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COMPACT AND PRECISION RANGE FINDER USING SELF-MIXING SEMICONDUCTOR LASER

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ABSTRACT: Proposed is improved compact self-mixing type semiconductor-laser range finder, which measures mode-hop time interval (MHI). Measurement error caused by the fluctuation of MHI is greatly reduced by averaging many contiguous MHI's. The main cause of measurement error 1.5% at ranges from 0.1m to 0.8m is attributed to the optical phase change of a returned light from a focusing lens. Accuracy improvement by stabilization of the returned light is suggested.

1. INTRODUCTION

The optical triangulation range measurement principle has been widely adapted to measure a distance to a target with rough surface. However, the range finder according to the principle has a disadvantage of large size. OPTOCATOR(1) has a high accuracy of 0.025% for measuring range of 8mm through 512mm, however its size is large.

An FM heterodyne measurement system using two Michelson interferometers(2) also has a disadvantage of large size despite its measurement accuracy of 0.01% for a range of 500mm.

As a range finder using the self-mixing effect of a laser diode, Beheim et al.(3) proposed to measure the number of mode hops induced by the light reflected from rough surface back into the laser diode. This method suffers from the one-count uncertainty or the standard deviation of 2.7mm when the range is less than 400mm. On the other hand, de Groot et al.(4) have demonstrated another self-mixing type range finder, which measures a beat signal frequency proportional to the target range. The accuracy was about 20mm for distances from 0.25m to 2.35m.

In this paper, we propose an improved self-mixing type range finder, which measures mode-hop interval(MHI), i.e., the time interval between successive external-cavity mode hops. The influence of the laser FM noise on the accuracy is investigated experimentally by varying LD drive current. Measuring error caused by the fluctuation of MHI can be greatly reduced to 0.1% by means of averaging a hundred contiguous MHI's. Furthermore, another causes of measuring error are investigated experimentally.

2. SETUP CONFIGURATION

Schematic configuration of an experimental setup for measuring a range from an LD to a target is shown in Fig.1. A light beam emitted from a frequency modulated LD is focused by a lens onto a white paper target. The light scattered back from the target into the laser causes external-cavity mode hops, which produce discontinuities in the light output power. A signal obtained from a photodiode(PD) is fed into a measuring circuit and processed by a microcomputer to give a measured range.

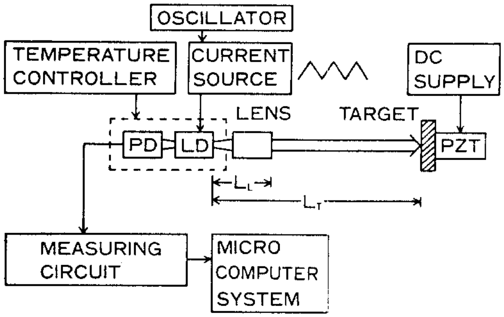

Fig.1 Schematic configuration of experimental setup for a range finder.

3. PRINCIPLE OF MEASUREMENT

The output signal from the PD and some waveforms in the measuring circuit are shown in Fig.2. The signal(a) from the PD has stair-like discontinuities, which are introduced by the mode hops. The mode-hop interval(MHI) corresponds to the free-running frequency difference between consecutive external-cavity modes. The PD output is differentiated through a high pass filter(HPF) to produce a pulse train(b). The gate

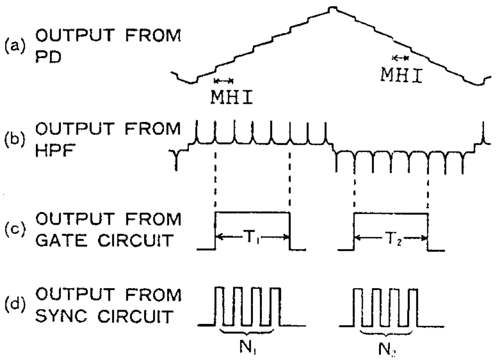

Fig.2 Principle and method of range measurement.

