

## PAPER

# Extended-Range High-Resolution FMCW Reflectometry by Means of Electronically Frequency-Multiplied Sampling Signal Generated from Auxiliary Interferometer

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**SUMMARY** High-resolution FMCW reflectometry is often realized by sampling the beat signal with a clock signal generated from an auxiliary interferometer. The drawback of this system is that the measurement range is limited to less than half of the optical path difference of the auxiliary interferometer to satisfy the Sampling theorem. We propose and demonstrate a method to extend the measurement range of the system. The clock signal generated from the auxiliary interferometer is electronically frequency-multiplied by using a PLL circuit. The measurement range is experimentally extended by a factor of 20 while keeping high spatial resolution, and is theoretically extended by a factor of 128. The advantage of the proposed system is that the optical path difference of the auxiliary interferometer can be kept short, which is very effective for obtaining the stable and low time-jitter clock signal.

**key words:** optical fiber sensing, optical ranging system, optical reflectometry, FMCW, OFDR

## 1. Introduction

Frequency-modulated continuous-wave (FMCW) reflectometry is a promising candidate for absolute optical ranging, and for measuring reflections of fiber connectors, packaged optical devices and optical integrated devices [1]–[10]. Figure 1(a) shows the basic configuration of the FMCW reflectometry, and Fig. 1(b) shows the waveform of the optical frequency of the reflected and the reference lights. The FMCW reflectometry is composed of a frequency swept laser source and a two-beam interferometer, and a device under test is located in an arm of the interferometer. The reflected light from a surveying point within the device under test interferes with the reference light from the another arm of the interferometer on a photodetector. The interference signal has a beat frequency corresponding to the optical path difference, and then the device under test is diagnosed by the Fourier analysis of the interference signal. When the optical frequency of the laser source is swept in triangular waveform as is shown in Fig. 1(b), the beat frequency  $f_b$  is given as;

$$f_b = 2f_m \Delta F \times \tau \quad (1)$$

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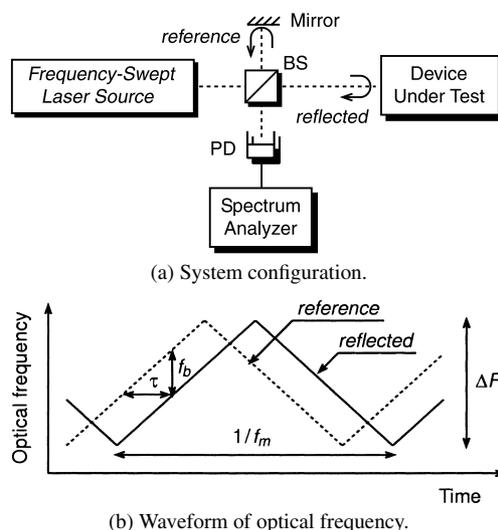
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**Fig. 1** Basic configuration of FMCW reflectometry. BS: Beam splitter, PD: Photodetector.

where  $f_m$  is the repetition frequency of the optical frequency sweep,  $\Delta F$  is the tuning range of the optical frequency sweep, and  $\tau$  is time delay of the reflected light relative to the reference light. The spatial resolution  $\delta z$  is given as [4], [5];

$$\delta z = \frac{c}{2n\Delta F}. \quad (2)$$

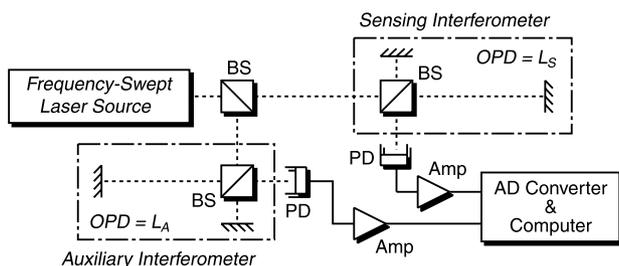
For example,  $\delta z = 1$  mm is obtained for  $\Delta F = 100$  GHz and  $n = 1.5$ .

A laser diode is often used as the frequency-swept light source because its optical frequency can be easily changed by modulating the injection current. The optical frequency change of a laser diode, in general, lags behind the injection current change due to thermal resistance of the laser, and therefore, the linear optical frequency sweep cannot be achieved by only linearly modulating the injection current. As a result, the beat spectrum is blurred and the spatial resolution of the FMCW reflectometry is degraded [11].

