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Phase-Decorrelated FMCW Reflectometry for Long Optical Fiber Characterization by Using a Laser Diode with Modulated External-Cavity

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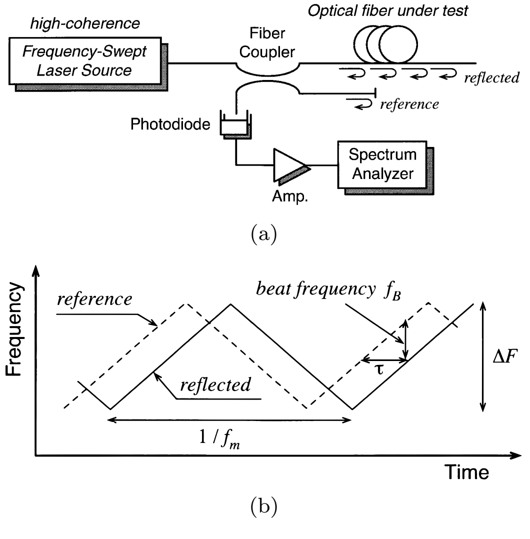
SUMMARY We describe FMCW reflectometry for characterization of long optical fibers by using an external-cavity laser diode as a light source. Since the optical path difference between the reference beam and the reflected beam from the optical fiber under test is much longer than the coherence length of the light source, the reference and the reflected beams are phase-decorrelated. As a result, the beat spectrum between the reference and the reflected beams is measured. In the phase-decorrelated FMCW reflectomety, the spatial resolution is enhanced by narrowing the spectral linewidth of the light source and increasing the repetition frequency of the optical frequency sweep as well as increasing the chirping range of the optical frequency sweep. In the experiments, an external-cavity DFB laser is used as a narrow linewidth light source, and the optical frequency is swept by minute modulation of the external cavity length. Long single mode optical fibers are characterized, and the maximum measurement range of 80 km is achieved, and the spatial resolutions of 46 m, 100 m and 2 km are achieved at 5 km, 11 km and 80 km distant, respectively. The Rayleigh backscattering is clearly measured and the propagation loss of optical fiber is also measured. The optical gain of an erbium-doped optical fiber amplifier (EDFA) is also estimated from the change in the Rayleigh backscattering level in the optical fiber followed after the EDFA.

key words: *optical fiber sensors, optical reflectometry, optical fiber characterization*

1. Introduction

Frequency-modulated continuous-wave (FMCW) reflectometry, also called optical frequency domain reflectometry (OFDR), is a promising candidate for characterization of optical fibers, fiber connections, packaged optical devices and optical integrated devices [1]–[5]. The FMCW reflectometry is composed of a frequency swept light source and a two-beam interferometer, and an optical fiber under test is located in an arm of the interferometer as shown in Fig. 1(a). The light from the light source is divided into two beams. One beam arrives at the photodetector directly and is used as a reference beam. The other beam, which is referred to as a probe beam, enters into the optical fiber under test. The reflected beam from a surveying point within the optical fiber under test interferes with the reference beam on a photodetector. Because the optical frequency of the light source is linearly swept in time, the interference signal has a beat frequency corresponding to the optical path difference between the reference and the reflected beams. The measurement range of the FMCW reflectometry is normally restricted by the coherence length of the light source, and the typical measurement range is about 10 m [6]. The extended-range FMCW reflectometry have been also studied [7]–[9]. The simple method to increase the measurement range is to use a narrow-linewidth laser diode as a light source, and the measurement range of more than 100 m was achieved.

Recently, phase-decorrelated FMCW reflectometry has been reported for long optical fiber characterization [10]–[12]. In such system, the optical path difference between the reference and the reflected beams is much longer than the coherence length of the light source, and therefore, the optical phases of the two beams are decorrelated. As a result, the beat spectrum



(a)

(b)

Fig. 1 Configuration and principle of the FMCW reflectometry. (a) Configuration. (b) Optical frequency changes of the reference and the reflected beams.

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between the two beams is measured in the frequency domain.

In this paper, we describe experimental results of the phase-decorrelated FMCW reflectometry for long optical fiber characterization. In our system, an external-cavity laser diode is used as the light source and the optical frequency is swept by minute modulation of the external cavity length.