pulse(c) synchronized with the pulse train(b) has gate widths T_1 and T_2, which are counted using a clock with a pulse rate of 10MHz. The number of mode hops N_1 and N_2 are also measured by counting the number of pulse contained in the output waveform from a synchronous circuit. Therefore the range L_T to the target is given by the following equations, provided that the target speed is not so high,

$$L_T=cT/(4i_m\,\Delta F_e T_M) \qquad (1)$$

$$1/T_M=(N_1/T_1+N_2/T_2)/2 \qquad (2)$$

where c is the light velocity, T the period of the triangular wave current, i_m the peak-to-peak amplitude of the current, ΔF_e the effective FM modulation efficiency, and T_M(=MMHI) the mean value of the N_1+N_2 MHI's. ΔF_e is defined as follows. For several properly chosen distances, several ΔF_e's are calculated by eq.(1) using measured T_M's corresponding to each distance. Then many points of thus measured ranges are plotted against the ranges measured with a metal scale. In this plot, a mean modulation efficiency obtained from the several ΔF_e's is used. Finally, by the least square method, a straight line that best fits the measured points is obtained. ΔF_e is defined from the straight line.

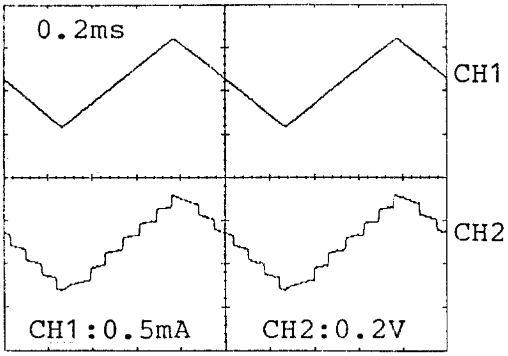

Fig.3 Modulation current waveform(upper) and PD output waveform(lower). L_T=30cm, f_m=1kHz, i_m=1mA_{p-p}, ξ_T=2.8

4. MEASUREMENTS, RESULTS AND DISCUSSION

4.1 Measurement Condition

An AlGaAs laser(SHARP LT024) with a maximum power output of 30mW is used. The wavelength λ is 780nm, and the drive current is 1.46-1.60 times threshold current I_{th}=46.2mA. The temperature of the laser mount is controlled within ±0.01°C. An assorted collimating lens(OLYMPUS AV9030) is placed near the LD.

4.2 Optical Feedback Ratio Required for Measurement

A laser modulation current waveform and a typical PD output waveform are shown in Fig.3. The modulation frequency f_m=1kHz, the current amplitude i_m=1mA_{p-p} and the range to a target L_T=30cm are set constant. In order to find the amount of returned light necessary to range measurement, both the PD output waveform and its differentiated waveform, i.e., the mode-hop pulse train are measured and recorded as a function of the optical feedback parameter ξ_T, the definition of which will be given in eqs.(3)-(5). The parameter ξ_T for an identical LD is proportional to square root of the returned light normalized by the emitted light(5). The parameter ξ_T is adjusted by an ND filter inserted between the LD and the target. In case of ξ_T=2.8, both the magnified PD output waveform and the mode-hop pulse train are shown in Fig.4. One clear and stable mode-hop pulse at every onset time of mode hop is obtained in Fig.4, therefore the MHI can be measured by counting the time interval between the two successive mode-hop pulses by the use of a clock counter.

When the optical feedback parameter is set in the range of $1.6\lesssim\xi_T\lesssim3.3$ the stable mode-hop pulse train is obtained, and the range measurement is performed. However, in the two regions of the feedback parameter as $0.7\lesssim\xi_T\lesssim1.5$ and

