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Long range and high resolution reflectometry by synthesis of optical coherence function at region beyond the coherence length

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Abstract: A long-range and high-resolution reflectometry by synthesis of optical coherence function at region beyond the coherence length is proposed. We discuss and simulate the principle of the reflectometry system. In basic experiments, the reflectivity distribution is successfully measured at the region beyond the coherence length with a spatial resolution of 19 cm and a measurement range of 1 km. We have also proposed two methods to improve dynamic range of the system. In the experiments, dynamic range of 45 dB is successfully achieved.

Keywords: coherence length, coherence function, reflectometry
Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

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1 Introduction

Optical fiber reflectometry with cm-order spatial resolution and several-km -order measurement range is required in applications, such as optical fiber subscriber systems. However, it is difficult to elongate the measurement range with keeping the high spatial resolution in conventional techniques, such as optical frequency domain reflectometry [1]. One of the reasons for the differenty is optical phase noise by environmental fluctuation in a long measurement range within the time for data acquisition, though the system has recently been improved [2].

On the other hand, we have proposed a reflectometry by synthesis of optical coherence function, and have applied it to long-range measurement [3, 4]. In these methods, the data acquisition time for one measurement point is short, then cm-order spatial resolution has been realized at a long distance. However, the measurement range was limited by the coherence length of the light source.

In this paper, a reflectometry by synthesis of optical coherence function at the region beyond the coherence length is proposed. We discuss and simulate the principle of the proposed system, and the reflectivity distributions are successfully measured at the region beyond the coherence length with a spatial resolution of 19 cm and a measurement range of 1 km. We also propose two methods to improve the dynamic range of the system.

2 Proposed system and simulations

Fig. 1 (a) shows a schematic configuration of the proposed system. Continuous lightwave from a tunable DFB-LD is divided by a 3 dB coupler to launch into a fiber under test and a reference arm. Reflected or backscattered lightwave from the fiber and the reference lightwave, whose frequency is shifted by an acousto-optical modulation (AOM), are mixed at photo detectors (PD). An intermediate frequency component is extracted by an electrical band pass filter and is detected by a square law detector. The light source frequency is modulated with a sinusoidal waveform, so that the narrow correlation windows, which are called correlation peak, are synthesized along the fiber, as shown in Fig. 1 (a). Then, the reflectivity at the correlation peak position can selectively be measured. By sweeping the peak with changing the modulation frequency, we can obtain the distributed information. When the

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interferometer works within the coherence length, distributed measurement can be realized with a similar mechanism mentioned above [5]. We prove below that the mechanism can also work beyond the coherence length.

The modulation of the light source frequency can be expressed as

$$f(t) = f_0 + f_1 \sin(2\pi f_2 t), \tag{1}$$

where f_0 is the center frequency, f_1 the amplitude of the frequency modulation, and f_2 the modulation frequency. To elongate the measurement range, we need to increase the correlation peak interval [5], so that only one peak exists in the measurement range. This can be realized by reducing the frequency f_2.

However, in this case, the signal and the reference lightwaves have the path length difference beyond the coherence length of ordinary semiconductor lasers. Under the condition, the PD current is expressed as

$$i(t) = \cos\left(2\pi f_A t + 2\pi f_0 \tau_d + 2\frac{f_1}{f_2}\sin\left(2\pi f_2\left(t - \frac{\tau_d}{2}\right)\right) + \theta(t) - \theta(t - \tau_d)\right), \tag{2}$$

where τ_d is time delay difference between the two interferometer arms, f_A the optical frequency shift, and $\theta(t)$ the phase noise of the lightwave. Then, the auto-correlation of the PD output current $i(t)$ can be expressed as

$$\begin{aligned} R(\tau) = \langle i^*(t) \times i(i+\tau)\rangle = \sum_{n=-\infty}^{\infty} \Big[& J_n(\beta)^2 \exp(j2\pi(f_A + nf_2)\tau) \\ & \times \exp\left(-4\int_0^\infty \mathrm{S_F}(f)\left(\frac{\sin\pi f\tau}{f}\right)^2 (1 - \cos 2\pi f\tau_d)\, df\right)\Big]. \end{aligned} \tag{3}$$

Here

$$\beta = 2\frac{f_1}{f_2}\sin\pi f_2 \tau_d, \tag{4}$$

where J_n is the Bessel function of the first kind with an order n, and $S_F(f)$ is the FM noise spectrum of the light source. Assuming the FM noise is white gaussian,

$$S_F(f) = \frac{\delta f}{\pi} \tag{5}$$

is obtained, where δf is the linewidth of the light source [6].

