Wideband Rare-earth-doped Fiber Amplification Technologies—O-band and S-band Amplification Technologies

Shinichi Aozasa†, Tadashi Sakamoto, Hirotaka Ono, Atsushi Mori, and Makoto Yamada

Abstract

Ultralarge-capacity dense wavelength division multiplexing (DWDM) and wideband coarse wavelength division multiplexing (CWDM) are expected to be deployed in transmission systems in the near future to provide systems with transmission rates of several terabits per second and inexpensive short/medium-distance transmission systems, respectively. To support these systems, as well as access networks and local area networks, the amplification bandwidth of rare-earth-doped optical fiber amplifiers must be expanded beyond the C band (1530–1565 nm) and L band (1565–1625 nm). In this article, we introduce new O-band (1260–1360 nm) and S-band (1460–1530 nm) amplification technologies and a fiber amplifier for broadband CWDM transmission based on S-band amplification.

1. Importance of band expansion

The development of optical fiber amplifiers covering new bands in addition to the C band (1530–1565 nm) and L band (1565–1625 nm) can be expected to expand transmission capacity per optical fiber and generate new applications. In particular, the O band (1260–1360 nm) is a zero-dispersion region for single-mode fiber that enables the transmission of high-speed signals without dispersion effects. This band is currently finding widespread use in access networks and local area networks. In addition, the S band (1460–1530 nm) can be combined with the C and L bands to increase significantly the number of channels and transmission capacity of wavelength division multiplexing (WDM) transmission in medium- and long-haul photonic networks.

NTT Photonics Laboratories has developed O-band amplification technology using a praseodymium(Pr^{3+})-doped fiber amplifier (PDFA) [1]-[3] and S-band amplification technology using a thulium(Tm^{3+})-doped fiber amplifier (TDFA) [4], [5] or erbium(Er^{3+})-doped fiber amplifier (EDFA) [6]. We are also developing (S+C)-band amplification technology by connecting this Tm^{3+}-doped fiber amplifier in series with a C-band EDFA. And using this technology, we are developing a fiber amplifier that can be applied to a coarse wavelength division multiplexing (CWDM) transmission system, which is soon to be introduced as a low-cost transmission system [7].

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2. O-band optical fiber amplifier

The energy levels of the praseodymium ion (Pr^{3+}) used for O-band amplification are shown in **Fig. 1(a)**. Here, O-band optical amplification uses the $^1G_4 \rightarrow {}^3H_5$ stimulated emission transition. However, the existence of another level ($^3F_4$) at 3000 cm^{-1} below the upper level ($^1G_4$) of this transition means that an excited ion may resonate with lattice vibration in ordinary silica fiber doped with Pr^{3+}, resulting in thermal relaxation without emission (non-radiative transition). To achieve efficient optical amplification here, the glass used as the optical fiber material must make it difficult for non-radiative transitions to occur. For this purpose, we developed indium-fluoride glass [1].

The configuration of an optical fiber amplifier in which the core of the indium-fluoride fiber is doped with Pr^{3+} is shown **Fig. 1(b)**. Its amplification char-

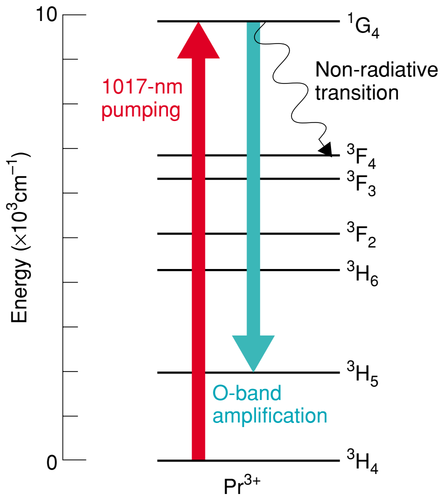

Fig. 1(a). Energy diagram of Pr^{3+}.

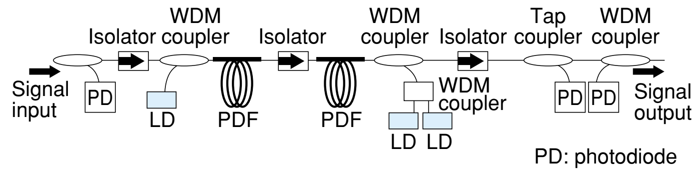

Fig. 1(b). Configuration of PDFA with our developed fluoride fiber.