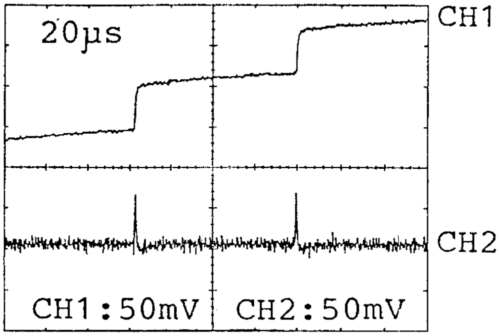

Fig.4 PD output waveform (upper) and mode-hop pulse train(lower). ξ_T=2.8

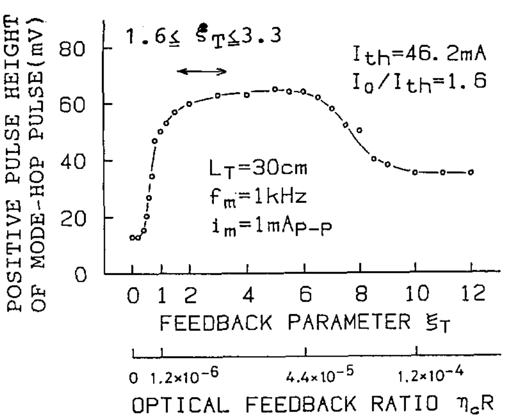

Fig.5 Positive pulse height of the mode-hop pulse train versus the feedback parameter ξ_T or the optical feedback ratio $\eta_c R$.

$3.5 \lesssim \xi_T \lesssim 6$ the PD output has stair-like waveform with one or a few jitter pulses at the rise or fall time of the waveform. Consequently, the mode-hop pulse train has several consecutive positive-negative-double pulses in the vicinity of the occurrence of mode hopping. Furthermore, in case of $\xi_T \gtrsim 12$ the mode-hop phenomenon is not observed presumably due to generation of multimodes in the LD.

A positive pulse height of the mode-hop pulse train is shown in Fig.5 as a function of the feedback parameter ξ_T or the optical feedback ratio $\eta_c R$. According to eq.(1) in reference(5) the ξ_T is given as

$$\xi_T = Z\, \tau_T (1+\alpha^2)^{\frac{1}{2}} \qquad (3)$$

$$Z = (c/2nl)[(1-R_D)/(R_D)^{\frac{1}{2}}](\eta_c R)^{\frac{1}{2}} \qquad (4)$$

$$\tau_T = 2L_T/c \qquad (5)$$

where τ_T is a round trip time between the LD and the target, α the linewidth enhancement factor, n refractive index of the LD cavity, l the length of the LD cavity, R_D the reflectivity of the laser facet, η_c the ratio of the light power illuminating the laser facet to the returned light power, R the ratio of the returned light power to the emitted power i.e., the apparent optical feedback ratio. By putting L_T=30cm, α=2.5, n=3.6, l=300μm, and $R_D=(n-1)^2/(n+1)^2$, the optical feedback ratio $\eta_c R$ is expressed as

$$\eta_c R = 1.24 \times 10^{-6}\, \xi_T^2 \qquad (6)$$

Using an estimated value of η_c=3.2%, the stable region of the apparent optical feedback ratio is given as

$$10^{-4} \lesssim R \lesssim 4.4 \times 10^{-4} \qquad (7)$$

,which indicates the magnitude of the optical feedback ratio. When the distance L_T is changed the R changes approximately proportionally to $1/L_T^2$, while the round trip time changes proportional to L_T. Therefore, according to eq.(3) ξ_T has tendency to be maintained almost constant independent of distance. In fact, range measurement has been performed over a wide dynamic range of 0.1m to 0.8m.

4.3 Error Reduction by FM Noise Reduction

MHI Fluctuation Due to FM Noise: As can be seen from Fig.3 every MHI differs slightly from each other. One of the cause of the MHI variation may be attributed to the FM noise of the LD. Fig.6 shows the oscillation characteristics of an LD with FM noise. In case of (a), when the solitary laser frequency f_0 is increased linearly by decreasing drive current proportionally to time the actual oscillation frequency f of emitted light varies as shown with a solid curve. The mode hop occurs at frequencies of f_{01} and f_{02}, where the derivative of the dotted curve becomes infinity(6). On the other hand, the PD output varies as shown with a solid curve in case of (b). The mode-hop interval(MHI) corresponding to the frequency difference of $f_{02}-f_{01}=c/2L_T$ is shown.

