A NOVEL TECHNIQUE OF OPTICAL FREQUENCY SWEEP LINEARIZATION OF A DFB LASER FOR HIGH RESOLUTION FMCW REFLECTOMETRY

ABSTRACT

FMCW reflectometry suffers from nonlinearity issue in optical sweep frequency of DFB laser. The first part of this paper, we proposed a linearization method by modifying the modulation waveform through external sampling technique to overcome the nonlinearity issue. In this technique, the triangle modulation signal is externally sampled with the non-equal interval clock pulses generated from the nonlinear interference beat signal and was then analyzed using Fast Fourier Transform (FFT). Through the external sampling clock where temporal sampling coincides with the interference beat signal caused the shape of triangle waveform to deform and distorted slightly. Tiny deterioration at the turning point of triangular modulation waveform was obtained. The modified waveform was later relaunched into the system and the processes were repeated until the beat signal of sweep frequency approaches linearity. The proposed linearization method has been worked out through experimentation, and after the 2nd iteration, the result showed that this method effectively reduced the issue of the nonlinear optical frequency sweep. Linear indicator estimation is used to validate the linearity improvement throughout the proposed method. Linearity reduction at 60% was accomplished from the first experiment. The second part of the paper presented our next investigation in achieving better resolution on frequency interval of the beat spectrum. Proper selection of certain parameters during FFT analyzation, can sharpen the frequency spectrum which contribute to higher resolution. Thus, second involvement in this work is paying close attention to other criteria and parameters during the experiment that are important in improving the whole system to a considerable degree of preciseness. Through modulation waveform optimization, it is proved that the best combination of repetition frequency and modulation amplitude, together with skip function and zero adding technique in FFT analysis can sharpen the frequency spectrums which contribute to range measurement system's accuracy. The spectrum purification is evaluated using FWHM concept where 66% improvement in frequency interval was achieved. The proposed methods above are a very promising method to linearize optical frequency sweep and, as a result, to enhance the spatial resolution of FMCW sensing system.

1. Introduction

The use of fiber optics has become very common in a long range communication system. Among the famous usage of an optic-based apparatus is non-contact sensing technique. Optical techniques used in measuring target distance have a large range of functions and applications. This interferometric technique is being employed for its fast and automated measurement in both very long and short distance. The adeptness of interferometry in utilizing the wavelength of light as a basis for measurement and later to transform the constituent of wavelength into numerical data has made optical interferometry an invaluable tool for precision measurements. Frequency-modulated continuous-wave (FMCW) interferometry has become a more popular technique in recent years and is being widely used in optical ranging measurements. In an ideal system, the optical frequency sweep of the laser occurs linearly and periodically in time resulting in a constant beat frequency in time, of which the information regarding the distance can be extracted after FFT analysis

However, practically, linearity in a sweep frequency ramp is difficult to obtain, and this leads to a nonlinear beat frequency. In most cases, the beat frequency is fluctuated in time because of nonlinearity optical frequency sweep that caused by nonlinear modulation waveform change against injection current. Fluctuation and inconsistency in the beat frequency will degrade the precision of the ranging since it causes the spectrum to broaden, makes it hard to determine the distance to the target and the spatial resolution. Broadening of the beat spectrum is caused by fluctuation of the beat frequency. Conversely, if the optical frequency is linearly swept, a constant beat frequency is obtained and the distance to the target can be accurately extracted. To date, scholars around the world are still in research to address the longtime issue of nonlinear frequency swept of DFB laser in optical FMCW. Further, proper selection of certain parameters during FFT analyzation can sharpen the frequency spectrum which contribute to higher resolution. Thus, second involvement in this work is paying close attention to other criteria and parameters during the experiment that are important in improving the whole system to a considerable degree of preciseness.

The basic configuration of optical FMCW interferometry has been developed resemble the classical parallel beam Michelson interferometer. However, it differs from Michelson principle where, in optical FMCW frequency modulated laser semiconductor is a light source. Typically, the transmitter of optical communication system consists of a laser diode that is being modulated either directly or indirectly. A direct modulation of a laser is obtained via the injection current while indirect modulation (also called external modulation) of a laser is obtained via an optical modulator. The modulation signal can select any waveform fashion such as sawtooth-wave, sine-wave, or triangle-wave also can take a form of amplitude, phase or frequency modulation.