2. Principle

The system configuration of the phase-decorrelated FMCW reflectometry is the same with the conventional FMCW reflectometry shown in Fig. 1(a). The only difference is that the length of the optical fiber under test is much longer than the coherence length of the light source. Figure 1(b) shows the waveform of the optical frequency change of the reference and the reflected beams, in which the optical frequency of the light source is assumed to be triangularly swept. Let the length of the optical fiber under test, the refractive index of the fiber, and the light speed in vacuum be L, n, and c, respectively, the propagation delay time between the reflected and the reference beams, τ, is given by $\tau = 2nL/c$. Then the beat frequency f_B is given by the following equation;

$$\begin{aligned} f_B &= \frac{4nf_m\Delta F}{c}\,L \\ &= \frac{2n}{c}\,\gamma L \end{aligned} \tag{1}$$

$$\gamma = 2f_m\Delta F \tag{2}$$

where ΔF and f_m are the chirping range of the optical frequency sweep and the repetition frequency of the optical frequency sweep, respectively, and γ means the optical frequency chirp rate. The beat frequency f_B is proportional to the chirp rate γ. From Eq. (1), the spatial resolution δL is given as;

$$\delta L = \frac{c}{4nf_m\Delta F}\,\delta f_B \tag{3}$$

where δf_B is the spectral width of the beat spectrum. Since the reflected and the reference beams are phase-decorrelated, the beat spectrum is broadened due to the linewidth of the light source as well as the finite chirping range ΔF. If the spatial resolution is determined by the finite chirping range ΔF, then $\delta f_B = 2f_m$ because the chirping range ΔF is obtained for the time period $1/(2f_m)$. As a result, the spatial resolution δL_c is expressed as;

$$\delta L_c = \frac{c}{2n\Delta F}. \tag{4}$$

If the spatial resolution is determined by the linewidth of the light source, then $\delta f_B = 2\Delta\nu$ by assuming the Lorentzian spectral profile with the linewidth (defined as full-width at half-maximum) $\Delta\nu$. As a result, the spatial resolution δL_s is expressed as;

$$\delta L_s = \frac{c}{2nf_m\Delta F}\,\Delta\nu. \tag{5}$$

For conventional FMCW reflectometry, in which the reference and the reflected beams are phase-correlated, the spatial resolution is given by Eq. (4). The spatial resolution is enhanced by increasing the chirping range of the optical frequency sweep ΔF. However, in the phase-decorrelated FMCW reflectometry, the spatial resolution is determined by both Eq. (4) and Eq. (5). The spatial resolution is enhanced by narrowing the spectral linewidth $\Delta\nu$ and increasing the repetition frequency f_m as well as increasing the chirping range ΔF. For example, if the spectral linewidth of the light source $\Delta\nu = 100$ kHz, the chirping range of the optical frequency sweep $\Delta F = 1$ GHz, the repetition frequency of the optical frequency sweep $f_m = 1$ kHz and the refractive index of the fiber $n = 1.46$, then the spatial resolution δL_c and δL_s are given by

$$\delta L_c = 10.3\,\mathrm{cm} \tag{6}$$

$$\delta L_s = 10.3\,\mathrm{m}, \tag{7}$$

and the spatial resolution of the system is determined by the linewidth of the light source.

Next, we discuss the measurement range of the phase-decorrelated FMCW reflectometry. Since the optical frequency is triangularly swept with the repetition frequency f_m, the propagation delay time between the reference and the reflected beams, τ, must be smaller than $1/(2f_m)$. This is expressed as

$$\tau = \frac{2nL}{c} < \frac{1}{2f_m}. \tag{8}$$

From Eq. (8), the maximum measurement range L_{max} is determined by the repetition frequency f_m and is expressed as

$$L_{max} < \frac{c}{4nf_m}. \tag{9}$$

In other word, if the measurement range is determined to be L_{max}, the repetition frequency of the optical frequency sweep f_m must be satisfied the following relation;

$$f_m < \frac{c}{4nL_{max}}. \tag{10}$$

Finally, we discuss the influence of nonlinearity in the optical frequency sweep on the spatial resolution. The spatial resolutions given by Eqs. (4) and (5) are achieved only when the optical frequency is perfectly linearly swept. If the optical frequency sweep is nonlinear, the instantaneous beat frequency varies in time becasuse the optical frequency chirp rate γ varies in time. As a result, the beat spectrum is spread out and