In Fig.6, owing to the FM noise, the timing when f_0 becomes f_{01} or f_{02} is different every cycle of the triangular wave. Therefore, the MHI in a definite order during the half period is different every cycle to cycle. The maximum MHI deviation Δt from the mean value of many definite order MHI's is equal to the maximum onset-time deviation Δt as shown in Fig.6(b). The Δt is assumed proportional to the amplitude of FM noise. According to Fig.8, the Δt measured for L_T=30cm is two times the standard deviation, i.e., 10μs, which is 12% of the mean MHI of 82μs. The Δt corresponds to the frequency variation of the solitary laser, i.e., $60\mathrm{MHz}_{p-p}$, which agrees well with the measured frequency variation of $50\mathrm{MHz}_{p-p}$. Therefore, it is expected that measurement error due to FM noise can be reduced by reduction of the laser FM noise.

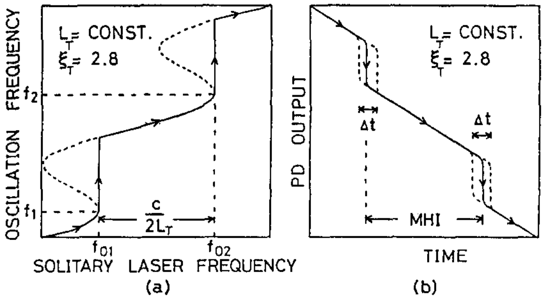

Fig.6 Oscillation characteristics of laser diode with FM noise.

Error Reduction by FM Noise Reduction: Fig.7 shows the standard deviation of measured MHI as a function of the square root of the power spectral density of the LD without external feedback. Parameter is a drive current normalized by the threshold current. The FM noise of the free-running laser diode is reduced by increasing the drive current(6). Only one MHI positioned in the second order among the four MHI's during the ascending half period is measured. The standard deviation of a hundred thus measured MHI's is shown by black circles, while white circles show the standard deviation calculated from both the former and the latter half of the hundred MHI's. From Fig.7 it is confirmed that the measurement error can be reduced by reducing the FM noise of the free-running laser. However further study is required on reducing the FM noise of a frequency modulated laser diode to obtain a remarkable reduction of error by only this method.

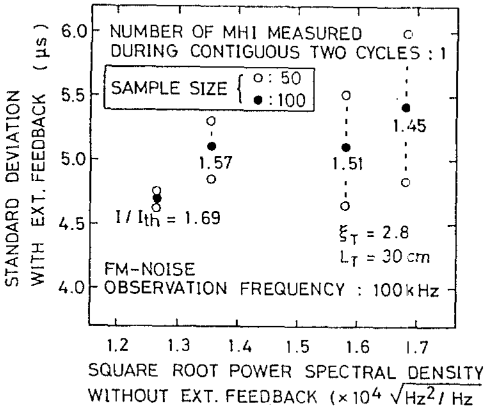

Fig.7 Standard deviation of measured MHI as a function of square root of the power spectral density of laser diode without external feedback.

4.4 Error Reduction by Averaging Several MHI's

First, only one MHI positioned in the second order among several MHI's during one ascending half period is measured. Both the averaged value and the standard deviation of a hundred thus measured MHI's are shown in Fig.8 with white circles as a function of a range L_T. Secondly, the mean MMHI of several (four to seven) MHI's during contiguous two cycles is measured. Both the averaged value and the standard deviation of a hundred thus obtained MMHI's are also shown with white triangles.

The averaged value of the hundred MMHI's is assumed as a measured T_M shown in eq.(1). The theoretical straight line calculated from eq.(1) fits well with the measured T_M shown by the white triangles.