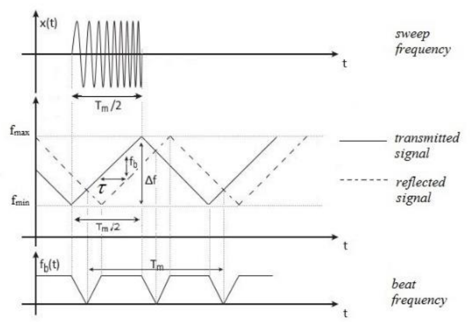


Fig. 1. Linear Sweep Optical FMCW system

FMCW works on the frequency difference between the reflected signal and reference signal received at the photo detector; this is known as beat frequency. The beat signal is used to calculate the target range distance. FMCW system with linear frequency modulation sweep gives the constant value of the frequency beat as illustrated in fig. 1. Thus, the targeted distance can be measured accurately using (1) and (2).

$$d = \frac{fb \times c \times Tm}{4 \times \Delta f} \quad \text{(eq. 1)}$$

$$\tau = \frac{2d}{c} \quad \text{(eq. 2)}$$

The equation above can be used to calculate the targeted distance d, where fb is the beat frequency that refers to the difference between transmitted (reference) signal and received (reflected) signal, $c = 3x10^8 ms$ is the velocity of light, Tm indicates the time for one period of modulation frequency, Δf represents the bandwidth of ramp signal and τ denotes the delay between reflected and reference signal.

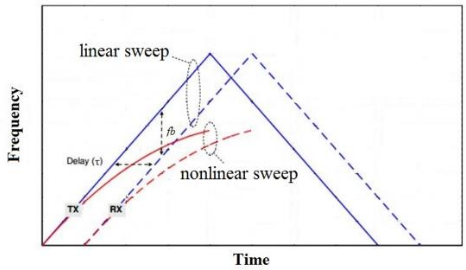


Fig. 2. Linear Sweep Optical FMCW system

In fig. 2, ideal system, the sweep frequency of the laser diode modulate linearly and periodically in time. Therefore, the beat frequency is constant everywhere and the accurate information on the distance range can be extracted after demodulation. On the other hand, in most cases, nonlinearity in sweep frequency ramp is occurred. This leads to a nonlinear beat frequency. During the ramp of nonlinear sweep frequency, fb: τ is not constant everywhere. Consequently, the beat spectrum is broadened. In fig. 3, a little delay in frequency sweep is obviously seen that at the beginning of each turning point of each interval.

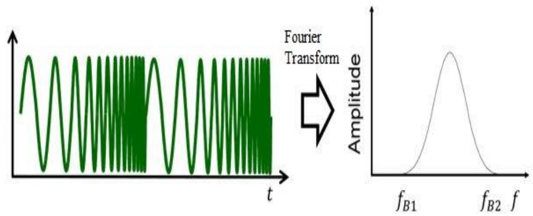


Fig. 3. Linear Sweep Optical FMCW system

The performance of FMCW sensing interferometry is degraded by the broad spectrum shape of beat frequency which is caused by fluctuation of the beat frequency. The fluctuation (inconstant) beat frequency is then affected by a nonlinear sweep of the modulation frequency. Linear optical frequency sweep, on the other hand is difficult to obtain. This is because the optical change of frequency against injection current is nonlinear. This caused a linearity in optical frequency sweep difficult to realize even if we modulate the injection current with a linear modulation triangular signal.

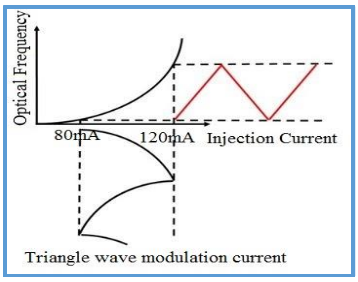


Fig. 4.Nonlinear modulation waveform produces linear sweep frequency

Modulating the injection current linearly, as mentioned above, with the nonlinear relation between optical frequency changes with injection current, the sweep frequency appear nonlinear. Therefore, the feasible method is, for the optical frequency to sweep linearly, the waveform generation of the modulation current must be nonlinear. Therefore, our target was to construct nonlinear modulation frequency to nonlinear injection current and perhaps linear frequency sweep can be achieved.

In order to correct or, at least, improve the nonlinearity of the optical frequency sweep, the delay at the beginning of each turning point must be reduced. The interval of each cycle of interference frequency must be spaced equally. This can be done by externally sampling the reference signal with the interference signal so that all data assimilated from the interferometer have accurately identical interval.

2. Linearization of nonlinear beat frequency in FMCW interferometry through waveform modifying technique

Fig.5 shows the configuration setup of FMCW interferometry system in constructing a modified waveform of a triangular modulation signal. A triangular modulation frequency chirping is launched by the laser diode. A time difference between transmitted waveform and reference waveform and a delay interference signal produce a difference in frequency that is known as beat frequency. From the eq. 1 & 2 beat frequency is seen proportional to the rate of the frequency sweep.

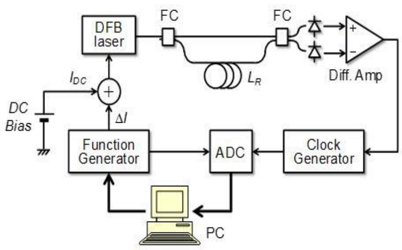


Fig. 5. Optical FMCW interferometry setup

In brief, we modified the frequency modulation (FM) waveform through the external sampling technique to reduce the effect of nonlinear beat frequency. In this technique, triangle-wave FM sweep is generated from a DFB laser source and transmitted through the system and re-sampled by the Analog Digital Converter at the external sampling rate (temporal sampling).