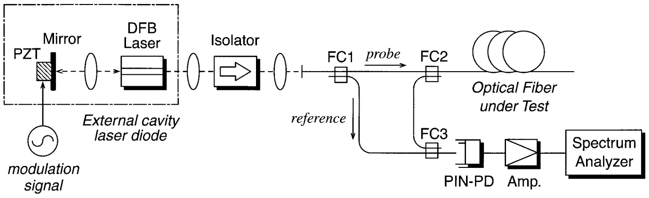


Fig. 2 Experimental setup.

the spatial resolution is degraded. In such a case, an additional optical frequency control circuit is required to improve the spatial resolution [4], [14]. The other method to enhance the spatial resolution in case of nonlinear optical frequency sweep is time-gated spectrum analysis. In this method, a portion of the beat signal is extracted by the gate signal, and then the beat spectrum of the extracted beat signal is analyzed. By appropriately choosing the gate width and the gate position, the broadening of the beat spectrum can be eliminated and the spatial resolution is improved because the optical frequency sweep is assumed to be linear in the gated period. If the gate width is given by T, the resultant effective chirping range of the optical frequency sweep ΔF_e is given as $\Delta F_e = 2f_m T\Delta F$, and then the spatial resolution due to the finite chirping range δL_c is rewritten as

$$\delta L_c = \frac{c}{2n\Delta F_e} = \frac{c}{4nf_m T\Delta F}. \tag{11}$$

3. Experiments

3.1 System Configuration

Figure 2 shows the experimental setup. The DFB laser emitting at 1552 nm was used as a light source, and the spectral linewidth of the DFB laser was narrowed by external cavity configuration using a mirror. The resultant spectral linewidth was about 130 kHz and the corresponding coherence length was about 400 m. The light from the DFB laser was divided into two beams by a 10 dB coupler (FC1). The weak beam was used as the reference beam, and the strong beam was coupled into the optical fiber under test (probe beam), and the beat spectrum between the reference beam and the reflected beam from the optical fiber under test was measured by the spectrum analyzer. The optical frequency was swept by minute modulation of the external cavity length which was achieved by vibrating the external cavity mirror by using a PZT. The repetition frequency of the optical frequency sweep f_m was 1 kHz, and the chirping range ΔF was about 600 MHz. Since the optical frequency sweep by this method was nonlinear due to nonlinear response of the PZT against the applied voltage, the beat spectrum was broadened and the spatial resolution was degraded.

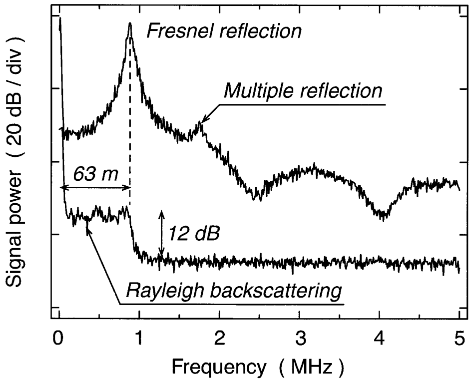


Fig. 3 Measured beat spectrum for an 63 m-long optical fiber. The upper trace is the result when the Fresnel reflection at the far end of the fiber was not suppressed, and the lower trace is the result when the Fresnel reflection at the far end of the fiber was suppressed.

3.2 Phase-Correlated (Short Range) Measurements

Figure 3 shows the measured beat spectrum for an 63 m-long optical fiber. In this case, the reference beam and the reflected beam from the far end of the fiber are phase-correlated because the fiber length is smaller than the coherence length of the laser, and then the spatial resolution is determined by Eq. (11). The gate width T was 20 μs, and the resultant theoretical spatial resolution is given as

