HIGH ACCURACY OPTICAL 3-D SHAPE MEASUREMENT USING A FREQUENCY-SHIFTED FEEDBACK LASER

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ABSTRACT

A frequency-shifted feedback (FSF) laser, which generates a comb of chirped frequency components, has the potential for long distance and high accuracy optical ranging. In this report, the principles and performance of an FSF laser ranging based on optical frequency-domain ranging were first reviewed. It was confirmed that the laser could achieve a high accuracy, which was less affected by distance up to range of 1Km. An application of the FSF laser to 3-D shape measurement system was described. Preliminary results are reported.

1. INTRODUCTION

Optical frequency-domain ranging (OFDR) is attractive for a wide range of applications such as remote sensing, 3-dimensional shape measurements, medical diagnostics and so on [1,2]. In most systems, the frequency of a laser source is swept over a wide band to generate a frequency chirp. Usually, the linearity of the frequency sweep limits the distance accuracy and the source coherence length limits the range [1]. A frequency-shifted feedback (FSF) laser, which uses an intracavity frequency shifter, has the capability for generating a comb of ideally linear and highly chirped frequency components over a broad bandwidth. Such a light source is promising for long-distance high-accuracy optical ranging applications [3]. In this study, the performance of FSF lasers in OFDR is studied and an application in coordinate measuring systems is reported.

2. FSF LASER OPTICAL RANGING

An FSF laser has a frequency shifter incorporated in its laser cavity such that the intracavity field frequency is shifted by a fixed amount at every round trip transit. As a consequence, the output of the FSF laser behaves differently from conventional lasers [3]. Experimental and theoretical studies suggest that the FSF laser output field is a comb of chirped frequency components. The instantaneous frequency of the chirping components can be expressed as

$$\nu_q(t) = \frac{\nu_S}{\tau_{RT}} t - \frac{q}{\tau_{RT}} + \nu_0 , \qquad (1)$$

where ν_s is the frequency shift, τ_{RT} is the cavity round trip time, q is an integer. Fig.1 shows a schematic of a chirp comb.

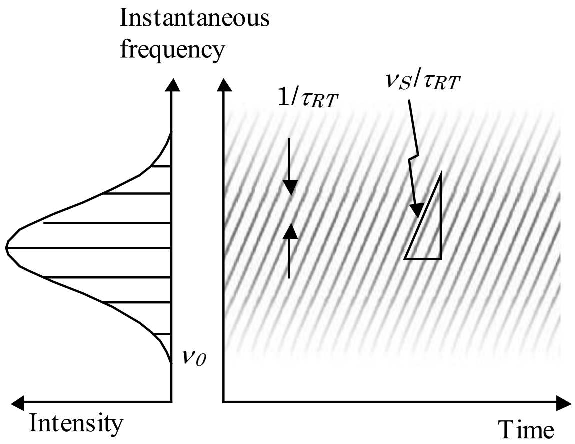

Fig. 1. Schematic of a comb of chirped frequencies

OFDR using an FSF laser is based on the same principle as conventional OFDR techniques. The laser output is injected into an interferometer, then interference between beams from the reference and measurement arms generate a beat signal at a photodetector. This beat signal can be visualized using a spectrum analyzer, for example after performing a Fourier transform of the photodetector time domain electrical signal.

However owing to the FSF laser's output structure consisting of a comb of chirped frequency components, multiple beat signals are simultaneously generated from interference between light beams from a reference arm and the measurement arm. These beat signals can be expressed as [3]

$$\nu_{Bm} = \frac{1}{\tau_{RT}} \left(\nu_S \frac{2z}{c} - m \right) \qquad (2)$$

$$m = \nu_S \tau_{RT} \frac{\Delta \nu_{Bm}}{\Delta \nu_S} - \tau_{RT} \nu_{Bm} \qquad (3)$$

Here c is the speed of light, z is the measurement distance, m is an integer.