As temporal sampling changed with time, this resulted in a tiny deterioration in the FM waveform at the beginning of each ramp. Thus, a pre-distorted FM waveform was obtained. One period interval of that distorted FM waveform was extracted and used to reconstruct a new FM waveform signal. This newly constructed signal was later retransmitted to the system as a new FM sweep signal. The process was repeated until the linearity of the beat frequency was noticeably improved. After the first time, the shape of the modulation waveform is seen to have tiny distortion at each of the turning points and is slightly curved compare to the original modulating waveform. The proposed linearization method has been worked out through experimentation, and after the 2nd iteration, the result showed that this method effectively reduced the issue of nonlinear beat frequency.

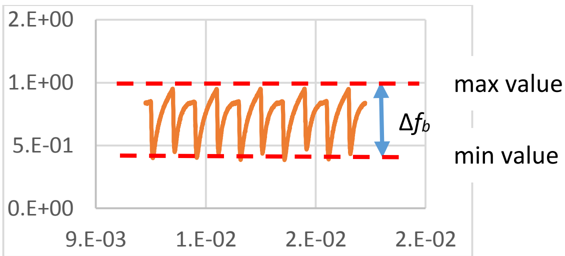


Fig. 6 Linearity indicator of beat frequency

To ensure the optimum result of frequency beat is obtained, we introduce a linearity indicator to benchmark the effectiveness of the proposed technique as in fig. 6. The optimum value of frequency beat when the value of $\Delta f_b/max$ is lowest.

Fig. 7 & 8 compare the results of beat fr*equency* for non-sampling and 2nd -time re-sampling of the modulation frequency. The non-sampling waveform of frequency modulation gives a larger and nonlinear value of the frequency beat. After the 2nd re-sampling, the linearization of the frequency beat can be clearly seen. The reduction on nonlinear frequency beat obtained was related to the significant change in the frequency modulation signal after being sampled up to the 2nd time. Tiny deterioration in the frequency modulation waveform, especially at the beginning of each rising up and falling down edges, slowly occurred as the number of sampling times increased.

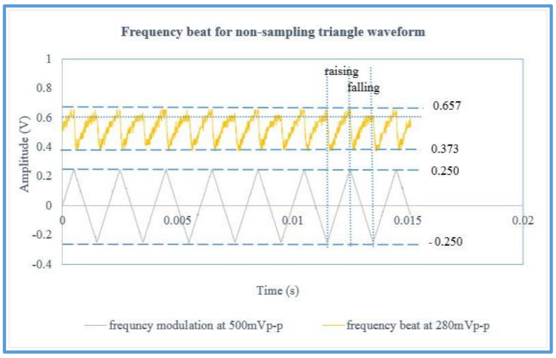


Fig. 7 Beat frequency and modulation waveform at no sampling

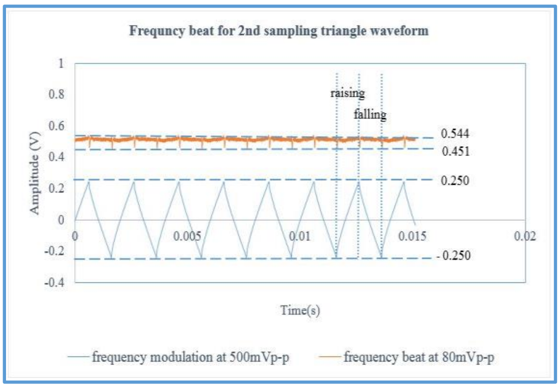


Fig. 8 Beat frequency and modulation waveform at 2nd sampling

Nonlinearities in the frequency sweep can cause a nonlinear frequency beat. FFT analysis showed that nonlinearity issues affect the broadening of the frequency spectrum of the interference beat signal. As indicated in fig. 9, FFT analysis onto the resampled frequency modulation shows the frequency spectrums are narrowing accordingly. The more the signal waveform is resampled, the narrower the frequency spectrum becomes. Expectedly, accurate data can be extracted and the targeted distance precisely measured.

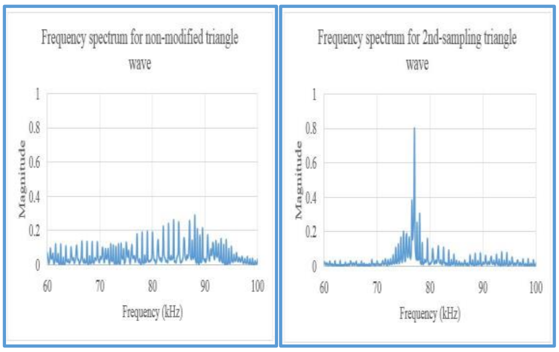


Fig. 9 Beat frequency spectrum at no & 2nd sampling

Computing the Δfb/max value of each frequency beat of different parameters gives an overview of how the number of resampling times affects the frequency beat linearity as depicted in fig. 10. It shows the higher the number of sampling times, the smaller the value of Δfb/max we could achieve. This indicates that the linearization of frequency beat is improving firmly.