$$\delta L_c = 4.3 \text{ m}. \tag{12}$$

The resolution bandwidth of the spectrum analyzer was 10 kHz, which was determined by the gate width and the gate position. The strong peak appeared at 900 kHz was the Fresnel reflection at the far end of the fiber, the weak peak appeared at 1.8 MHz was due to the multiple-reflection at the input and the far ends of the fiber. The spatial resolution at the far end of the fiber is estimated to be 5.3 m, which is almost the same with the theoretical value. The undulating noise-like spectrum around 900 kHz was caused by the phase noise of the laser, and the shape is determined by the spectral linewidth of the laser and the optical path difference between the reference and the Fresnel-reflected beams. This noise-like spectrum is called source phase-noise-induced intensity noise. The Rayleigh backscattering in the fiber is masked by the source phase-noise-induced intensity noise. This is because the source phase-noise-induced intensity noise is spread over the bandwidth of the beat spectrum for the Rayleigh backscattering. The Rayleigh backscattering could be clearly measured by suppressing the Fresnel reflection at the far end of the fiber by applying an index matching oil to the far end of the fiber and then bending near the end of the fiber, and the result is also shown in Fig. 3. The Rayleigh backscattering inside the fiber can be clearly measured,

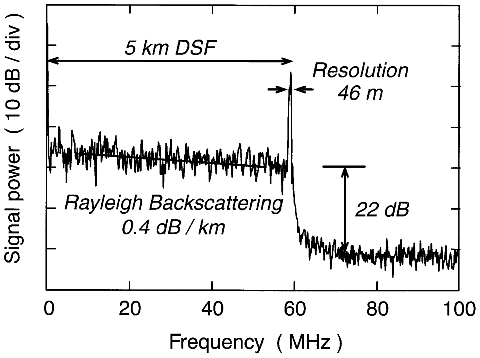


Fig. 4 Measured beat spectrum for a 5 km-long dispersion shifted optical fiber (DSF).

and the signal-to-noise (SN) ratio is about 12 dB. It is also found that the Rayleigh backscattering is about 50 dB weaker than the Fresnel reflection of the far end of the fiber. If we use a laser diode with narrower spectral linewidth and the spatial resolution is enhanced by increasing the effective chirping range of the optical frequency sweep, the strong peak appeared at 900 kHz is narrowed, and the source phase-noise-induced intensity noise spectrum is reduced in its magnitude and is narrowed in its width. As a result, we can measure the Rayleigh backscattering and the Fresnel reflection simultaneously [13].

3.3 Phase-Decorrelated (Long Range) Measurements

In the phase-decorrelated (long range) measurements, the gate width T was 5 μs and the resultant effective chirping range of the optical frequency sweep ΔF_e was about 6 MHz. In the experiments, the spatial resolutions determined by the spectral linewidth of the light source δL_s and by the time-gated spectral analysis δL_c are calculated by;

$$\delta L_s = 22.3\,\text{m} \tag{13}$$
$$\delta L_c = 17.1\,\text{m} \tag{14}$$

where $n = 1.46$. The theoretical spatial resolution of the system is determined from both Eqs. (13) and (14), and is not clearly obtained in this case because Eqs. (13) and (14) are comparable. However, the theoretical spatial resolution is deduced to be about 40 m by taking account of contributions of Eqs. (13) and (14).

Figure 4 shows the measured beat spectrum for a 5 km-long dipersion shifted optical fiber (DSF). In this case, the reference beam and the reflected beam from the far end of the fiber are phase-decorrelated because the fiber length is longer than the coherence length of the laser. The resolution bandwidth of the spectrum analyzer was 100 kHz. The Fresnel reflection was not intended to be suppressed. The Fresnel reflection at the far end of the fiber and the Rayleigh backscattering are clearly measured. This is because the spread of the source phase-noise-induced intensity noise spectrum is much smaller than the spectral range of the beat spectrum for the Rayleigh backscattering. The propagation loss of the fiber can be estimated from the slope of the Rayleigh backscattering to be 0.4 dB/km, which is almost the same with that measured by the OTDR. The SN ratio for the Rayleigh backscattering at the far end of the fiber is found to be about 22 dB, and accordingly, the SN ratio at the input of the fiber is 26 dB (= 22 dB+0.4 dB/km × 5 km × 2 (round-trip propagation)). This value of the SN ratio means that the maximum measurement range is 65 km for an optical fiber with 0.2 dB/km attenuation (26 dB/(2 × 0.2 dB/km)). The difference in the SN ratio for the phase-correlated and the phase-decorrelated cases is maybe due to the difference of the probe beam power.