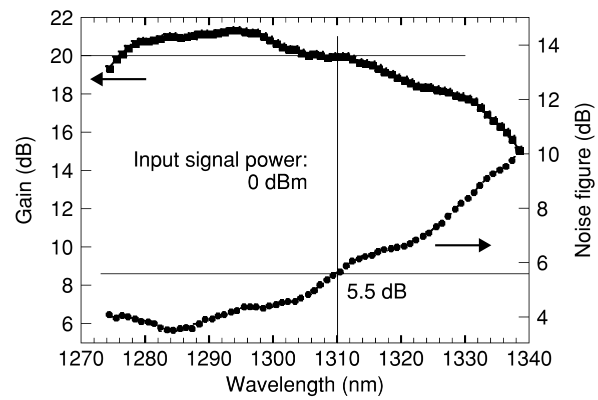

Fig. 1(c). Amplification characteristics of PDFA with our developed fluoride fiber.

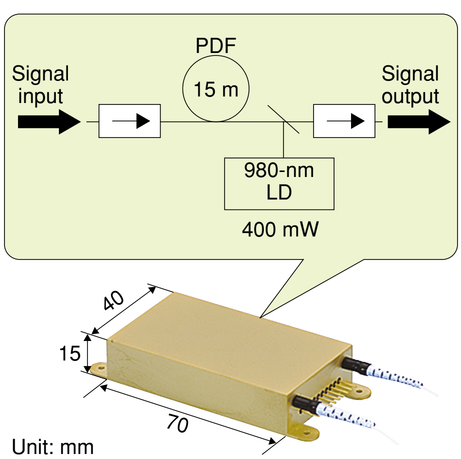

Fig. 2(a). Configuration and overview of gain block employed with our developed fluoride fiber.

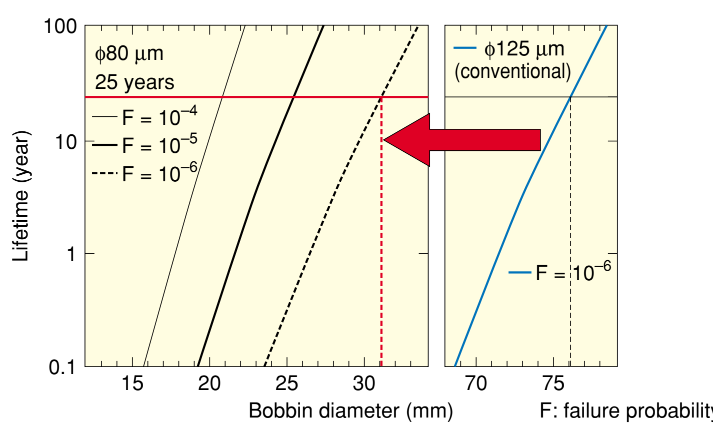

Fig. 2(b). Estimated lifetime versus bobbin diameter.

acteristics are shown in **Fig. 1(c)**. Using a 980-nm laser diode (LD) as a pump source, this amplifier achieved good amplification characteristics, namely, a gain of 20 dB or more, an output of 20 dBm, and a noise figure of 5.5 dB, in the 1276–1310 nm wavelength region [2].

We also investigated ways of reducing the amplifier's size. **Figure 2(a)** shows a compact PDFA that we developed with dimensions of 70 × 40 × 15 mm [3]. It contains 15 m of Pr^{3+}-doped indium-fluoride fiber wound on a bobbin. To make the amplifier small, one must reduce the bobbin diameter, but this increases the bending stress applied to the fiber, which shortens its lifetime. Fluoride fiber has less mechanical strength than silica fiber, and the bobbin diameter can be no smaller than 75 mm to guarantee a fiber lifetime of 25 years with a failure probability of 10^{-6}. To counteract this increase in bending stress on the fluoride fiber, we designed a new fiber with a smaller diameter of 80 µm instead of 125 µm for the conventional fiber. As a result, we maintained the 25-year guaranteed lifetime with failure probability of 10^{-6} using a bobbin diameter of 31 mm, which is less that half the conventional diameter (**Fig. 2(b)**). This compact amplifier achieves an output of 13 dBm and a gain of 15 dB or more in the 1287–1318 nm wavelength region. Besides replacing conventional amplifiers, we expect this PDFA to be used for new applications such as post-amplifiers in transmitters and channel amplifiers for optical add/drop multiplexers (OADMs).

3. S-band optical fiber amplifiers

S-band rare-earth-doped fiber amplifiers are made using two approaches:

1) Using a thulium(Tm^{3+})-doped fiber (TDF) as the amplification medium
2) Using an S-band EDFA, which is a conventional EDFA with its amplification region expanded into the S band [4].