$$\Delta fb = max\ value - min\ value \qquad (eq.\ 4)$$

$$linearity\ indicator = \frac{\Delta fb}{max\ value} \qquad (eq.\ 5)$$

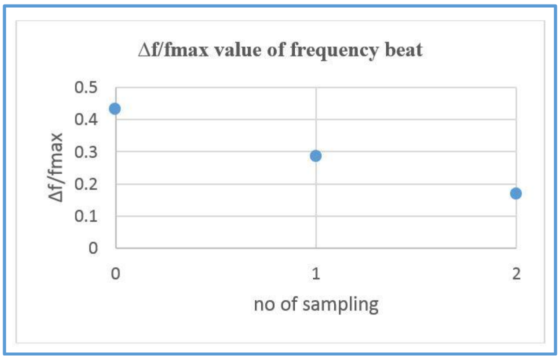


Fig. 10 Linearity indicator of beat frequency vs no. of sampling times

3. Linearizing optical frequency sweep of a DFB laser by modulation waveform optimization for high resolution FMCW sensing system

In the previous section, we demonstrated the effectiveness of the proposed linearization method of optical frequency sweep with randomly pick parameters value. Here we measured the beat spectrum with different repetition frequency and modulation amplitude, and FFT analysis.

In order to ensure the most appropriate selection of parameters value, we conducted another experiment that will be explained further in this chapter. The best selection of parameters values is important in purifying the beat frequency spectrum and enhancing the spatial resolution of the FMCW sensing technique for higher system accuracy.

Regardless of other criterion, in this study, we were considering only to four parameters that we believe can contribute to the development of higher system accuracy. These parameters are repetition frequency, modulation amplitude, skip data function and zero addition in FFT analysis. Optimization of these parameters has significantly improved the spectrum resolution.

In this experiment, the linearity is estimated by beat spectrum purity utilizing FWHM (full width half maximum) concept. We measured the full width at half maximum of the beat spectrum, $\delta f_{0.5}$ and full width at 10% maximum, $\delta f_{0.1}$ in Fig. 11, and the beat spectrum purity is estimated as $\delta f_{0.5} / f_b$ and $\delta f_{0.1} / f_b$, where f_b is the frequency for peak amplitude.

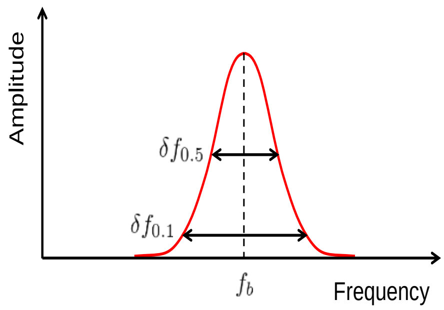


Fig. 11 FWHM definition of spectral width for estimation of beat spectrum purity.

$$\delta f0.5 = \frac{\text{full width at 50\% max}}{fb} x\ 100\% \qquad \text{(eq. 5)}$$

$$\delta f0.1 = \frac{\text{full width at 10\% max}}{fb} x\ 100\% \qquad \text{(eq. 6)}$$

A. *Repetition frequency*

The first parameters value to be tested for its optimum result is repetition frequency. In order to elect the best value we conducted a series of experiment with a variation of repetition frequency ranging from 100Hz up to 1000Hz. The modulation amplitude, however, is fixed at 20mAp-p for all condition.

Fig. 12 presented the beat spectrum measured for different repetition frequency of modulation signal after waveform modification for 3m fiber length. In overall, the beat frequency is increased as the repetition frequency and the beat spectrum is seen degraded with the increase of repetition frequency.

While repetition frequency is at 100 Hz, the beat spectrum has a pedestal, indicating the beat frequency is slightly non-constant and fluctuating in time. The reason of this issue might be due to electrical noise in the clock generator (voltage comparator) that generating a TTL signal from the interference signal for modulation waveform sampling.

From the above consideration, as represented in the fig. 5-3, the optimum repetition frequency is ranged from 200 Hz and 400 Hz, and the optimum range will be increased by carefully designing the differential amplifier and the clock generator.

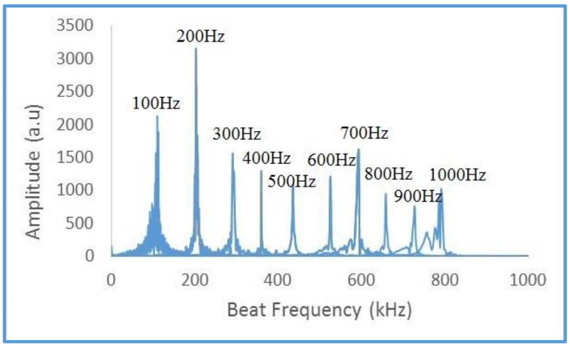


Fig. 12 Beat frequency spectrum of repetition frequency variation from 100Hz to 1000Hz

B. *Modulation amplitude*

The next parameter's value to be selected for optimum condition of modulation waveform is modulation amplitude. Modulation amplitude has a big influence in the linearity of the beat frequency. The beat frequency linearity differences between rising and falling edge interval of a modulation signal is getting worse as the modulation amplitude value increase. Therefore, we performed this experiment in order to decide the best value of modulation frequency for better accuracy of the system. In this experimentation, the injection current of the modulating triangle waveform is varied at 10mAp-p, 20mAp-p, 40mAp-p and 60mAp-p (500mVpp, 1Vpp, 2Vpp & 3Vpp respectively) at predetermined repetition, 400Hz. The 400Hz is chosen for its best result in the earlier experiment.