Figure 2 shows the FMCW sensing system to compensate the degradation of the spatial resolution due to nonlinear optical frequency sweep [2]. The system has two interferometers, one is the sensing interferometer, and the other (auxiliary interferometer) is used to generate the sampling clock signal for the sensing interferometer. The beat sig-

nal of the sensing interferometer is sampled by the generated sampling clock, and is then analyzed by means of the Fourier transform in the computer. The generated sampling clock signal also contains the information of the nonlinear optical frequency sweep, and then the effect of the nonlinear optical frequency sweep in the beat signal of the sensing interferometer can be canceled. From the Sampling theorem, the beat frequency of the auxiliary interferometer must be more than double of the beat frequency of the sensing interferometer, and, as a result, the optical path difference (OPD) of the auxiliary interferometer must be more than double of the OPD of the sensing interferometer. The maximum measurement range is restricted to half of the OPD of the auxiliary interferometer. The measurement range is extended by increasing the OPD of the auxiliary interferometer, however, the generated sampling clock signal becomes unstable due to environmental perturbation to the auxiliary interferometer, and then the spatial resolution is degraded. If the auxiliary interferometer is isolated from environmental perturbation, such instability may be removed and the OPD of the auxiliary interferometer may be extended to coherence length limit. Such a system cannot be easily configured in practical application because the system is used not only in laboratories but also in noisy factories and in working field in heavy industries. Perfect isolated system from environmental perturbation raises cost of the system.

In this paper, we propose a method to extend the mea-

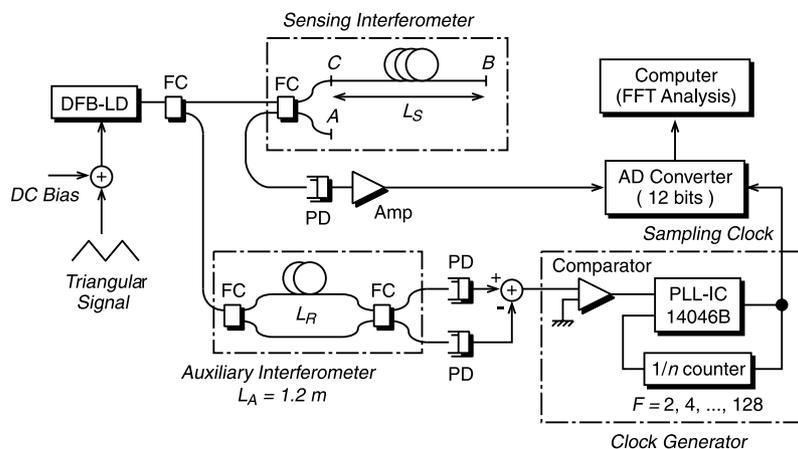


**Fig. 2** System configuration of high-resolution FMCW reflectometry with an auxiliary interferometer. BS: Beam splitter, PD: Photodetector.

surement range of the FMCW reflectometry without increasing the OPD of the auxiliary interferometer [12]. The sampling clock signal generated from the auxiliary interferometer is electronically frequency-multiplied, and the frequency-multiplied sampling signal is used to sample the beat signal of the sensing interferometer. Due to the electronic frequency-multiplication of the sampling clock signal, the OPD of the auxiliary interferometer can be kept short, which gives stable sampling clock signal. The proposed system is very useful to achieve low-cost, stable and high-resolution FMCW sensing systems.

## 2. System Configuration

Figure 3 shows the configuration of the proposed extended-range FMCW reflectometry with an auxiliary interferometer. The optical system is basically the same with Fig. 2, and the clock generator is newly designed and configured. A DFB laser diode module with an optical isolator (DFB-LD) emitting at  $1.55 \mu\text{m}$  is used as a light source and the optical frequency is swept by modulating the injection current with a triangular waveform. The beat signal of the auxiliary interferometer is converted to a TTL signal by a comparator. The TTL signal is electronically frequency-multiplied with a PLL circuit, and the frequency-multiplied TTL signal is used as the sampling clock signal. The fiber-length imbalance of the auxiliary interferometer is  $L_A = 1.2 \text{ m}$ . The sensing interferometer is a Michelson interferometer. The beat signal of the sensing interferometer arises from the interference between the cleaved-end fiber ends (points A and B), and the beat signal is sampled by the 12-bits AD converter with the sampling clock signal generated by the clock generator, and is then analyzed by means of the Fast Fourier Transform (FFT) in the computer. No window function is used for the FFT. Since the sampling clock signal contains the information of nonlinearity in the optical frequency sweep, the effect of nonlinear optical frequency sweep is canceled from the sampled beat signal of the sensing interferometer.