3.1 TDFA

The energy level diagram of the Tm^{3+} ion is shown in **Fig. 3(a)**. S-band amplification makes use of the stimulated emission between the $^3H_4$ and $^3F_4$ levels. We also use fluoride glass to achieve this amplification more efficiently. (Although amplification is possible with silica glass, its efficiency is about one-third that with fluoride glass.) Here, the $^3H_4$ upper level has a shorter fluorescence lifetime than the $^3F_4$ lower level. As a result, a population inversion forms by a 1st excitation process from the $^3H_6$ ground state to the $^3F_4$ lower level and by a 2nd excitation process that excites ions accumulated at the $^3F_4$ lower level to the $^3H_4$ upper level. In the TDF gain spectrum, a gain peak appears at 1460 nm in a high population-inversion state, but for a population-inversion state of about 40%, we can achieve an amplification band with a peak at the center of the S band, as shown in **Fig. 3(b)**. To form such a relatively low population inversion of 40%, we developed a method for doping the fiber with a high concentration of Tm^{3+} ions [5]. The addition of about 6000 ppm of Tm^{3+} ions shortens the distance between the ions and generates an interaction (cross relaxation) between them thereby increasing the number of ions excited to the $^3F_4$ lower level. The amplification characteristics of a TDFA made using this method are shown in **Fig. 3(c)**. By using a gain equalizer (GEQ), we achieved a high gain of 26 dB, a gain excursion of 0.6 dB, and a noise figure of 6 dB or less in the 1480–1510-nm wavelength region, demonstrating excellent amplification characteristics. Here, 1400-nm semiconductor laser diodes were used for both excitation processes.

When this amplifier is used in an actual system, it must be controlled so that the gain of each signal wavelength is fixed; that is, any gain fluctuation

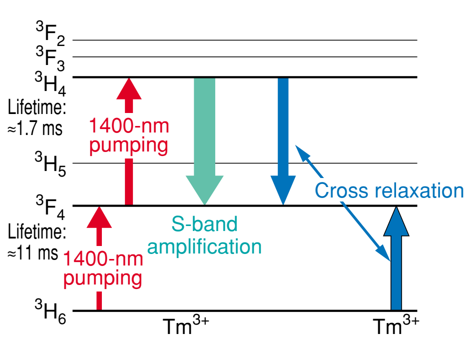

Fig. 3(a). Energy diagram of Tm^{3+}.

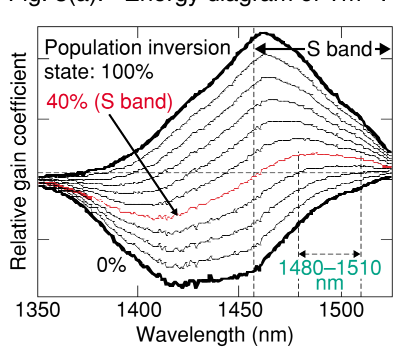

Fig. 3(b). Gain spectrum for various population inversion states.

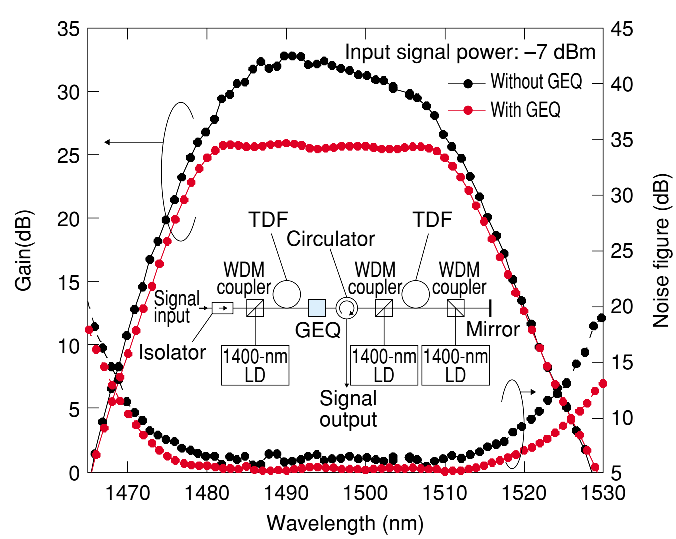

Fig. 3(c). Amplification characteristics of S-band TDFA.

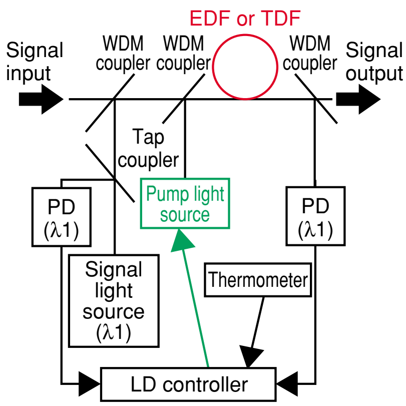

Fig. 4(a). Configuration of gain control unit for EDFA.