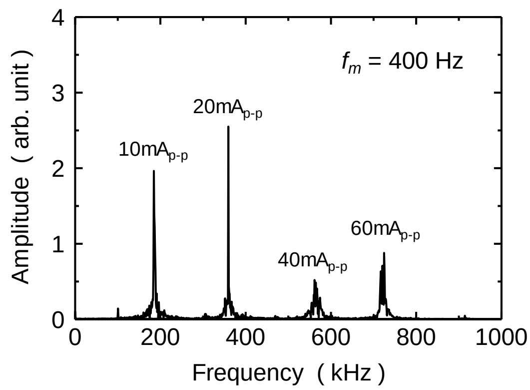


Fig. 13 Beat frequency spectrum of modulation amplitude variation from 10mApp to 60mApp

Fig. 13 shows the shape of beat spectrum for variation of modulation amplitude values ranging at 10mApp, 20mApp, 40mApp and 60mApp. The relationship between optical sweep frequency and injection current can be represented by the following relationship, ΔI∞ ΔF. In other words, the optical sweep frequency ΔF is proportional to the injection current of the modulation signal. Consequently, the increased in sweep frequency directly will increase the beat frequency.

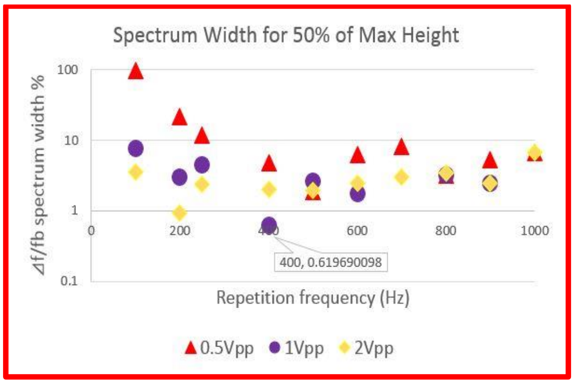


Fig. 14: FWHM at 50% of max

From the above figure, $\delta f_{0.5}$ calculated using eq. 5, give the overall view of beat spectrum purification. The best value for repetition frequency and modulation amplitude is at 400Hz, 1Vpp respectively for 3m fiber length.

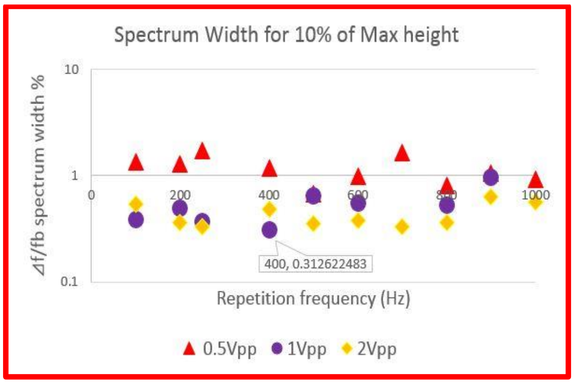


Fig. 15 FWHM at 10% of max

For $\delta f_{0.1}$, modulation amplitude of 1Vpp shows the lowest value at 400Hz repetition frequency. In this case, the optimum beat spectrum purification is obtained for 400Hz repetition frequency and 20mApp (1Vpp) modulation amplitude. Resolution can be estimated using eq. 6. Since the relative 50% width is less than 1% (from the above graph), resulting in the spatial resolution of less than 3 cm for LR = 3m

C. Skip data function in FFT analysis

The optical frequency sweep of a DFB laser approached linearity with significant improvement in the spatial resolution of the FMCW sensing by the proposed method in the previous chapter. However perfect linearization cannot be achieved because the beat frequency immediately after the turning point between ascending modulation interval and descending modulation interval of the modulation waveform is not constant. Therefore, a small fraction of the interference signal at that spot of the modulation waveform was skipped for data acquisition for high-resolution distance measurements.

The next parameter's value to be experimented is skip function in FFT analysis. Before going into further details of skip function, the understanding of data number is essential because, in the analysis of skip function, it involve of data number usage.

Data number is the number of data sampled in the time domain (N). In Fourier transform, the efficient number of sampled data is N/2 corresponding to the maximum measurement range to satisfy the Sampling Theorem. For Fs/N, where Fs is input signal sampling rate (sampling frequency) and N is a number of FFT points used, to get smaller bin FFT, we can either run the FFT longer or we can decrease the sampling rate Fs.

