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LINEARIZATION OF NONLINEAR BEAT FREQUENCY IN FMCW INTERFEROMETRY THROUGH WAVEFORM MODIFYING TECHNIQUE

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ABSTRACT

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, in which the information regarding the distance can be extracted after FFT analysis. However, practically, linearity in the optical frequency sweep is difficult to obtain, and this leads to variation of the beat frequency in time. Nonlinear optical frequency sweep has become a challenging issue in the research topic to be solved recently. In this report, we proposed a linearization method by modifying the frequency modulation (FM) waveform through the external sampling technique to reduce the effect of nonlinear optical frequency sweep. In this technique, triangle FM sweep is generated 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 new constructed signal was later retransmitted to the system as a new FM sweep signal. The process was repeated until the stability of the beat frequency was noticeably improved. 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 optical frequency sweep.

Keywords: linearization method, modified waveform, non-linear beat frequency, optical frequency sweep, pre-distorted waveform, sampling technique.

1. INTRODUCTION

FMCW works on the frequency difference between the reflected signal and reference signal received at the photo detector; this is known as a beat signal. The beat signal shifts in frequency as the relative delay between the references and reflected signals changes, and is used to calculate the target distance.

Ideally, the FMCW system with linear frequency sweep gives the constant frequency beat as illustrated in Figure-1. Thus the targeted distance can be measured accurately using (1) and (2).

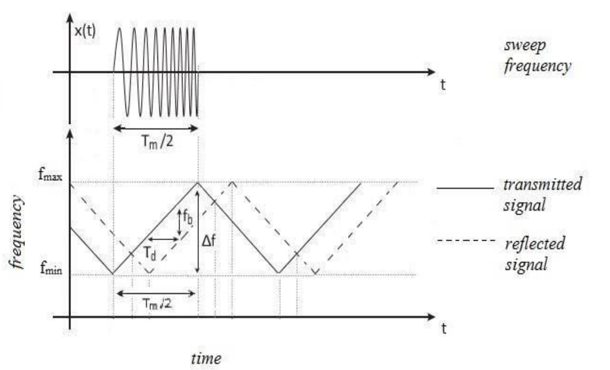

Figure-1. Optical FMCW system of linear frequency sweep gives constant value of beat frequency.

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, $= 3 \times 10^8$ m/s is the velocityof light, Tm indicates the period of the optical frequency sweep, Δf represents the span width of the optical frequency sweep, and τ denotes the delay between reflected and reference signal.

However, the performance of FMCW is affected by the span width and the period of the optical frequency sweep, and linearity of the optical frequency sweep. Nonlinear optical frequency sweep can severely degrade the measurement accuracy because it causes ambiguity in the system, making it hard to determine the target range and range resolution [1] [7].

This is because nonlinearities in the optical frequency sweep can cause non-steady interference beat signal because the beat frequency is not focused at a single frequency. Conversely, if the frequency is linearly swept, constant beat frequency allows the system to focus at a single frequency, and the target distance's information can be extracted accurately [5] [7]. Figure-2 illustrates how nonlinear frequency sweep affects the frequency beat's constancy.

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$$\bar{T}_{mn} \quad \underline{f_b \times \square \times} \tag{1}$$

$$\overline{4\times\Delta} f\_ \tag{2}$$

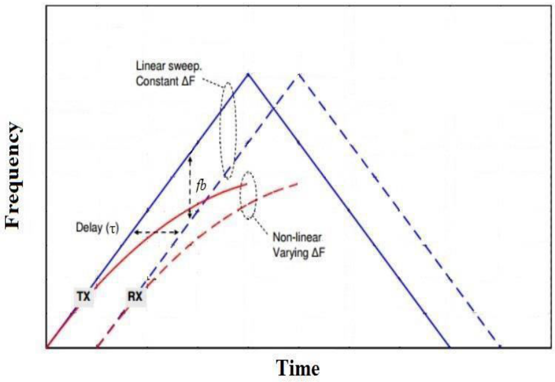

Figure-2. Optical FMCW system of non-linear frequency sweep contributes to the nonlinearity of beat frequency.