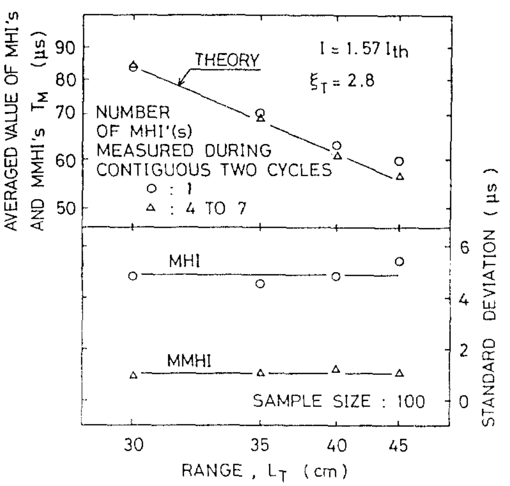

Fig.8 Averaged value and standard deviation of both MHI's and MMHI's versus range. Note:The coordinates is logarithmic.
MHI=MODE-HOP INTERVAL, MMHI=MEAN MHI

On the other hand, the standard deviation obtained from the hundred MMHI's is reduced to approximately a fifth of that obtained from the hundred MHI's. This fact demonstrates that obtaining a range data from the mean value of several contiguous MHI's is effective in reducing measurement error. The standard deviation of MMHI is almost independent of ranges from 30cm to 45cm. The measurement accuracy expressed by one σ is 1.1% to 1.9% for ranges from 45cm to 30cm. It will be discussed in the next section 4.5 that the accuracy of a few percent is caused by the optical phase change of a returned light reflected back from the collimating lens.

4.5 Error Caused by Phase Change of Two Returned Lights Reflected from Both Lens and Target

Time Dependent FM Modulation Efficiency: When an LD is frequency modulated with a triangular wave current, the frequency waveform of an output light slightly differs from the ideal one(7). Both a modulation frequency f_m $(=1/T)=0.5$kHz and a modulation current $i_m=7\text{mA}_{p-p}$ are set constant in and after this experiment. Fig.9 shows the theoretical waveform of the normalized instantaneous FM modulation efficiency $\Delta F(t)$ for a frequency-modulated LD with optical feedback from only a lens. The curve of $\Delta F(t)$ has two similar pseudo-sinusoidal waves superimposed on a monotonously increasing periodic curve during both the first and the second half cycle of the triangular wave. The ideal modulation efficiency A_1 shown by the dotted line is given by

$$A_1 = \Delta f / i_m \qquad (8)$$

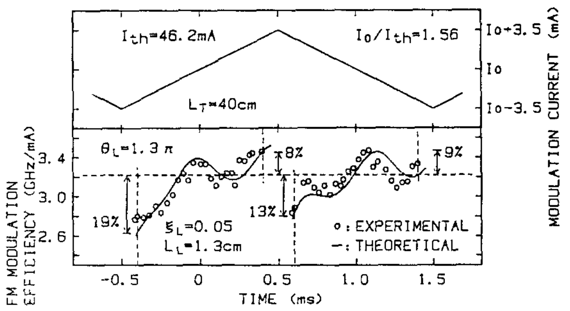

Fig.9 Theoretical instantaneous FM modulation efficiency(solid line) of laser with optical feedback from lens only, and experimental FM modulation efficiency (white circles) versus time.

where Δf is the maximum frequency deviation of the solitary LD without optical feedback. The experimental curves shown by white circles agree well with the theoretical one(7). The experimental condition is that i_m=7.00mA, L_T=30.0cm and T=2.00ms, while the theoretical assumption is that the feedback parameter of the lens ξ_L=0.05, the distance to the lens L_L=1.3cm and θ_L=1.8π. Where θ_L is an approximate value of the effective optical phase of the returned light from the lens. The amplitude of the pseudo-sinusoidal wave is approximately proportional to the ξ_L, and the position of peaks and valleys in that waveform are moved within the half period in accordance with the phase change of the returned light from the lens.

Variation of Instantaneous Modulation Efficiency Due to Lens : In order to intentionally change the optical phase of a light reflected from the fixed lens, the optical frequency is varied by setting the laser drive current from 71mA to 76mA. An instantaneous FM modulation efficiency calculated from the one MHI positioned near the center of ascending half cycle is shown in Fig.10 as a function of a bias current. To avoid the influence of the phase variation of the light reflected from the target, the center time of the measuring gate pulse shown in Fig.2 is maintained almost zero μs, i.e., the center of the ascending half cycle. According to Fig.10, the FM modulation efficiency varies pseudo-sinusoidally as a function of current, namely, an optical frequency.