Equation (2) indicates that a pair of beat signals is generated within the free-spectral range (FSR) of the FSF laser cavity, given by $1/\tau_{RT}$, and the beat frequencies vary linearly with a variation in interferometer optical path difference as shown in Fig.2. Therefore in contrast to conventional OFDR techniques, the detection bandwidth can be limited to the FSR for any distance. By determining the integer m and with sufficient beat signal power, absolute optical ranging beyond tens of kilometers is possible using the FSF laser.

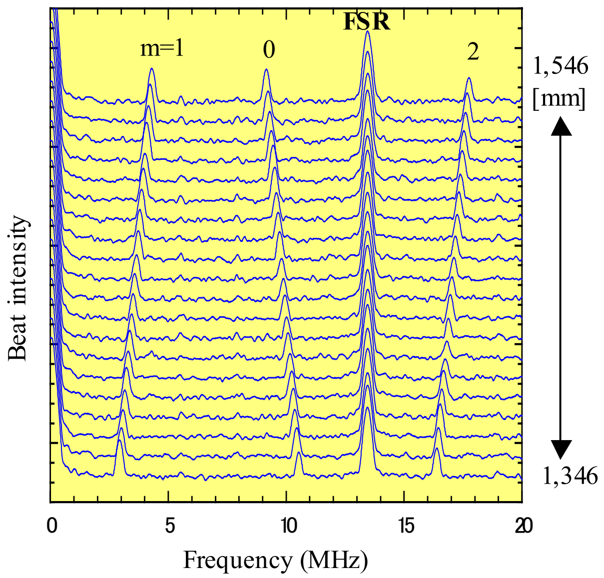

Fig.2. Beat signal variation as a function of interferometer path difference.

The performance of the FSF laser in long-distance ranging technique can be evaluated from the accuracy of the distance measurement. This accuracy is related to the error in determining the center frequency of a beat frequency. Applying the principle of error propagation on the expression in (1) and inserting the FSF laser and measurement system parameters, the distance accuracy can be express as

$$\sigma_z^2 = \frac{c^2}{4\nu_c^2 \nu_s^2}\left(\sigma_{\nu_{Bm}}^2 + \frac{\nu_{Bm}^2}{\nu_c^2}\sigma_{\nu_c}^2\right) + \frac{z^2}{\nu_s^2}\sigma_{\nu_s}^2 \qquad (4)$$

where, $\Delta\nu$ is the laser chirp range or oscillation bandwidth, ν_{Bm} is the beat frequency, ν_c is the cavity free-spectral range (FSR), $\sigma_{\nu c}$ is the error on the FSR, $\sigma_{\nu s}$ is the error on the frequency shift.

3. FSF LASER SOURCE

The FSF laser we used in these studies was a fiber based, σ-type cavity configuration as shown in Fig. 3. The σ-type cavity consists of polarization maintained ring section and non-polarizing section compensated by replacing the polarization axis of a round trip, which are combined using a polarizing beam splitter (PBS). To avoid disturbances due to polarization mode coupling, the ring section was made by simple composition of an isolator and a 0-th order half-wave plate (HWP). The angle of the HWP adjusts the output-coupling ratio (= Sin^2□$_{HWP}$) of the cavity. The non-polarized section has an acousto-optic frequency shifter (AOFS, NEOS Inc. N23090-1-1.55-LTD-3F0) coupled with first order diffracted light and an Erbium-doped fiber amplifier (EDFA) as a gain medium. The AOFS is driven at 80 MHz with diffraction loss of 5 dB between fiber-collimator-pair. The unsaturated gain of EDFA is 24 dB at pumping current of 450 mA. The laser oscillates with a bandwidth of 0.2nm, the chirp rate of this laser was 1.76 PHz/sec.