The beat frequency variation can be categorized into two groups: inter-ramp variation and intra-ramp variation. As in Figure-3, inter-ramp beat frequency variation is obviously seen between ramp-up (ascending modulation interval) and ramp-down (descending modulation interval) of the waveform signal due to the heating and cooling effect of a laser diode. In contrast, intra-ramp beat frequency variation occurs due to a delay, especially at the beginning of both ramping up (ascending modulation interval) or at the beginning of the ramping down (descending modulation interval) before the solid beat frequency period can be seen [5]. This phenomenon can be clearly seen as in Figure-4.

Figure-3. Inter-ramp nonlinear beat frequency illustration that shows the non-identical value of beat frequency during signal rising and falling.

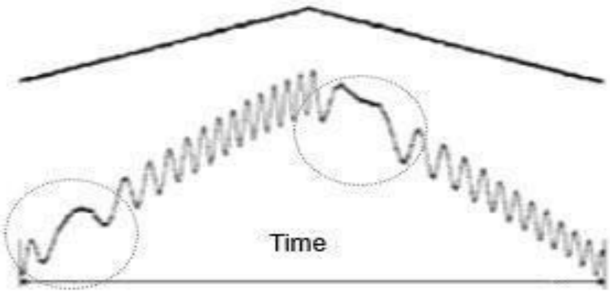

Figure-4. Intra-ramp nonlinear beat frequency illustration that shows that the non-identical value of beat frequency occurs at the beginning of each rising and falling signal span [5].

References [3] [6] mentioned that by creating adelay or adopting a delay structure to the system, this nonlinear issue can be successfully corrected. Some early efforts to improve the linearity of the frequency sweep have been made in hardware and software approaches such as Voltage Controlled Oscillator (VCO) [2], Fixed Delay structure [3] and Linearization Algorithm on simulated data [4] adopted in the FMCW system for its linearization. In this document, the main idea is to focus on linearizing the optical frequency sweep for constant beat frequency by modifying the FM waveform. Tiny deterioration of FM waveform was obtained after the signal was sampled at the external sampling rate (temporal sampling).

2. NONLINEAR CORRECTION

In this experiment, we focused on generating a constant beat frequency by modifying the triangle FM waveform through the external sampling technique. The FM triangular signal was sampled with the sampling interval corresponding to the instantaneous period of the interference signal. The sampling interval is constant when the optical frequency is linearly swept, and is varied in time if the optical frequency is nonlinearly swept. After sampling the FM triangular signal with the AD Converter, one period interval of the sampled FM triangular signal was extracted and was used to reconstruct a new FM triangle signal. Then the new constructed FM triangular signal was transmitted back to the system. The shape of the FM triangular signal after two iterations of external sampling showed pre-distortion at both high peak and low peak of the wave, as shown in Figure-7 & 9 in Section 3. Nonlinearity at the beginning of each ramp can be slowly corrected by this resampling technique. This is because resampling the FM triangular signal creates a tiny distortion on the waveform signal, especially at the beginning of each ramp (ascending and descending modulation interval). In this report, we concentrated on correcting the inter-ramp nonlinear issue, specifically to reduce the effect of nonlinear beat frequency as seen at the beginning of the ramp since the intra-ramp

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nonlinear issue involves the switching process of heating and cooling of the laser diode.

To ensure the optimum result of frequency beat is obtained, the value can be measured by the $\Delta fb/fmax$ formula. Evaluating the $\Delta fb/fmax$ of the frequency beat could obtain a significant value of the linearity drawback as shown in Figure-5. The optimum value of frequency beat is best at the lowest value of $\Delta fb/fmax$.

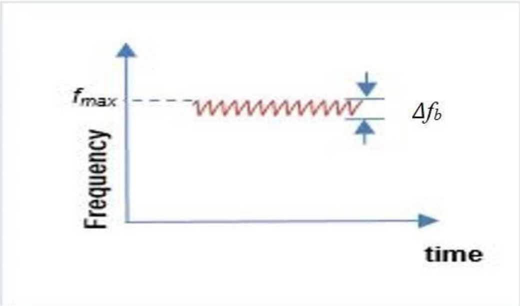

Figure-5. Evaluation of the significant value of frequency beat.