The measured period of current 2.7mA corresponds to optical frequency change of 11.1GHz, which agrees well with the free spectral range of $c/2L_L$=11.5GHz calculated using the estimated value of L_L=1.3cm. Furthermore, the maximum deviation of the FM modulation efficiency 11.2% agrees well with the estimated corresponding value of $(1+\xi_L)/(1-\xi_L)$ =11.1%. This fact verifies that the waveform of the instantaneous modulation efficiency changes in accordance with the optical phase change of a light reflected from the lens.

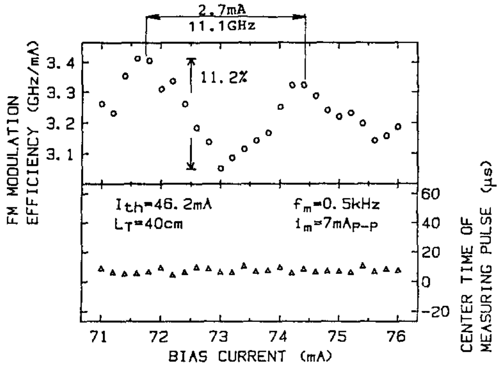

Fig.10 Instantaneous FM modulation efficiency obtained from one MHI as a function of laser bias current. (Error due to lens.)

Error Due to Lens: The mean modulation efficiency ΔF_M is measured for a target fixed at L_T=40cm is shown in Fig.11 as a function of a bias current. The maximum variation of ΔF_M or a measuring error is 1.74%, which is observed during the current period of 2.7mA, which corresponds to the optical phase change of 360 degrees. The reduced error of 1.74% is approximately a sixth of the maximum deviation 11.2% in Fig.10. This fact demonstrates that an influence of the sinusoidal variation has been reduced by averaging many MHI's(in this case 31) within the measuring gate pulse. A measurement error of ΔF_M caused by the laser temperature change is estimated 4.2%/°C from Fig.11 during the temperature change ±0.1°C, when operated at I=72mA.

The estimated changes of both the room temperature and the laser temperature during 2 minutes of measurement are 0.1°C and 0.004°C, respectively. It is confirmed that in this measurement not only the error due to the target but the the error due to the lens induced by the room temperature change are negligible.

Error Due to Target: The stair like waveform produced by the mode hop is shifted by a certain time interval along the slope of the triangular wave, when the optical phase of the returned light from the target is changed. The maximum shift of the position of the measuring gate pulse caused by the phase change is the MHI. Because MHI is inversely proportional to the range L_T, a maximum error due to the measuring gate shift is expected at the lower bound of a dynamic range of measurement. The mean FM modulation efficiency ΔF_M measured for a fixed target at L_T=10cm is shown in Fig.12 as a function of the voltage applied to the PZT supporting the target. The half-wavelength voltage of the piezoelectric transducer(PZT) is 15V.

According to Fig.12, the maximum

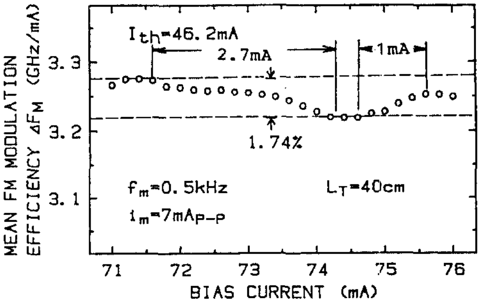

Fig.11 Mean FM modulation efficiency ΔF_M obtained from a hundred MMHI's as a function of laser bias current.
(Error due to lens.)

deviation of ΔF_M is 0.64%, which is mainly due to the optical phase change of the returned light from the target. Because a measurement error due to the measuring gate shift is approximately inversely proportional to the range L_T, the measured error due to the target for a range L_T=40cm is estimated as a fourth of the 0.64%, i.e., 0.1%. This value approximately coincides with the 0.073% shown in Fig.13.