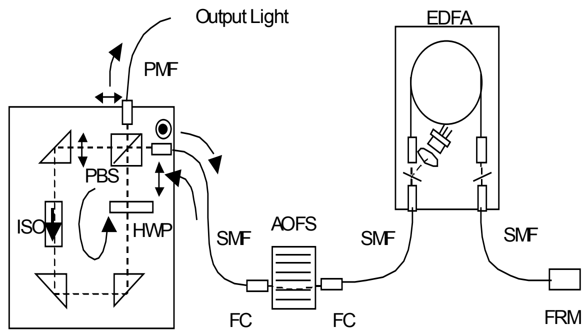

Fig. 3. Schematic of the Sigma-type FSF laser.

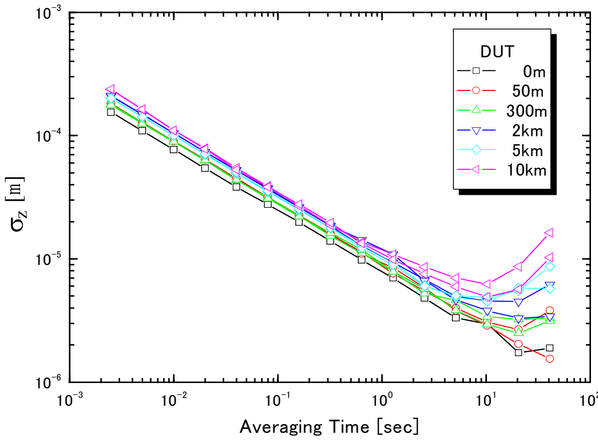

Fig. 4. Distance accuracy variation with distance.

Figure 4 is a plot of the distance accuracy as a function of measurement distance, using dispersion shifted optical fibers of different lengths placed in a temperature-controlled environment. It was confirmed with optical fibers that, up to a few kilometers, the distance accuracy was only affected by the laser parameters and not the distance.

4. 3-D SHAPE MEASUREMENT USING AN FSF LASER

Optical 3-dimensional measurements are in great demand for various applications such as industry prototyping, reverse-engineering, medical application, digital archive, simulation, and so on [4]. Especially, in automobile industry, there are demands for 3-D shape measurements of large-volume objects located at distance of several meters, with high accuracy and high-speed, insensitive to the lighting and object optical conditions.

An FSF laser has the potential for long-distance and high-accuracy ranging. Its use as light source in 3-D shape measurement based on OFDR is a giant leap toward reaching the needs mentioned above. We describe an FSF laser 3-D shape measurement system using a high precision scanner.

Figure 5 shows the schematic diagram of the FSF laser 3D shape measurement system (see next page). The beat signals are obtained by balanced heterodyne detection between reflected light from target object and reference light. The signal-processing section incorporates a Fast Fourier Transform (FFT) unit to analyze the beat frequency.

The scanner as shown in Fig. 6 uses two hollow direct drive motors. Those are mounted in orthogonal and are rotating an elliptic deflection mirror, and its built-in precise encoders of 4 Mega-pulse/rotation acquire the optical ray angles vertical θ of 60-degree span and horizontal ϕ of 360-degree. Lens barrel of 50-mm diameter and a manual-focusing unit are compactly stored in of motor's hollow space and base unit. Focused spot sizes are 330μm at 1,250-mm distance and 1048μm at 5,000-mm from pivot of the mirror.

Figure 8-(a) shows the 3-D shape measurement of a carved wood doll of 190-mm in height for the demonstration of this system. High density point cloud of 2.2Mega 3-D coordinate data (Fig.8-(b)) was obtained at a standoff distance of 1.25m. The carving lines can be clearly seen and the patterns were faithfully reproduced. However, the omissions in the plinth and hair ornament were cause by infrared absorption. Fig.8-(c) shows the reconstructed polygons and its shaded image surface. Most of the surfaces seen from the viewpoint are well covered, and the three-dimensional impressions are well shown.