3. EXPERIMENT

3.1 Experiment setup

The experiment setup of optical FMCW laser ranging system is shown in the block diagram in Figure-6. P1 indicates the reference path signal while P2 represents the delay path signal. In this experiment, a 1-meter fiber was added to P2 to create a delay in the signal that represents the reflected signal. The waveform voltage generator generated the frequency carrier signal at different selected frequencies; 500Hz was used in this experiment, with an amplitude of 500mVpp. By imposing a 500Hz Frequency Modulation on a laser diode the signal was transmitted through the isolator then split into two paths: P1 and P2. The signal was later detected by the photo detector and captured by the oscilloscope as depicted in Figure-6 before sending it to the Analog Digital Converter for FFT analysis. In this experiment, we used the triangle type of waveform signals.

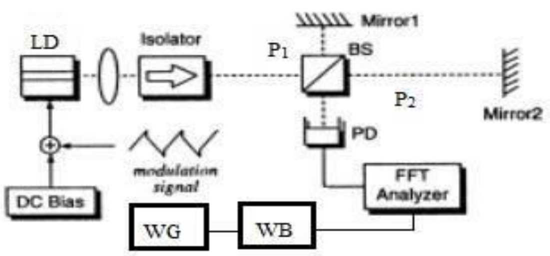

Figure-6. Block diagram of FMCW laser ranging experiment.

After 1st- sampling the frequency modulation signal, tiny distortion was formed on the triangle waveform. By using Waveform Builder software (Agilent Technology), one period interval of distorted waveform was extracted and a new triangle waveform of 500Hz Frequency Modulation was constructed. This process was repeated for the 2nd- sampling process. The results of frequency beat and frequency spectrum were captured and saved during the experiment for each sampling condition.

3.1 Experiment parameters and methodology

Waveform type signal:	Triangl e
Frequency variation:	500Hz
Amplitude variation:	500mVpp
Data number:	8192
Delay length P2:	100cm

Referring to the block diagram of FMCW laser range as in Figure-6, the experiment was executed following the steps in Table-1.

Table-1. Experiment chronology

Steps	Operating method
Step 1	Generate triangle FM wave, 500Hz at 500mVpp, and launch the laser diode to transmit the signal through P1 and P2
Step 2	Observe the FM triangle waveform and capture the beat frequency waveform at oscilloscope
Step 3	Signal Processor/ADC – Perform FFT analysis (external sampling at 8192 data number) and save the new FM waveform after sampling
Step 4	Import the saved waveform and use Waveform Builder software to extract one period interval of the triangle waveform and reconstruct new FM signal waveform
Step 5	Export the new constructed FM waveform to the wave generator/modulator
Step 6	Re-transmit the signal and capture the frequency beat waveform at the oscilloscope. Save the waveform.
Step 7	Perform FFT analysis for the 2nd time (external re-sampling at 8192 data number) and save waveform
Step 8	Repeat steps 4, 5, 6 and 7.

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4. RESULT AND DISCUSSIONS

4.1 Resampling effect on frequency beat and signal deterioration

Figure-7 & 9 compare the results of frequency beat variation (converted to voltage by using frequency-to- voltage converter) among non-modified, 1st time sampling of frequency modulation and 2nd time re-sampling of frequency modulation. Non-sampling waveform of frequency modulation gives a larger and nonlinear value of the frequency beat. After the 1st external sampling of frequency modulation, the frequency beat is seen becoming linear gradually as shown in the graph. However, after the 2nd re-sampling, the linearization of the frequency beat can be clearly seen.