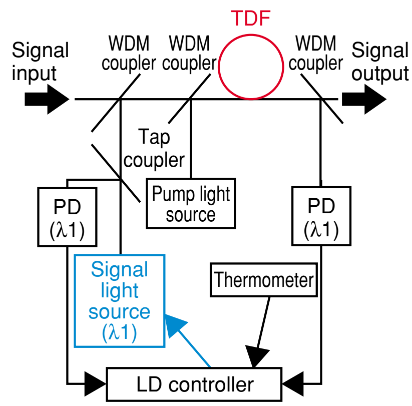

Fig. 4(b). Configuration of gain control unit for TDFA.

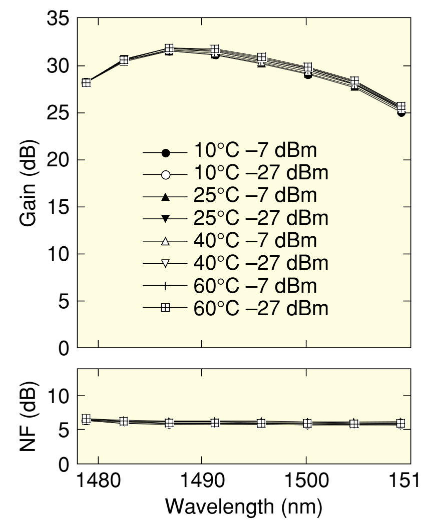

Fig. 4(c). Gain spectra and noise figures (NFs) when the gain control unit was operating against a total input signal power of –27 to –7 dBm and a temperature of 10 to 60 °C.

caused by channel and temperature fluctuations must be suppressed. Because only two levels contribute to amplification in an EDFA, such control can be achieved by monitoring the signal of only one wavelength and adjusting the pump power so that the gain of that signal is fixed (green arrow in **Fig. 4(a)**). In contrast, three levels contribute to amplification in a TDFA, which prevents the gain from being held constant by a control technique as simple as that used with the EDFA. In response to this problem, we decided to keep the pump power constant while controlling the power of a built-in light source (which was dedicated to providing a monitor signal) so as to keep the gain of that signal constant (blue arrow in **Fig. 4(b)**). The end result was a control system as simple as that used for the EDFA [6]. Using this technique, we achieved a gain excursion of less than 0.6 dB for a total input signal power change corresponding to the change from 100 channels to 1 channel. This system also has a simultaneous compensation function to handle changes in temperature. This function enabled us to obtain good gain deviation at 0.8 dB even for a temperature jump from 10 to 60°C in addition to the channel fluctuation (**Fig. 4(c)**).

3.2 S-band EDFA

The Er^{3+} ion also has stimulated emission in the S band, and gain can be obtained by forming a high population inversion. However, the gain in the C band is higher than that in the S band, and the effects of laser oscillation and large amplified spontaneous emission (ASE) that occur in the C band make for a low population inversion. As a result, it is generally difficult to obtain a large gain in the S band. To avoid the effects of this laser oscillation and ASE in the C band, we employed distributed filters that provide loss in the C band throughout the amplifier. This led to high gain in the S band. **Figure 5** shows the configuration of this S-band amplifier and its good amplification characteristics. A gain of more than 21 dB and a noise figure of less than 6.7 dB were obtained in the 1486–1518-nm wavelength region [7].

4. (S+C)-band amplification and a CWDM amplifier

Eight-channel CWDM transmission systems are starting to be introduced, but their transmission scale is determined by the span loss. By using optical amplifiers, we can relax this constraint and expand the applicable range of a CWDM system. In CWDM transmission, optical amplification must operate over a wide wavelength region of 1470–1610 nm. Although wideband erbium-doped tellurite fiber amplifier (EDTFA) technology (described in the previous article) can cover amplification in the long-wavelength four-channel region (1550–1610 nm), a TDFA by itself is insufficient for the short-wavelength four-channel region (1470–1530 nm) because

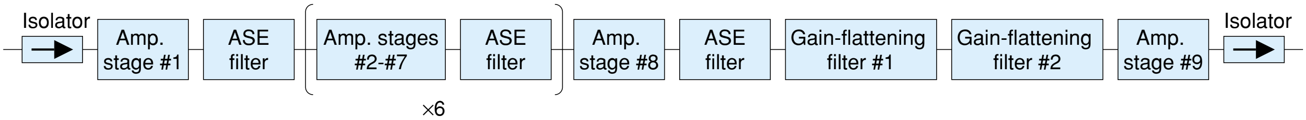

Fig. 5(a). Configuration of S-band EDFA.