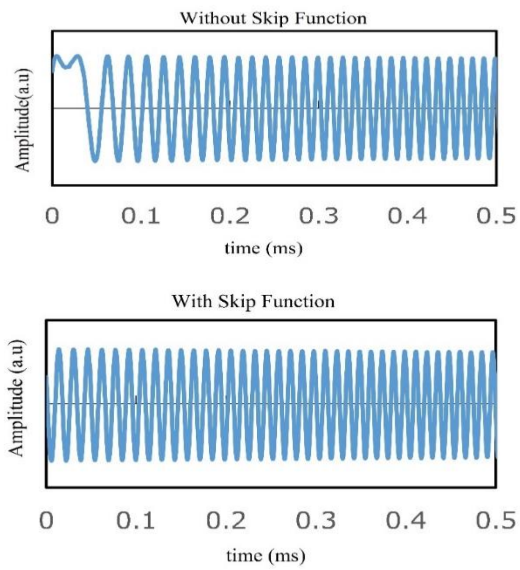


Fig. 16 Skip function in FFT

The default skips no is 0. Its mean that the whole signal is captured including the unwanted signal. As illustrated in fig. 16, at the starting of turning points of the modulation signal, interference beat signal is in constant even after applying the modifying waveform technique. A little delay is seen before the solid steady signal succeeded.

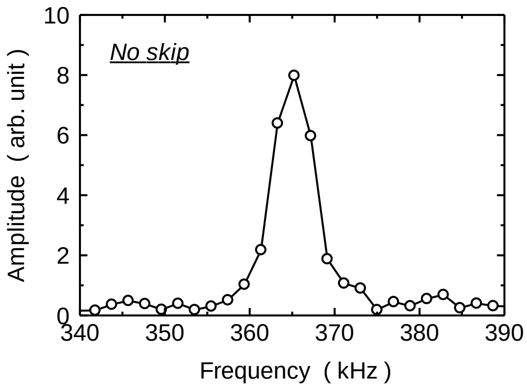
Skip data function, generally helps in performing the FFT analysis efficiently because we can eliminate or skip the unwanted signal without jeopardizing the total number of data points. This is important because it indicates that the absolute information of the interference signal is preserved.

The experiment of this section began with omitting (skipping) data at various percentages.

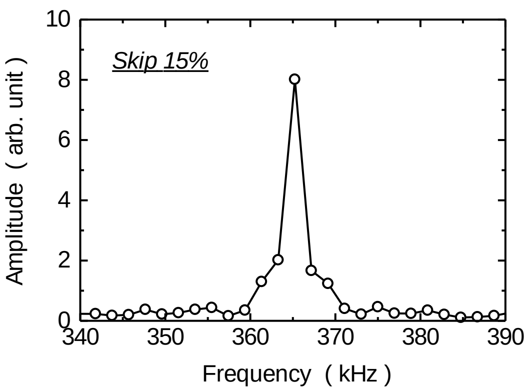
After series of trial, the most considered percentage of data to be skipped was achieved. The preceding parameters, repetition frequency and modulation amplitude were maintained at 400Hz and 20mApp respectively. The measured beat spectrum without skip function and with 15% acquisition skip just after the turning point of the modulation waveform for repetition frequency 400 Hz with 20 mA modulation amplitude are shown in fig 17 respectively.

Without skip function, the beat spectrum is appeared broadening compared to 15% acquisition skip. Narrower beat spectrum is obtained by utilizing acquisition skip because the beat frequency fluctuation immediately after the turning point between ascending modulation interval and descending modulation interval of the modulation waveform is eliminated.

The result in fig. 17 is executed with sampling frequency is 4 MHz, number of sampled data is 2048, and the acquired time is 0.512 ms, (40% of the decreasing section of the modulation waveform) in 2 kHz frequency interval. Skip function makes the beat spectrum more readable.



(a) without acquisition skip



(b) with 15% of acquisition skip

Fig. 17 Beat spectrum with and without acquisition skip

D. Zero addition of FFT analysis

Zero adding or zero padding function in FFT analysis indicate the action of inserting (adding) zeros "0" to end of a time domain in order to increase its length. This is a popular technique for taking a bigger FFT to make the beat spectrum more readable. In the effort to get longer FFT for higher resolution, we can increase the number of data to be sampled. However, if the number of the sampled data is increased, the sampled data contains the interference signal around the turning point of the modulation waveform, and this will cause the beat spectrum is degraded because of beat frequency fluctuation immediately after the turning point of the modulation waveform.