**Fig. 3** System configuration of the proposed high-resolution FMCW reflectometry. FC: Fiber coupler, PD: Photodetector.

The PLL-IC used in the clock generator is a Motorola MC14046B. The lock range of the PLL circuit should cover the range of the beat frequency variation in the auxiliary interferometer. In our system, the maximum and the minimum oscillation frequencies of the voltage controlled oscillator (VCO) in the PLL-IC are adjusted to be about 50 kHz and 0 Hz, respectively, and the resultant lock range of the PLL circuit is 0–50 kHz.

The features of the proposed system are (1) a short OPD of the auxiliary interferometer is possible, which is effective to achieve stable sampling clock signal, and (2) the measurement range can be easily extended by changing the  $1/n$  counter in the clock generator.

As is shown in Eq. (1), the beat frequency is proportional to the delay time  $\tau$  between the reference and the reflected lights. The delay time of the auxiliary interferometer,  $\tau_A$ , is given as  $\tau_A = nL_A/c$ , where  $c$  is the light speed in vacuum and  $n$  is the refractive index of the fiber, and the delay time of the sensing interferometer,  $\tau_S$  is given as  $\tau_S = 2nL_S/c$ , where  $L_S$  is the fiber-length imbalance of the sensing interferometer. The beat frequency of the auxiliary interferometer,  $f_{bA}$ , and the sensing interferometer,  $f_{bS}$ , are then expressed as;

$$f_{bA} = \frac{2nf_m\Delta F}{c} \times L_A \times F \quad (3)$$

$$f_{bS} = \frac{4nf_m\Delta F}{c} \times L_S \quad (4)$$

where  $F$  is the frequency multiplication factor at the PLL circuit. The maximum measurement range  $L_{max}$  is given from the value of the  $L_S$  when  $f_{bA} = 2f_{bS}$  because of the limitation of the Sampling theorem, and is expressed as;

$$L_{max} = \frac{L_A}{4} \times F \quad (5)$$

When the number of sampled data in the time domain is  $N$ , the effective number of the data in the Fourier transformed data is  $N/2$ , and the data point  $N/2$  corresponds to the maximum measurement range  $L_{max}$ . When the beat spectrum appears at the data point  $D$  in the Fourier transformed data, the actual length  $z$  is given from the relation;

$$\frac{N}{2} : L_{max} = D : z \quad (6)$$

and then  $z$  is calculated as;

$$z = \frac{L_A}{2N} \times F \times D. \quad (7)$$

From Eq. (7), the spatial resolution by the FFT,  $\delta z_{FFT}$ , which is the differential distance between adjacent points, is given by setting  $D = 1$  in Eq. (7) as

$$\delta z_{FFT} = \frac{L_A}{2N} \times F. \quad (8)$$

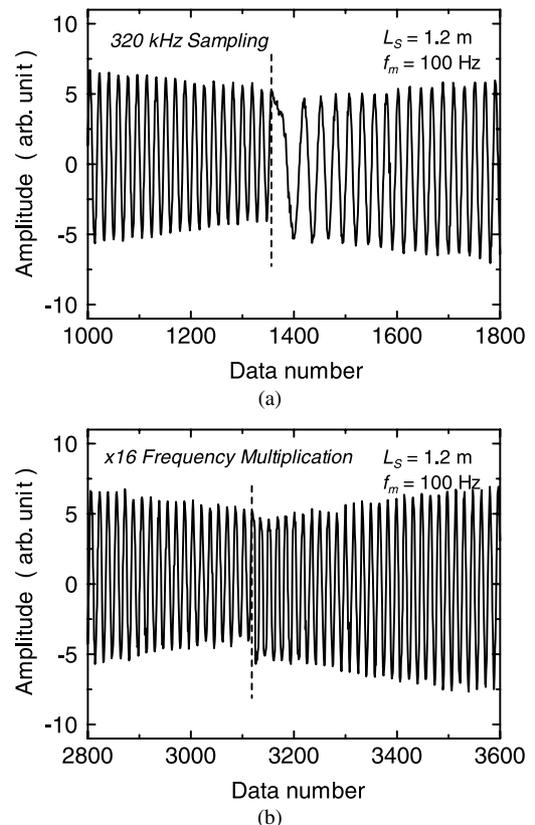
Equation (8) shows that  $\delta z_{FFT}$  is degraded with increasing the frequency multiplication factor  $F$ . The actual spatial resolution is given by both Eq. (2) and Eq. (8). When