4.6 Proposal to Eliminate Error Due to Lens

For a target fixed at range L_T=40cm, a hundred contiguous MMHI's are measured and processed by a microcomputer(PC8801) for about 0.8 seconds. In this case, every MMHI is obtained during 2ms, i.e., the one period of the triangular wave. The average of the hundred MMHI's is assumed as a measured T_M, which is converted into ΔF_e using eq.(1) However, in this experiment, the ΔF_e should be replaced by ΔF_M, which means the mean FM modulation efficiency calculated from the average of many MMHI's. Fig.13 shows twenty five ΔF_M's measured continuously during 20 seconds as a function of time.

The peak-to-peak variation of ΔF_M measured during 20 seconds is 0.073%. This value coincides with the estimated variation of 0.1%, which is caused by the optical phase change of a returned light from the target due to a estimated room-temperature change of 0.015°C during the twenty seconds. On the other hand, the variation of ΔF_M caused by the optical phase change of a returned light from the lens due to the same change of the room temperature is estimated as 0.02%, which is approximately a hundredth of 1.74% shown in Fig.11.

Consequently, provided that the temperature of a lens holder determining the distance L_L between the LD and the lens is controlled within a deviation of 0.015°C, it will be possible to obtain a 0.1% variation of ΔF_M, namely 0.1% measurement accuracy.

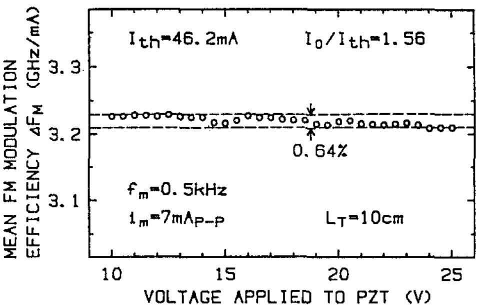

Fig.12 Mean FM modulation efficiency ΔF_M obtained from a hundred MMHI's as a function of voltage applied to PZT.
(Error due to target.)

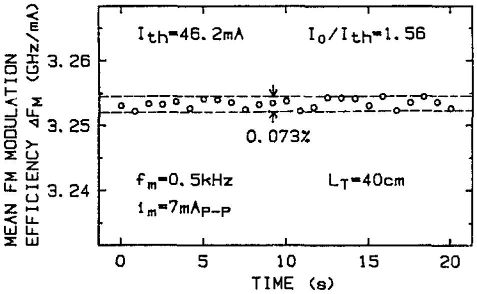

Fig.13 Twenty five mean FM modulation efficiency ΔF_M's measured continuously during twenty seconds.
(Error during short time.)

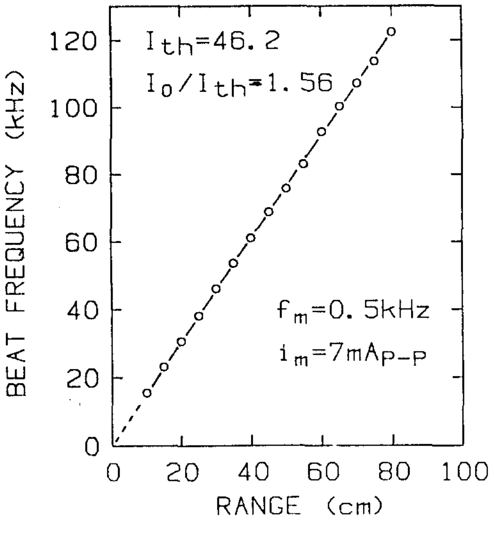

Fig.14 Beat frequency versus range.

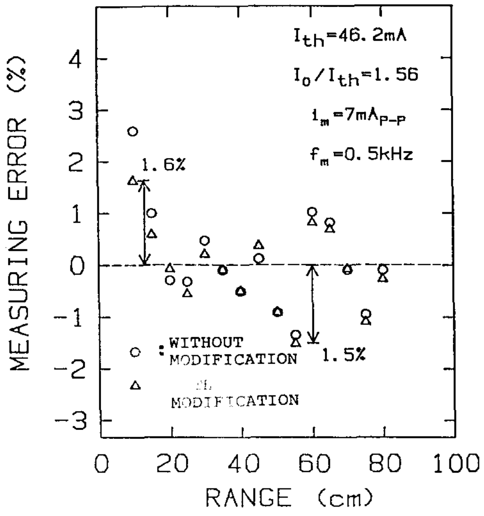

Fig.15 Measuring error with and without modification versus range.