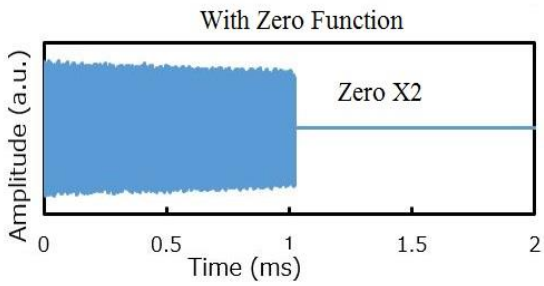


Fig. 18 Interference signal with zero adding function

Instead of increasing the number of sampled date, after undergoing skip function, we added zero values after the sampled data. In our experiment, the number of sampled data is 2048 and more 2048 points of zero data are added. This will double up the length of total times.

In Fig. 17 (b), the FFT-analyzed data shown as circles are arranged in 2 kHz frequency interval, and the frequency interval is determined by the total acquisition time. The frequency interval of the FFT analysis also affects the spatial resolution, and narrow frequency interval is desired for high-resolution measurement. However if the number of the sampled data is increased, the sampled data contains the interference signal around the turning point of the modulation waveform, this will lead to the degradation of the beat spectrum.

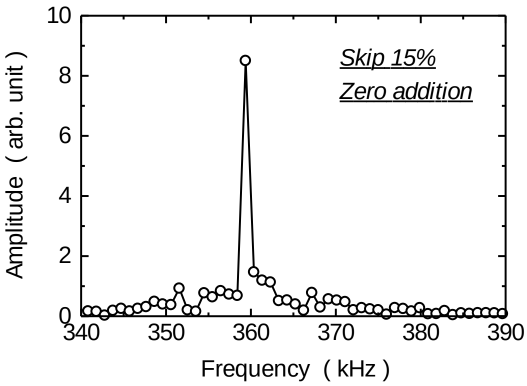


Fig. 18 Beat spectrum with and without acquisition skip

Instead of increasing the number of sampled data, we add zero values after the sampled data. In our experiment, the number of sampled data is 2048 and more 2048 points of zero data are added. Fig. 18 shows the measured beat spectrum. Acquisition skips after the turning point are 15%. By adding the zero function, the frequency interval is about 1 kHz, which is half of the frequency interval of Fig. 17(b). The beat spectrum is narrower in Fig. 18. The relative 50% width $\delta f_{0.5} / f_b$ is 0.33%, resulting in the spatial resolution of 1 cm.

4. Conclusion

We have developed linearization method of optical frequency sweep of a laser diode for FMCW sensing system. The modulation waveform is sampled with the interference sampling signal produced at the interferometer, and then a laser diode is modulated with the sampled waveform. In addition, the interference signal just after the turning point of the modulation waveform is skipped from sampling because the optical frequency sweep immediately after the turning point between the ascending modulation interval and descending modulation interval of the modulation waveform is not perfectly linearized and then the beat frequency fluctuates. And zeros data are added after the sampled data to decrease frequency interval in FFT analysis while avoiding acquisition of the interference at the spot. As a result, by repeating the waveform modification procedure a few times, the optical frequency sweep is linearized, and then the spatial resolution of FMCW sensing system is significantly improved. The degree of linearization of optical frequency sweep depends on both the repetition frequency of the modulation signal and the modulation amplitude. In our experiments, the optimum repetition frequency is about 400 Hz from the viewpoint of spatial resolution, and the optical repetition frequency range can be expanded by decreasing electrical noise in the clock generator.

In conclusion, the nonlinear effect of optical frequency sweep is canceled from the modification of modulation waveform through the sampled beat signal of the beat interference. Proper selection of certain parameters value can sharpen the beat spectrum and improve the resolution (frequency interval) of the spectrum. As a result, the beat frequency approaches linearity, the degradation of the spatial resolution is considerably improved as well as the measurement accuracy greatly increased.

1) Based on first experiment analysis, linearity indicator Δfb/max, the beat frequency linearity is improved from 0.427 to 0.170, approximately 60% reduction in nonlinearity.
2) From the second experiment, based on FWHM estimation, frequency interval of the beat spectrum was reduced from 3cm to 1 cm (based on 3-meter fiber length) estimated to 66% resolution intensity improved.

Thus, we conclude the objective of this research "Optical frequency sweep linearization of a DFB laser for high-resolution FMCW reflectometry" is achieved.

5. References

[1] A. Lazam, K. Iiyama, T. Maruyama, Y. Kimura, and N. Van T, "Linearization Of Nonlinear Beat Frequency In FMCW Interferometry Through Waveform Modifying Technique," ARPN J. Eng. Appl. Scinces, vol. 10, no. 8, pp. 3817–3822, 2015.

[2] A. Lazam, A. Igarashi, N. Atsushi, T. Maruyama, and K. Iiyama, "Linearizing optical frequency sweep of a DFB laser by modulation waveform optimization for high resolution FMCW sensing system," Int. J. Electr. Electron. Res., vol. 5, no. 6, pp. 1–10, 2015.