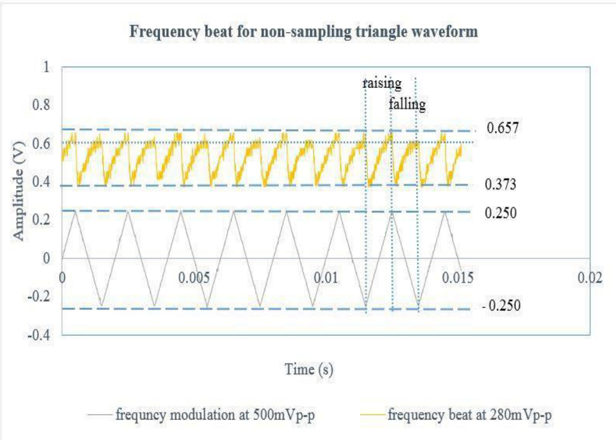

Figure-7. Frequency beat for non-sampling frequency modulation.

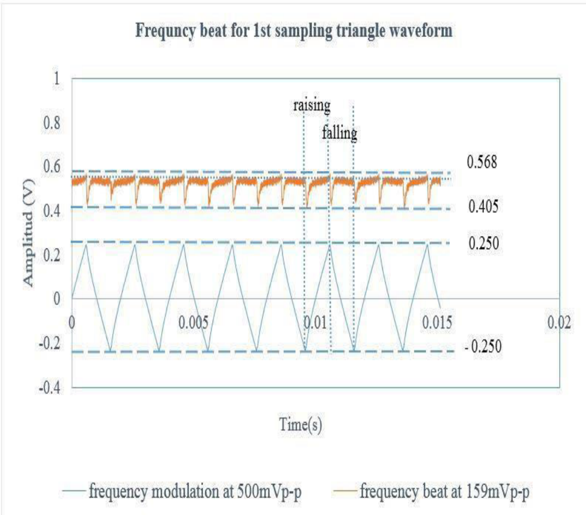

Figure-8. Frequency beat after 1st sampling frequency modulation.

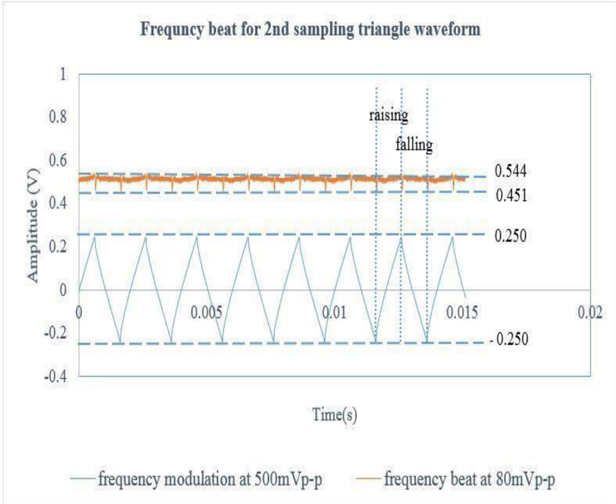

Figure-9. Frequency beat after 2nd sampling frequency modulation.

The reduction on nonlinear frequency beat obtained was related to the significant change in the frequency modulation signal after being sampled the 1st and 2nd time. During the observation of the triangle waveform frequency modulation signal as depicted in Figure-7 & 9, a tiny deterioration in the frequency modulation waveform, especially at the beginning of each rise up and fall, slowly occurred as the value of the number of sampling times increased.

4.2 Frequency spectrum

Nonlinearities in the frequency sweep can cause a nonlinear frequency beat. FFT analysis showed that nonlinearity issues effect the broadening of the frequency spectrum of the interference beat signal. Figure-10 shows the broad spectrum due to nonlinear frequency sweep after undergoing FFT analysis.

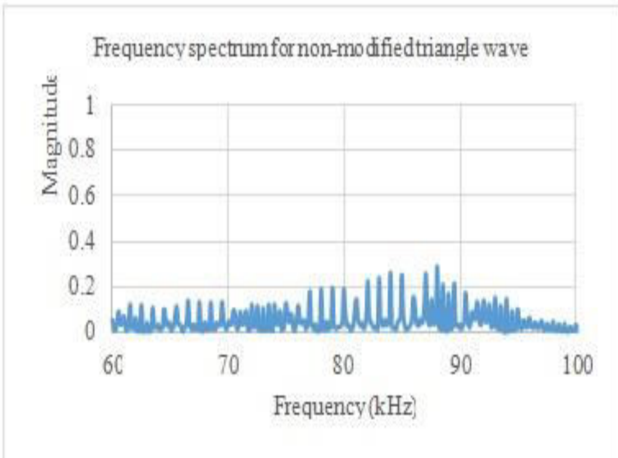

Figure-10. Frequency spectrum of non-modified frequency modulation signal.