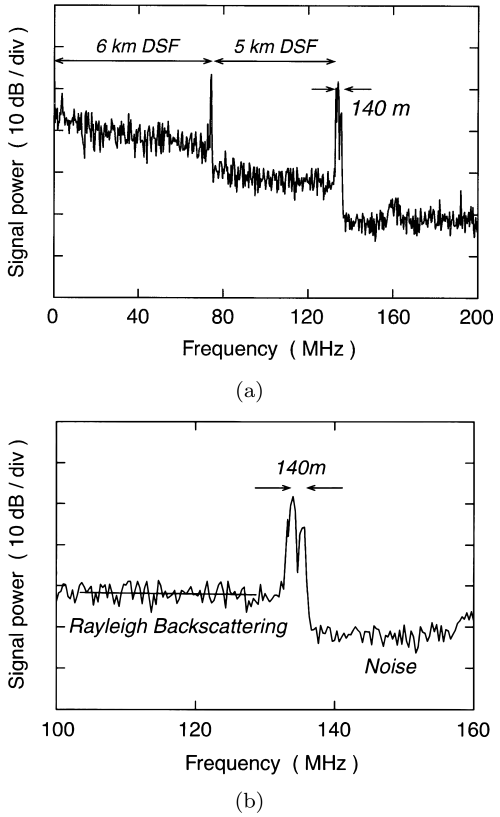


Fig. 5 Measured beat spectrum for connected three optical fibers (6 km, 5 km and 140 m). (a) Whole spectrum. (b) Magnified figure around the far end of the fiber.

The spatial resolution at the far end, which is defined by the full-width at half-maximum, is about 46 m. This value is resonable because the theoretical spatial resolutions determined by the spectral linewidth of the laser δL_s and by the time-gated spectral analysis δL_c are given by Eqs. (13) and (14), respectively.

Figure 5 shows the measured beat spectrum for connected three optical fibers (6 km, 5 km and 140 m). The Fresnel reflection at the connectors and the far end of the fiber are clearly measured, and the connec-

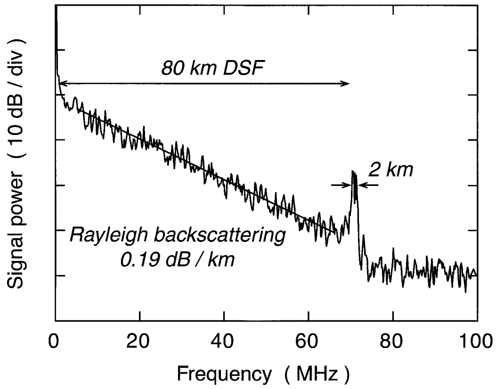


Fig. 6 Measured beat spectrum for an 80 km-long DSF.

tion loss between the 6 km and the 5 km fibers is estimated from the difference in the Rayleigh backscattering level to be 2.5 dB. From Fig. 5(b), the spatial resolution at 11 km is estimated to be about 100 m. This valus is worse than the theoretical spatial resolution. This is because the optical frequency sweep was nonlinearly swept within the period of the gate width. If the gate width is more narrowed, the spatial resolution is, ideally, improved because the optical frequency sweep is assumed to be linear within the period of the narrowed gate width. However, the magnitude of the beat spectrum was lowered due to the narrowed gate width. Hence the optimum gate width T was 5 μs in our experiments.

Figure 6 shows the measured beat spectrum for an 80 km-long DSF. The probe beam was amplified before launching into the fiber to enhance the signal to noise ratio. The repetition frequency of the optical frequency sweep, f_m, was 200 Hz in this experiment to satisfy Eq. (9). The spatial resolution at 80 km distant is about 2 km, which is due to nonlinear optical frequency sweep in our system. The Rayleigh backscattering is clearly measured and the loss of the fiber is estimated to be 0.19 dB/km, which is almost the same value with that measured by OTDR.