Power spectrum of the PD output current is the Fourier transform of the auto-correlation, which is calculated as

$$S(f) = \sum_{n=-\infty}^{\infty} J_n(\beta)^2 (F(f - (f_A + nf_2)) + F(f + (f_A + nf_2))), \tag{6}$$

where

$$\begin{aligned} F(f) = & \exp(-2\pi\delta f\tau_d) \times \delta(f) \\ & + \frac{\delta f}{\pi(f^2 + \delta f^2)} \times \left(1 - \exp(-2\pi\delta f\tau_d) \times \left(\cos 2\pi f\tau_d - \frac{f}{2\delta f}\sin 2\pi f\tau_d\right)\right) \\ & - \frac{1}{2\pi^2 f}\exp(-2\pi\delta f\tau_d)\sin 2\pi f\tau_d. \end{aligned} \tag{7}$$

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At the region beyond the coherence length, Eq. (7) becomes

$$F(f) \approx \frac{\delta f}{\pi\left(f^2 + \delta f^2\right)}. \tag{8}$$

Then, the spectrum of the output current from PD can be expressed as

$$S(f) = \sum_{n=-\infty}^{\infty} J_n(\beta)^2 \frac{\delta f}{\pi\left(\left(f - (f_A + n f_2)\right)^2 + \delta f^2\right)} + \sum_{n=-\infty}^{\infty} J_m(\beta)^2 \frac{\delta f}{\pi\left(\left(f + (f_A + m f_2)\right)^2 + \delta f^2\right)}. \tag{9}$$

We simulate the PD current spectrum, when only one reflection exists at the fiber end. We set $\delta f = 2\,\text{MHz}$, $f_1 = 5\,\text{GHz}$, $f_2 = 100\,\text{kHz}$, $\tau_d = 50\,\mu\text{sec}$, $f_A = 0\,\text{MHz}$. The 5th correlation peak is swept by changing f_2. Fig. 1 (b) shows the simulation result of the spectrum. The difference between the peak position and the reflection position is changed from 0 cm to 50 cm. When the