the number of the sampled data  $N$  is large or the frequency multiplication factor  $F$  is small, the actual spatial resolution is almost the same with Eq. (2), and when the number of the sampled data  $N$  is small or the frequency multiplication factor  $F$  is large, the actual spatial resolution is governed by Eq. (8).

### 3. Experimental Results

Figure 4 shows the sampled waveform of the interference beat signal; (a) is the waveform measured by a free-running sampling with 320 kHz sampling frequency, and (b) is the waveform measured by the proposed system when the frequency multiplication is  $F = 16$ . The fiber-length imbalance of the sensing interferometer is  $L_S = 1.2$  m. The repetition frequency and the tuning range of the optical frequency sweep are  $f_m = 100$  Hz and  $\Delta f = 22.5$  GHz, respectively. The dashed vertical lines show the turning point of the modulating triangular signal. In the free-running sampling, the beat frequency is time-dependent; that is, the beat frequency just after the turning point is low and the beat frequency just before the turning point is high. On the other hand, the beat frequency is constant in the proposed system as is shown in Fig. 4(b).

Figure 5 shows the measured beat spectrum by a free-running sampling and the proposed system. The fiber-length

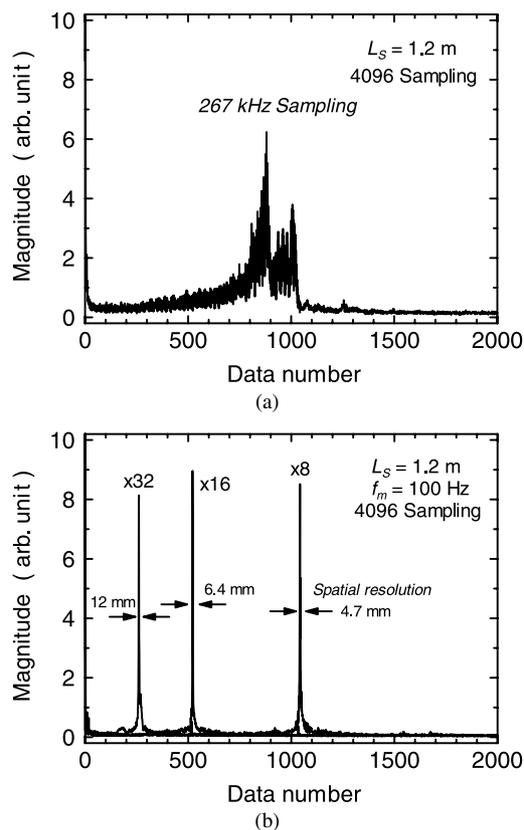


**Fig. 4** Sampled waveform of the interference beat signal (a) with a free-running sampling with 320 kHz sampling frequency, and (b) with the proposed system when the frequency multiplication factor is  $F = 16$ .

imbalance in the sensing interferometer is  $L_S = 1.2$  m. The number of the sampled data in the time domain is  $N = 4096$ . The repetition frequency and the tuning range of the optical frequency sweep are  $f_m = 100$  Hz and  $\Delta f = 22.5$  GHz, respectively. The theoretical spatial resolution  $\delta z$  is

