE Photonics Technology Letters*, vol. 16, pp.990-992, April 2004
- [13] J. Xi, Y. Yu, J. Chicharo and T. Bosch, "Estimating the parameters of semiconductor lasers based on weak optical feedback interferometry," *IEEE Journal of Quantum Electronics*, vol.41, No.8, pp.1058-1064, August 2005
- [14] Y. Yu, J. Xi, J. Chicharo and T. Bosch, "Toward Automatic Measurement of the Linewidth Enhancement Factor Using Optical Feedback Self-mixing Interferometry with Weak Optical Feedback," *IEEE Journal of Quantum Electronics*, in press, 2007
- [15] Y. Yu, H. Ye and J. Yao, "Analysis for the self-mixing interference effects in a laser diode at high optical feedback levels," *Journal of Optics A: Pure and Applied Optics*, vol. 5, No. 2, pp.117-122, 2003
- [16] G. P. Agrawal, "Intensity dependence of the linewidth enhancement factor and its implication for semiconductor lasers," *IEEE Photonics Technology Letters*, vol. 1, pp.212-214, 1989
- [17] P. J. D. Groot, G. M. Gallatin and S. H. Macomber, "Ranging and velocimetry signal generation in a backscatter modulated laser diode." *Applied Optics*, vol. 27, No.21, pp. 4475-4480,1988
- [18] W. M. Wang, W. J. O. Boyle, and K. T. V. Grattan, "Self-mixing interference in a diode laser: experimental observations and theoretical analysis." *Applied Optics*, vol. 32, No.9, pp.1551-1558,1993