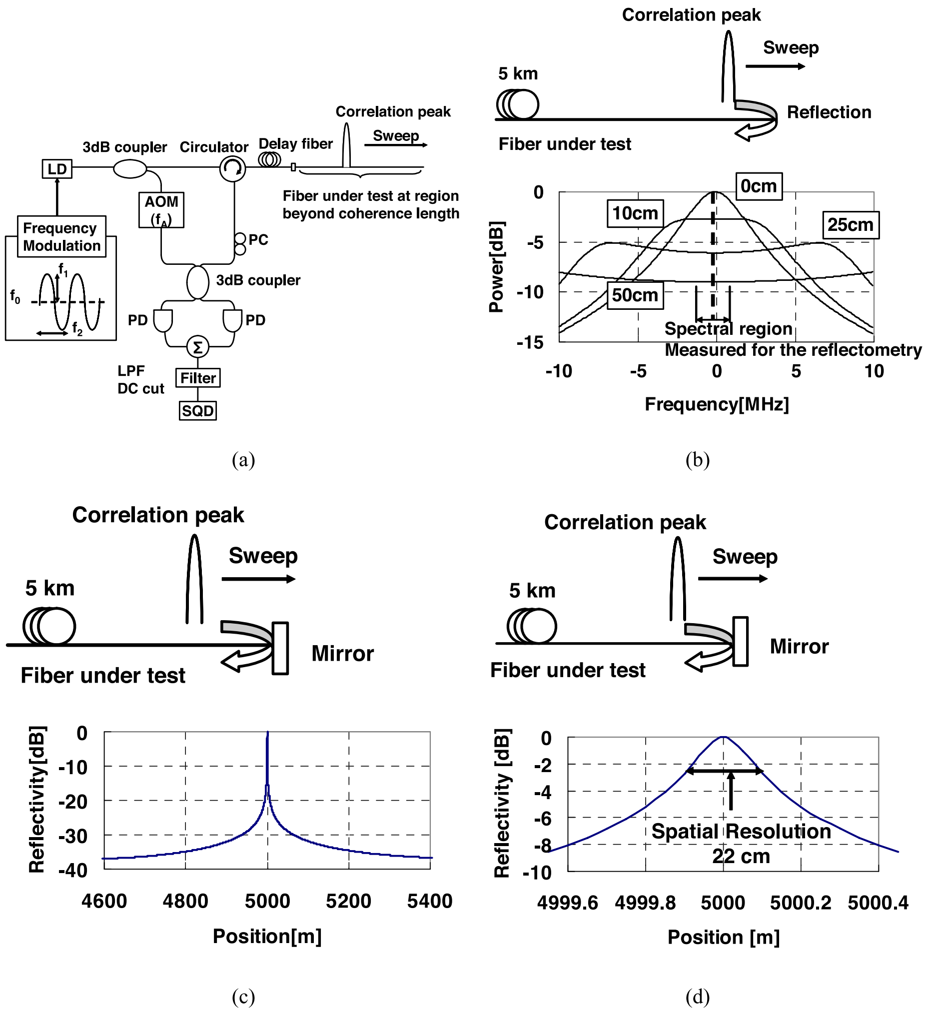

Fig. 1. Concept of the proposed reflectometry system (a) Schematic configuration (b) Simulated spectra of the output current from PD. (c) Change of IF component as a function of the correlation peak position (d) Detail around the reflection.

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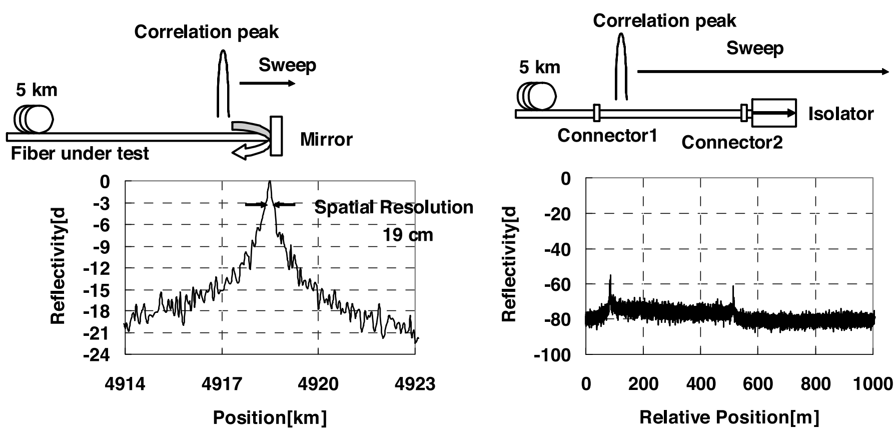
difference becomes large, the spectrum spreads and the component around the intermediate frequency decreases.

Fig. 1 (c) shows the change of the IF component when sweeping the correlation peak around the fiber end, from 4,500 m to 5,500 m. Because $f_2 \approx 100$ kHz, the correlation peak interval is 1 km. Therefore, there is only one correlation peak within this region. Fig. 1 (d) shows the detail around the reflection. The spatial resolution (FWMH) is 22 cm.

3 Basic Experiments

The reflectivity distributions around a distance of 5 km have been measured by this reflectometry system. In the setup, we used a three-electrode tunable DFB-LD (λ = 1555 nm) as the light source, which has the coherence length of about 60 m, an AOM (f_A = 300 kHz), and photo detectors (DC cut, bandwidth = 1 GHz). The length of the optical delay fiber placed in the signal path was 5 km (10 km in round trip). The modulation amplitude f_1 was 5 GHz. The modulation frequency f_2 was changed from 90 kHz to 110 kHz for sweeping the correlation peak position. In this experiment, the 5th correlation peak was used, which is the same as the simulation. Fig. 2 (a) shows the reflection at the mirror. The resolution was 19 cm. Fig. 2 (b) shows the reflectivity distribution, when two connectors are placed in the measurement range. The distance between the connectors was 500 m. The isolator was placed behind the connector2. A reflection of the connector1 at a relative position of 84 m was measured with a spatial resolution of 19 cm. The reflectivity of the connector was −54 dB. The reflection at a connector2 at 514 m was also measured with a spatial resolution of 19 cm. The reflectivity was −60 dB.

In this experiment, the measurement range or peak sweeping range was 1 km. To set only one correlation peak along the total length (5 km), we can use the temporal gating scheme [7], which we proposed for Brillouin sensing.



(a) (b)

Fig. 2. Reflectivity distribution measured at a distance of 5 km (a) Reflection at the mirror. (b) Reflections at two connectors.