$$\delta z = \frac{c}{2n\Delta f} = 4.6 \text{ (mm)} \quad (9)$$

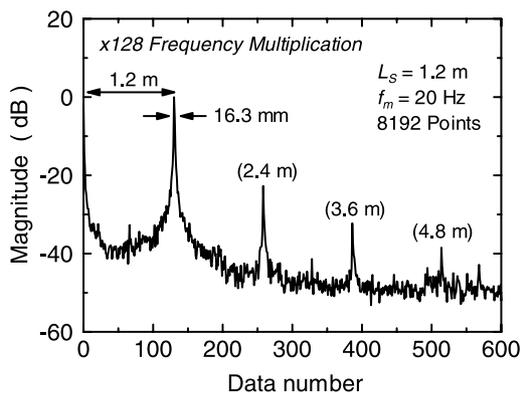
where  $c$  is the light speed in vacuum and  $n = 1.45$  is the refractive index of the fiber. Figure 5(a) shows the measured beat spectrum sampled with 267 kHz sampling frequency. The broad spectrum is due to nonlinearity in the optical frequency sweep. Figure 5(b) shows the measured beat spectrum with the proposed system for different values of the frequency multiplication factor  $F$ . Fine beat spectra are found



**Fig. 5** Measured beat spectrum (a) by a free-running sampling with 267 kHz sampling frequency, and (b) by the proposed system for different values of the frequency multiplication factor.

and the spatial resolution is significantly improved. The results are tabulated in Table 1. The peak position  $D$  is inversely proportional to the frequency multiplication factor  $F$ , and the measurement range increases according to the frequency multiplication factor. The spatial resolution is the same with the theoretical value when the frequency multiplication factor is  $F = 8$ , and is slightly degraded with the frequency multiplication factor. This is due to the FFT resolution,  $\delta z_{FFT}$ , which is also shown in Table 1, and fluctuation of the frequency-multiplied sampling clock signal due to environmental perturbation.

Figure 6 shows the measured beat spectrum for 128-times frequency multiplication ( $F = 128$ ),  $f_m = 20$  Hz,  $\Delta f = 22.5$  GHz, and  $L_S = 1.2$  m. The vertical axis is scaled in dB. The number of the sampled data in the time domain is  $N = 8192$ , and the data number of 4096 corresponds to 0.3 m without the frequency multiplication ( $F = 1$ ). A fine beat spectrum is observed at the data number of 130. The result is also tabulated in Table 1. Measured length  $z$  is the same with the actual fiber length. The spatial resolution is 16.3 mm. The spatial resolution can be improved by increasing the number of the sampled data,  $N$ , as is shown in Eq. (8) because the FFT resolution in this case is 9.2 mm, which is twice the theoretical spatial resolution shown in Eq. (9). The peaks appeared at the data number of 260, 390 and 520 are due to multiple reflection between the input and the output facets (points B and C in Fig. 3) of the 1.2 m-long fiber. The measurement range is theoretically extended to



**Fig. 6** Measured beat spectrum when the frequency multiplication factor is  $F = 128$ . The number of the sampled data in the time domain is  $N = 8192$ .

**Table 1** Summary of the experimental results shown in Fig. 5(b) and Fig. 6.

item	notation	value			
Modulation frequency	$f_m$	100 Hz	100 Hz	100 Hz	20 Hz
Frequency multiplication	$F$	8	16	32	128
Data number	$N$	4096	4096	4096	8192
Peak position	$D$	1042	521	261	130
Measurement range	$L_{max}$	2.4 m	4.8 m	9.6 m	38.4 m
Measured length	$z$	1.221 m	1.221 m	1.223 m	1.219 m
Measured resolution	$\delta z_{mea}$	4.7 mm	6.4 mm	12.0 mm	16.3 mm
FFT resolution	$\delta z_{FFT}$	1.17 mm	2.34 mm	4.68 mm	9.2 mm
Corresponding figure in the paper		Figure 5(b)		Figure 6	

37.8 m. If the Fresnel reflection at the output facet (points C in Fig. 3) is eliminated by immersing the far end into an index matching liquid or breaking the output facet appropriately, the Rayleigh backscattering may be observed.