4.7 Measured Accuracy Versus Range

The range to an aluminum foil target is measured using a collimated light beam. The inverse of the measured T_M, i.e., the beat frequency is shown in Fig.14 as a function of range. The T_M is the average of a hundred MMHI's obtained by the method as described in section 4.6. The straight line is drawn by the least square method. The effective FM modulation efficiency ΔF_e is obtained as 3.285GHz/mA, which is calculated from eq.(1) using the slope of the straight line.

As a measuring error, the deviation of the mean FM modulation efficiency ΔF_M from the ΔF_e=3.285GHz/mA is shown in Fig.15 as a function of range. White triangles and white circles represent the error calculated with and without a modification, respectively. The modification method corrects the measured ΔF_M by taking into the measuring gate shift, and is a little effective for measurement of short ranges as 10cm to 15cm. The measuring error of 1.5%-1.6% in Fig.15 is almost equal to the error of 1.74% shown in Fig.11. Furthermore, the phase change of the reflected light from the lens during measuring time of half an hour is estimated more than 180°.

Consequently, the measurement accuracy of a few percent obtained at present is mainly determined by the optical phase change of a reflected light from the lens.

5. CONCLUSION

An improved compact range finder using a self-mixing semiconductor laser successfully measures mode-hop interval (MHI) instead of the number of mode hops. The range to the target is obtained from the mean of several contiguous MHI's (MMHI) and an experimentally determined effective FM modulation efficiency ΔF_e. Measurement error caused by the fluctuation of MHI is greatly reduced by averaging several contiguous MHI's or a hundred MMHI's. The fluctuation of MHI is caused not only by the laser FM noise but by the time dependent FM modulation efficiency. The mean FM modulation efficiency ΔF_M calculated from the average of many measured MMHI's varies in accordance with the optical phase change of two returned lights from the lens and the target, respectively.

Measurement accuracy obtained at present is about 1.5% for ranges from 0.1m to 0.8m. The main cause of the error 1.5% is attributed to the optical phase change of a returned light from the lens. Provided that this returned light from the lens is stabilized, an improved accuracy of 0.1% will be achieved.

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REFERENCES

(1)Optocator, Selective Electronics Co., Sweden.

(2)T.Kobayashi et al.,'High Resolution FM Heterodyne Measurement of Distance Using a Semiconductor Laser', 4th Workshop on Optical Fiber Sensors, Japan Society of Applied Physics pp.53-59, Jan. 1987.

(3)G.Beheim & K.Fritsh,'Range Finding Using Frequency-Modulated Laser Diode', Applied Optics,25, 9, pp.1439-1442 1986.

(4)P.J.de Groot, G.M.Gallatin, and S.H. Macomber,'Ranging and Velocimetry Signal Generation in a Backscatter-Modulated Laser Diode', Appl. Opt., 27, 21, pp.4475-4480 1988.

(5)B.Tromborg, J.H.Osmundsen and H. Olesen,'Stability Analysis for a Semiconductor Laser in an External Cavity,' IEEE J. Quantum Elecron., QE-20, 9, pp.1023-1032 Sept. 1984.

(6)S.Saito, O.Nilsson and Y.Yamamoto, 'Oscillation Center Frequency Tuning, Quantum FM Noise, and Direct Frequency Modulation Characteristics in External Grating Loaded Semiconductor Lasers', IEEE J. Quantum Electron., QE-18, 6, pp.961-970 June 1982.

(7)S.Shinohara et al, 'FM-Modulation Distortion of Light Output from Semiconductor Laser Modulated with Triangular Wave Current', Trans. IEICE, E72, 4, pp.275-278 April 1989.