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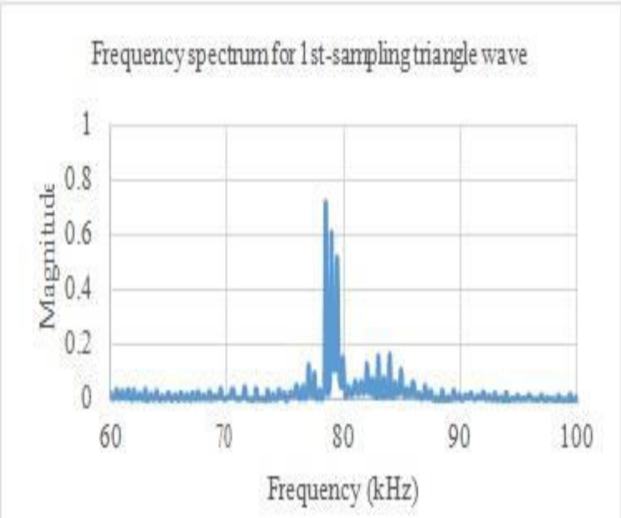

Figure-11. Frequency spectrum of 1st-sampling frequency modulation signal.

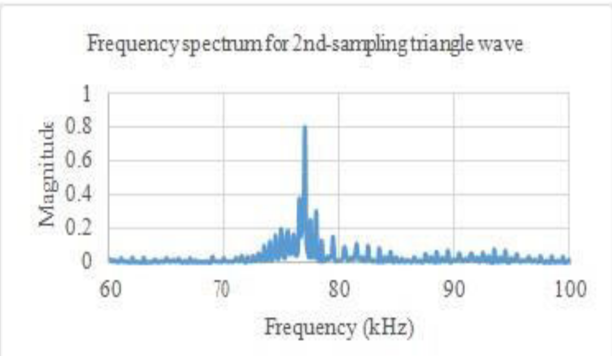

Figure-12. Frequency spectrum of 2nd-sampling frequency modulation signal.

As indicated in Figure-11 & 12, 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.

4.3 Spectrogram

Spectrogram is another useful tool for visualizing the time-depending frequency spectrum of a signal. Spectral representations created in the spectrogram show how the spectral density of signals varies with time. The result of the frequency spectrum of non-modified 1st and 2nd time external sampling can be seen in Figure-13 & 15 accordingly.

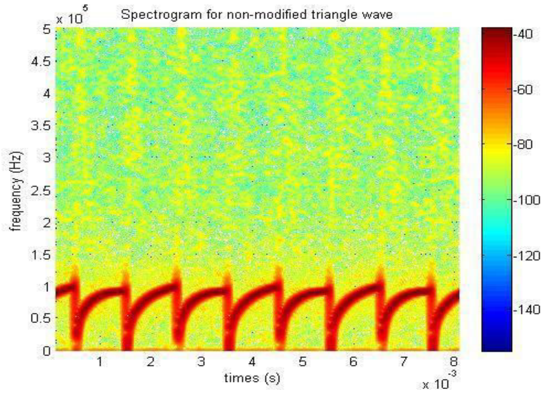

Figure-13. Frequency spectrum for non-modified frequency modulation signal using spectrogram.