[3] Mohammad U. Piracha, Dat Nguyen, Ibrahim Ozdur, and Peter J Delfyett, "Simultaneous ranging and velocimetry of fast moving targets using oppositely chirped pulses from a mode-locked laser",*Optics Express*, Vol. 19, Issue 12, pp. 11213-11219 ,2011

[4] Koichi Iiyama, Lu-Tang Wang and Ken-ichi Hayashi, "Linearizing optical frequency-sweep of a laser diode for FMCW reflectometry" *Journal of Lightwave*, Vol. 14, No 2. 1996

[5] Soo-Yong Jung, Seong Ro Lee and Chang-Soo Park, "Correction of nonlinear frequency sweep in frequency-modulated continuous-wave laser

range sensor", *International Journal of Distributed Network Sensor*, vol. 2013,article id 294967,6 pages,2013

[6] Stefan Scheiblhofer, Stefan Schuster and Andreas Stelzer, "Signal model and linearization for nonlinear chirps in FMCW radar SAW-ID Tag request", *IEEE Transactions on Microwave Theory and Techniques*, vol.54, n0.4, 2006

[7] Daniel Nordin and Kslevi Hyyppa, "Using a discrete thermal model to obtain a linear frequency ramping in an FMCW system", *Opt. Eng*. 44(7), 074202, July 07, 2005.

[8] Daniel Gomez Garcia Alvestegui, "A Linearization method for a UWB VCO-based chirp generator using dual compensation",M.S. thesis, Elect. Eng. Lab., Univ. Kansas, 2011

[9] Mohammad Umar Piracha, "A laser radar employing linearity chirped pulses from a mode-locked laser for long range, unambiguous, sub-millimeter resolution, ranging and velecimetry", PhD Thesis, Dept Elec Eng and Com. Sc., Univ. Central Florida, Orlando, Florida , 2012.

[10] Arseny Vasilyev, "The optoelectronic swept-frequency laser and its application in ranging, three-dimensional imaging, and coherent beam combining of chirped-seed amplifiers", PhD Thesis, Dept Eng. and Appl. Sc., California Int of Tech, 2013.

[11] Koichi Iiyama, Takuya Okamoto and Saburo Takamiya, "Linearizing optical frequency-sweep of a laser diode by injection current modulation with a rectangular-signal-superimposed triangular signal for FMCW reflectometry" *Electronics and Communications in Japan*, Part 2, Vol. 81, No 10. 1998

[12] I. Waveguides, U. Glombitza, and E. Brinkmeyer, "Coherent Frequency-Domain Reflectometry," vol. 11, no. 8, pp. 1377–1384, 1993.

[13] S. Jung, S. R. Lee, and C. Park, "Correction of Nonlinear Frequency Sweep in Frequency-Modulated Continuous-Wave Laser Range Sensor," vol. 2013, 2013.

[14] K. Iiyama, S. I. Matsui, T. Kobayashi, and T. Maruyama, "High-resolution FMCW reflectometry using a single-mode vertical-cavity surface-emitting laser," *IEEE Photonics Technol. Lett.*, vol. 23, no. 11, pp. 703–705, 2011.

[15] M. Song and S. Yin, "High-resolution LASER Chip Measurement Using Quadrature," *Microw. Opt. Technol. Lett.*, vol. 23, no. 6, pp. 335–337, 1999.

平成２８年　１月２７日

学位論文審査報告書（甲）

１．学位論文題目（外国語の場合は和訳を付けること。）

A novel technique of optical frequency sweep linearization of a DFB laser for high resolution FMCW reflectometry

（高分解能 FMCW リフレクトメトリのための DFB レーザの光周波数掃引の線形化）

２．論文提出者　(1) 所　　属　電子情報科学　専攻

(2) 氏（ふり）　名（がな）　Nor（ノル） Azlinah（アズリナ） Binti（ビンティ） Md Lazam（ラザム）

３．審査結果の要旨（600～650 字）

平成 28 年 1 月 27 日に第 1 回論文審査会を開催し，同日に口頭発表を実施し，その後に第 2 回審査委員会を開催した。慎重審議の結果，以下のとおり判定した。なお，口頭発表に対する質疑を最終試験に代えるものとした。

本論文は，レーザ光による距離計測・物体形状計測システムの 1 方式である FMCW (Frequency Modulated Continuous Wave) 法における空間分解能向上に関する研究である。FMCW 法ではレーザ光源の光周波数を時間的に線形に掃引する必要があるが，レーザ光源の光周波数変調の応答遅れにより光周波数掃引は非線形となり，空間分解能が大きく劣化する。そこで本論文では，光干渉計の干渉信号を用いてレーザ光源の変調波形をサンプリングして再構築する方法を提案し，光周波数掃引の線形性が 10 倍以上向上することを実証した。それに伴い，データ取得タイミングや信号処理の最適化も併用して空間分解能も 100 倍程度向上し，3 m の測定距離に対して空間分解能 1 cm を得た。

以上の研究成果は，FMCW 方式の光距離センサの性能を大幅に向上させ，正確な物体形状計測技術に貢献するものであり，博士（学術）に値すると判断した。

４．審査結果　(1) 判　　定（いずれかに○印）　（合　格）・　不合格

(2) 授与学位　博　士（　学術　）