Figure 7 shows the measured beat spectrum for different fiber-length imbalance  $L_S$  when the frequency multiplication factor is  $F = 32$ . The number of the sampled data in the time domain is  $N = 4096$ , and the modulation frequency is  $f_m = 100$  Hz. The tuning range of the optical frequency sweep is  $\Delta f = 22.5$  GHz, and the resultant theoretical spatial resolution is  $\delta z = 4.6$  mm. The spatial resolution by the FFT is  $\delta z_{FFT} = 4.68$  mm. The result is summarised in Table 2. The measured length,  $z$ , is the same with the actual fiber-length imbalance,  $L_S$ . The result shows that precise optical ranging is possible to up 6.46 m. The measurement range without the frequency multiplication ( $F = 1$ ) is 0.3 m because the fiber-length imbalance of the auxiliary interferometer is  $L_A = 1.2$  m, and therefore, the measurement range can be experimentally extended by a factor of 20. The decrease of the magnitude according to the fiber-length imbalance is due to the coherence of the DFB-LD because the spectral linewidth of the DFB-LD is  $\Delta\nu = 5$  MHz, which gives the coherence length be about  $c/(n\pi\Delta\nu) = 13$  m in a fiber. The spatial resolution is slightly degraded with increasing the fiber length. This is maybe due to instability of the sampling clock signal originating from the instability of the reference beat signal due to environmental perturbation.

From the experimental results, we can find out that the proposed system is very useful to extend the measurement range while keeping high spatial resolution. This method is basically irrespective of the waveform of the optical frequency sweep. We measured the beat spectrum when the injection current of the DFB-LD is sinusoidally modu-

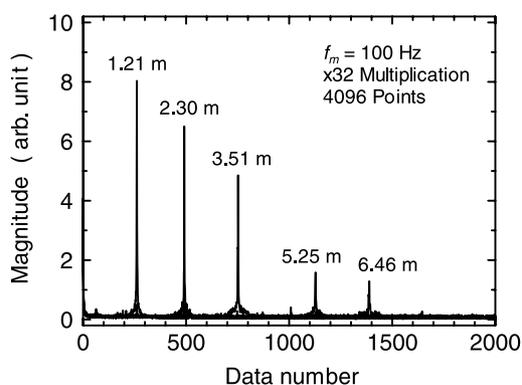


Fig. 7 Measured beat spectrum for different fiber-length imbalance when the frequency multiplication factor is  $F = 32$ .

Table 2 Summary of the experimental results shown in Fig. 7. The frequency multiplication is  $F = 32$  and the data number is  $N = 4096$ .

item	notation	value				
Fiber length imbalance	$L_S$	1.21 m	2.30 m	3.51 m	5.25 m	6.46 m
Peak position	$D$	261	491	752	1128	1388
Measured length	$z$	1.223 m	2.302 m	3.525 m	5.288 m	6.506 m
Measured resolution	$\delta z_{mea}$	10.8 mm	6.9 mm	1.4 mm	17.9 mm	24.4 mm

lated. The optical frequency is also sinusoidally modulated in this case. The modulation frequency is  $f_m = 100$  Hz, and the fiber-length imbalance in the sensing interferometer is  $L_S = 60$  cm. Figure 8(a) shows the sampled waveform by a free-running sampling with 200 kHz sampling frequency. The beat frequency is strongly time-dependent. The beat frequency around the data number of 1900 is extremely low, which corresponds to the time where the modulation waveform is almost minimum ( $\sin \omega t = -1$ ). Figure 8(b) shows the sampled waveform by the proposed system when the frequency multiplication factor is  $F = 16$ . The modulation waveform is almost minimum ( $\sin \omega t = -1$ ) around the data number of 2130 in this figure. The beat frequency is almost constant, and we can expect fine beat spectrum from the waveform.

The measured beat spectrum is shown in Fig. 9. Figure 9(a) shows the measured beat spectrum by a free-