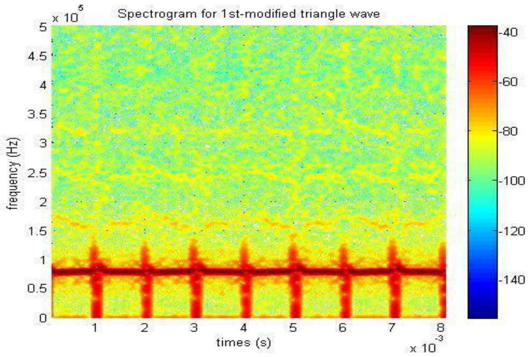

Figure-14. Frequency spectrum for 1st-sampling frequency modulation signal using spectrogram.

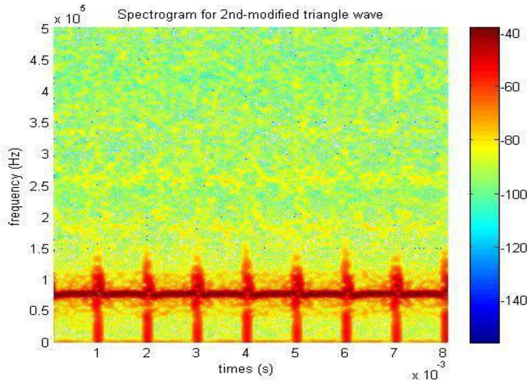

Figure-15. Frequency spectrum for 2nd-sampling frequency modulation signal using spectrogram.

4.4 Computation of $\Delta f_b/fmax$

Computing the $\Delta f_b/f_{max}$ 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 Figure-16.

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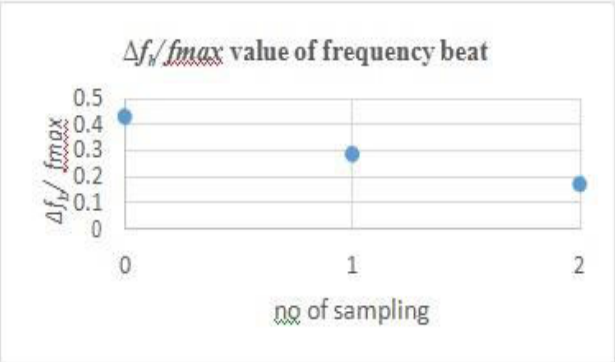

Figure-16. $\Delta f_b / f_{max}$ value of frequency beat against number of sampling times.

As can be seen from the above figure, the higher the number of sampling times, the smaller the value of $\Delta fb/fmax$ we could achieve. This indicates that the linearization of frequency beat is improving firmly.

5. CONCLUSIONS

In this paper, we tested a 100cm fiber length and the delay created at P2 was 6.67ns using equation (2). A symmetrical triangular sweep was employed due to its smooth transition and ease of realization which allowed easy separation of the difference frequency (5). All data collected in the experiment were focused at ascending modulation intervals of sweep frequency (ramp-up). We presented a modifying waveform technique through external sampling for nonlinear correction of the beat frequency. External sampling employed on FM created a tiny deterioration in the waveform and was introduced as a new transmitted FM signal to the fiber ranging system. After the 2nd iteration, the nonlinear issue was noticeably improved. When the frequency beat is linear, FFT spectral analyzer will focus at a single frequency, thus accurate information on the target distance can be extracted. From the experiment, the result clearly showed that this method effectively reduced the nonlinear effect on frequency beat.

REFERENCES

[1] Mohammad U. Piracha. 2011. 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, No. 12, pp. 11213-11219.

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

[3] Soo-Yong Jung, Seong Ro Lee and Chang-Soo Park. 2013. "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.

[4] Stefan Scheiblhofer, Stefan Schuster and Andreas Stelzer. 2006. "Signal model and linearization for nonlinear chirps in FMCW radar SAW-ID Tag request", IEEE Transactions on Microwave Theory and Techniques, Vol.54, No. 4.

[5] Daniel Nordin and Kslevi Hyyppa. 2005. "Using a discrete thermal model to obtain a linear frequency ramping in an FMCW system", Opt. Eng. Vol. 44, No. 7, 074202, July 07.

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

[7] Mohammad Umar Piracha. 2012. "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.

[8] Arseny Vasilyev. 2013. "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.

[9] Koichi Iiyama, Takuya Okamoto and Saburo Takamiya. 1998. "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.