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4 Improvement of dynamic range

When the system works within the coherence length, the side-lobes of the synthesized coherence function limit the dynamic range [4], and the side-lobes can be suppressed by apodizing the synthesized lightwave spectrum [5]. It is found that the dynamic range is improved by the apodization also in the system for the region beyond the coherence length. One way for the apodization is to use an optical filter as shown in Fig. 3 (a). The reflection at a mirror of a 5 km distance has been measured by this system. In the setup, we used an etalon filter (FWHM = 1 GHz). The 5th correlation peak was swept to obtain the reflection. Fig. 3 (b) shows the obtained data. The dynamic range was improved from 30 dB to 45 dB.

In Fig. 3 (c), we propose another way for the apodization. The light source frequency is modulated with a waveform modified for directly apodizing the averaged spectrum of the lightwave. The frequency modulation with the waveform shown in Fig. 3 (c) realizes directly the Hamming window. By changing the modulation frequency, the peak can be swept. Figure 3 (d)

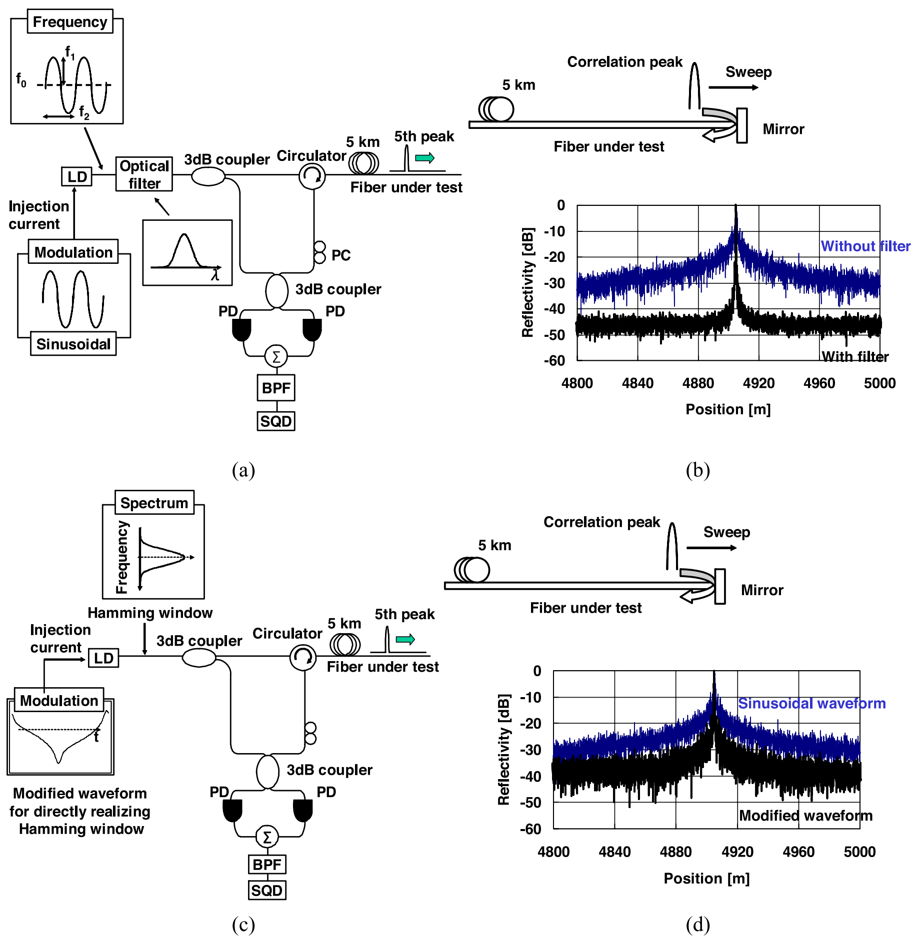

Fig. 3. Improvement of dynamic range. (a) Apodization with the optical filter. (b) Improvement of the dynamic range from 30 dB to 45 dB. (c) Apodization using the modified waveform (d) Improvement of the dynamic range from 30 dB to 40 dB.

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shows the reflection at the mirror. The system dynamic range was improved from 30 dB to 40 dB.

5 Conclusion

We have newly proposed the reflectometry by synthesis of optical coherence function at the region beyond the coherence length. We have discussed and simulated the principle of the reflectometry. It has been shown that the reflectivity distribution can be measured even at the region beyond the coherence length. In the basic experiments, the reflectivity distribution has been successfully measured with the spatial resolution of 19 cm and the measurement range of 1 km. We also proposed and demonstrated two methods to improve the dynamic range of the system. The dynamic range of 40 or 45 dB has been achieved.

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