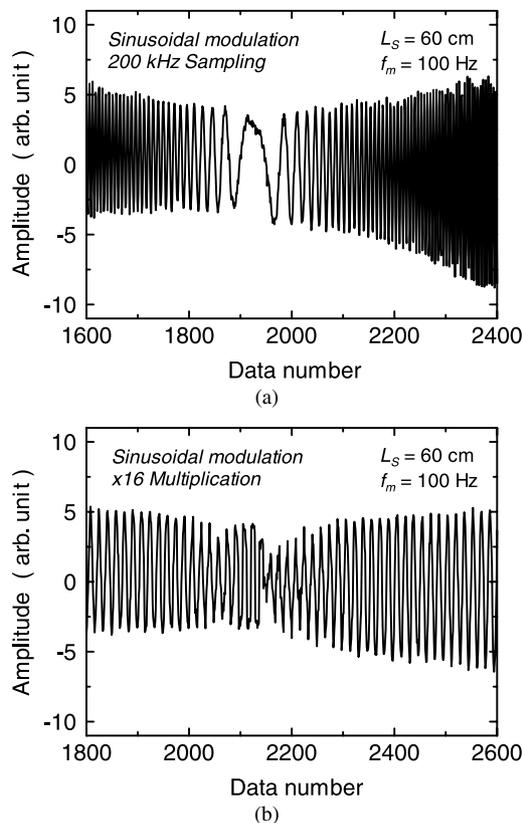
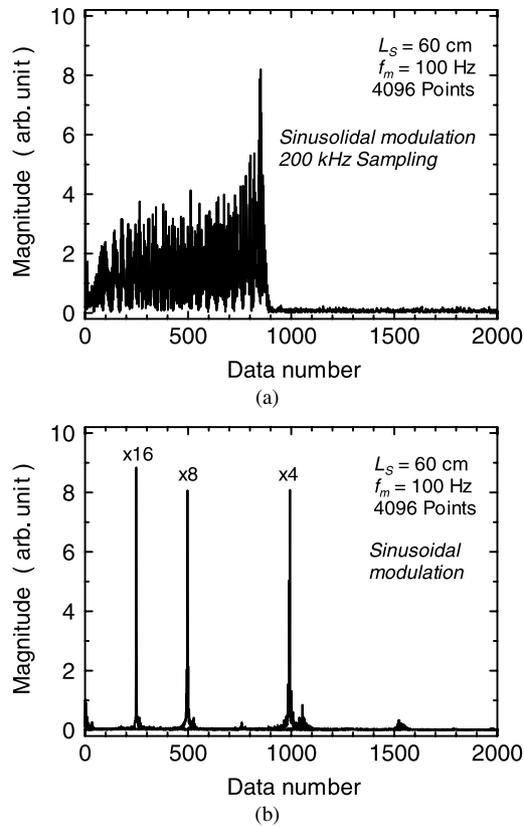


Fig. 8 Sampled waveform of the interference beat signal (a) by a free-running sampling with 200 kHz sampling frequency, and (b) by the proposed system when the frequency multiplication factor is  $F = 16$ . The injection current of the DFB-LD is sinusoidally modulated.



**Fig. 9** Measured beat spectrum (a) by a free-running sampling with 200 kHz sampling frequency, and (b) by the proposed system for different values of the frequency multiplication factor. The injection current of the DFB-LD is sinusoidally modulated.

running sampling with 200 kHz sampling frequency. The broad beat spectrum is attributed to large beat frequency change due to sinusoidal optical frequency change as shown in Fig. 8(a). Such large beat frequency change may cause unlocking of the PLL circuit, which may give two beat spectrum; one is a fine beat spectrum while the PLL circuit works well, and the other is a broad beat spectrum when the instantaneous beat frequency is out of the lock range of the PLL circuit. Figure 9(b) shows the measured beat spectrum by the proposed system for different values of the frequency multiplication factor. Only a fine beat spectrum is measured despite of the sinusoidal optical frequency change. This means that the lock range of the PLL circuit is sufficiently wide to cover the beat frequency change.

#### 4. Conclusion

We have proposed and demonstrated the extended-range high-resolution FMCW reflectometry with an auxiliary interferometer. In the FMCW reflectometry with an auxiliary interferometer, the beat signal of the sensing interferometer is sampled with the sampling clock signal generated from the beat signal of the auxiliary interferometer, and hence the measurement range is less than half of the OPD of the auxiliary interferometer to satisfy the Sampling theorem. In

the proposed system, the sampling clock signal generated from the beat signal of the auxiliary interferometer is electronically frequency-multiplexed with a PLL circuit, and the beat signal of the sensing interferometer is sampled with the frequency-multiplied sampling clock signal. As a result, the measurement range is extended over the OPD of the auxiliary interferometer. The measurement range can be experimentally extended by a factor of 20, and theoretically extended by a factor of 128. The difference between the experimental and the theoretical measurement range is due to the coherence of the light source. The proposed system is also applied when the optical frequency is sinusoidally modulated.

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