3.4 Estimation of Optical Gain of EDFA

Next, we estimated the optical gain of an erbium-doped optical fiber amplifier (EDFA) by using this system. The measurement setup is shown in Fig. 7. A 30 m-long EDFA was inserted between the 6 km and the 5 km fibers. In this system, the Rayleigh backscattering level in the 5 km fiber changes due to the optical gain in the EDFA, and the optical gain was estimated from the change of the Rayleigh backscattering level in the 5 km fiber. The measured spectrum is shown in Fig. 8(a). Since the spatial resolution of this system is about 46 m at 5 km distant, the gain distribution inside the EDFA could not be measured and only the input-output gain was measured. The Rayleigh backscattering level in the 5 km fiber increases with inceasing the pump power to the EDFA due to the optical gain. Figure 8(b) shows the optical gain against the pump power. In the figure, the line is the optical gain measured by an optical spectrum analyzer. The optical gain measured by this system agrees well with that measured by the optical spectrum analyzer.

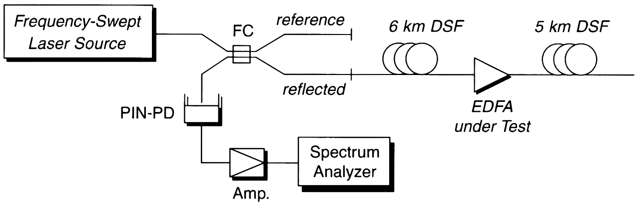
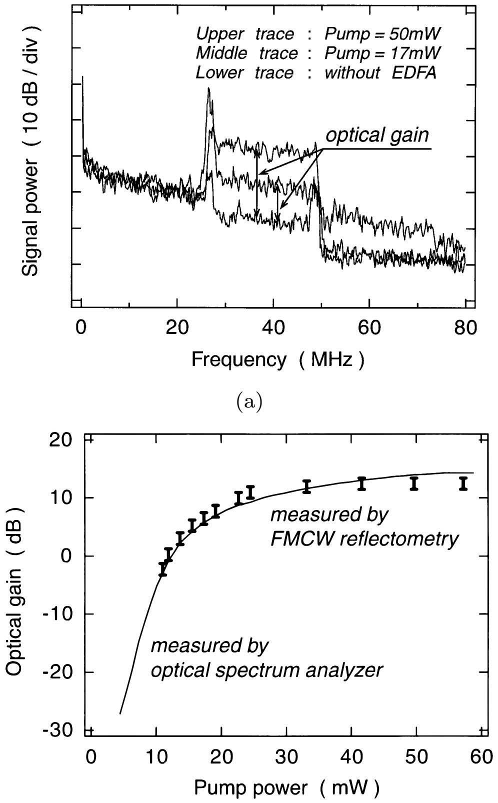


Fig. 7 Experimental setup for estimating the optical gain of an erbium doped optical fiber amplifier (EDFA).



(a)

(b)

Fig. 8 Measured beat spectrum for optical fibers incorporating the EDFA and the optical gain of the EDFA. The optical gain of the EDFA can be estimated from the change of the Rayleigh backscattering level in the 5 km fiber. (a) Measured beat spectrum. (b) Optical gain against the pump power.

4. Conclusion

We have described the phase-decorrelated FMCW reflectometry for characterization of long optical fibers. In this system, the optical path difference between the reference beam and the reflected beam from the optical fiber under test is much longer than the coherence length of the light source, and then, the reference and the reflected beams are phase-decorrelated. As a result, the beat spectrum between the reference and the reflected beams is measured. We have denoted that the spatial resolution is enhanced by narrowing the spectral linewidth of the light source and increasing the repetition frequency of the optical frequency sweep as well as increasing the chirping range of the optical frequency sweep. In the experiments, an external-cavity DFB laser was used as a narrow linewidth light source, and the optical frequency was swept by minute modulation of the external cavity length. Single mode optical fibers at 1.55 μm were characterized. The maximum measurement range of 80 km was achieved, and the spatial resolutions of 46 m, 100 m and 2 km were achieved at 5 km, 11 km and 80 km distant, respectively. The Rayleigh backscattering was clearly measured and the propagation loss of optical fiber was also measured. Finally, we estimated the optical gain of an erbium-doped optical fiber amplifier (EDFA). In this experiment, the Rayleigh backscattering level of the optical fiber followed after the EDFA changes due to the optical gain in the EDFA, and the optical gain is estimated from the change in the Rayleigh backscattering level. The estimated optical gain agrees well with that measured by the optical spectrum analyzer.

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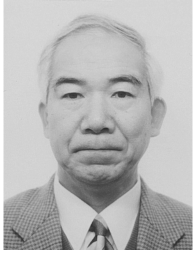

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