The measurement accuracy of this 3-D shape measurement system as a function of data acquisition time of the FFT unit is shown in Fig. 6.

Fig. 5. Picture of the high-precision scanner.

The accuracy is a function of the sampling time of the FFT unit and can be improved by choosing a longer time. The accuracy at the distance of 5m for 1ms sampling time, corresponding to 1000points/s, was 127μm.

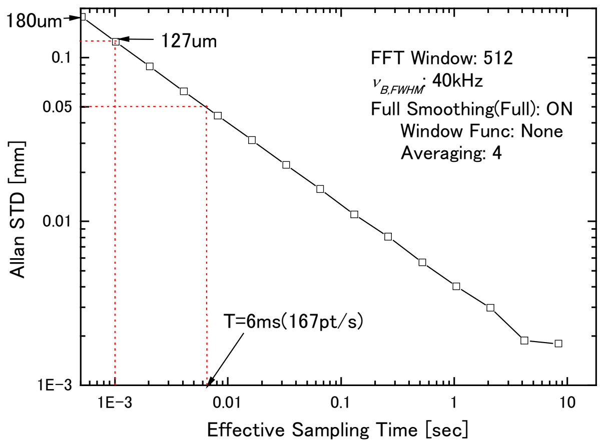

Fig. 6. Accuracy of the FSF laser 3-D measurement system.

Optical ranging using a frequency-shifted feedback (FSF) laser based on OFDR was discussed. The FSF laser demonstrated long-range and high accuracy capabilities with the properties that up to 1Km, the distance accuracy is almost unaffected by the distance. Such a system has great potentials for long-range 3-D shape measurements as we have described in this article, with preliminary measurement speeds above 1000points/s at standoff distances above 1m. Improvements on the measurement accuracy and acquisition time will be made possible by using an FSF laser with a high chirp rate. For that purpose, our research group is investigating FSF lasers using semiconductors amplifiers as gain media.

REFERENCES

[1] M. C. Amann et al., Opt. Eng. 40(1) 10–19 (2001)
[2] S. H. Yun, Optics Express, 11 (22) 2953-2963 (2003)
[3] K. Nakamura et al., IEEE J. Quantum Electron. 36(3) 305 (2000).
[4] F. Chen et al., Opt. Eng. 39, 1, 10-22 (2000).

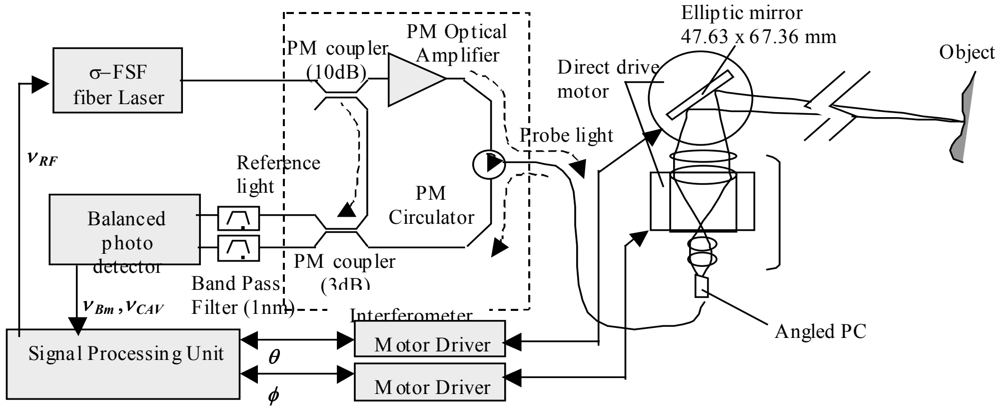

Fig. 7. Schematic diagram of the 3-D shape measurement system using the FSF laser. (PM: Polarization maintained)

(a) Point cloud (b) Shaded polygons (c) Photograph

Fig. 8. A woodcarving doll and measured 2.2M-points cloud data.