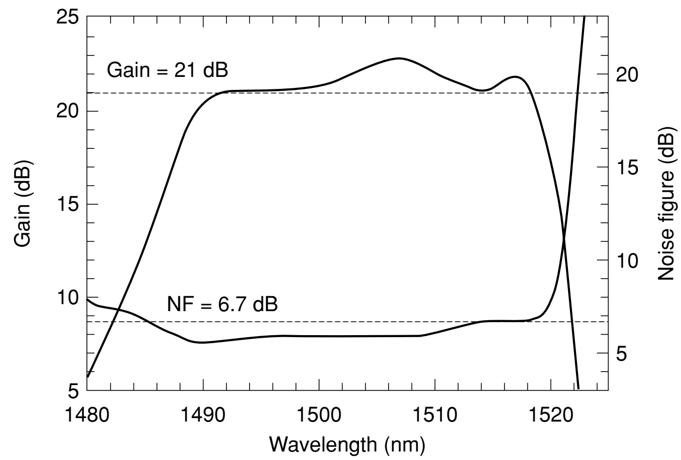

Fig. 5(b). Gain and noise figure spectra of S-band EDFA.

its upper amplification limit is 1510 nm. To cover this region, we developed (S+C)-band amplification technology by connecting a TDFA with an S-band EDFA in series (TDFA-EDFA hybrid amplification) [8]. This approach can provide seamless amplification over the S and C bands.

The configuration of our amplifier for CWDM transmission is shown in **Fig. 6(a)**. The input CWDM signals are divided into those for the short-wavelength four-channel region (1470–1530 nm) and those for the long-wavelength four-channel region (1550–1610 nm). The signals on the short-wavelength side are amplified by the TDFA-EDFA hybrid amplifier and those on the long-wavelength side by the wideband EDTFA. After amplification, these signals are recombined and output.

The amplification characteristics before gain equalization and the loss characteristics of the GEQ for both amplifier sections are shown in **Fig. 6(b)**. The hybrid amplifier section achieves a high gain in the wide (80-nm) region of 1460–1540 nm by combining the TDFA and EDFA gains, and the EDTFA section achieves a high gain in the 1540–1620-nm wavelength region. A large gain equalization of more than 30 dB is needed for the EDTFA section. To suppress any rise in the noise figure caused by this gain equalization, we divided the erbium-doped tellurite fiber (EDTF) into three sections and inserted GEQs between them (Fig. 6(a)).

The amplification characteristics of a CWDM amplifier with this configuration are shown in **Fig. 6(c)**. A gain of more than 20 dB and a noise figure of less than 8 dB are achieved for –20 dBm/ch × 8 channels of CWDM signal input. We have used this amplifier as an inline amplifier and confirmed that CWDM signals can be transmitted through 100 km × 2 spans of single-mode fiber [8].

5. Future developments

The effective use of the wideband transmission characteristics possessed by transmission optical fiber (≤0.4-dB/km low-loss equalization band: 1250–1680 nm) will enable the development of large-scale, broadband photonic networks and optical communication systems. In upcoming research, we plan to expand the amplification bandwidth even further into wavelength regions not covered by current rare-earth-doped fiber amplifiers to support the development of high-performance large-scale optical communication networks.

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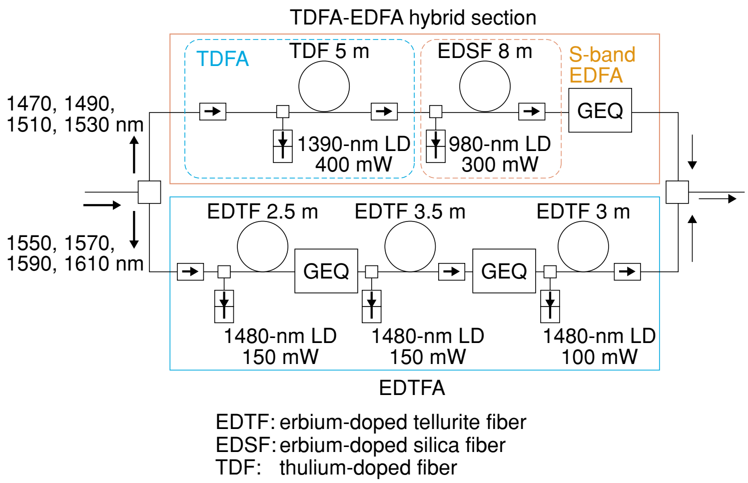

Fig. 6(a). Configuration of CWDM amplifier.

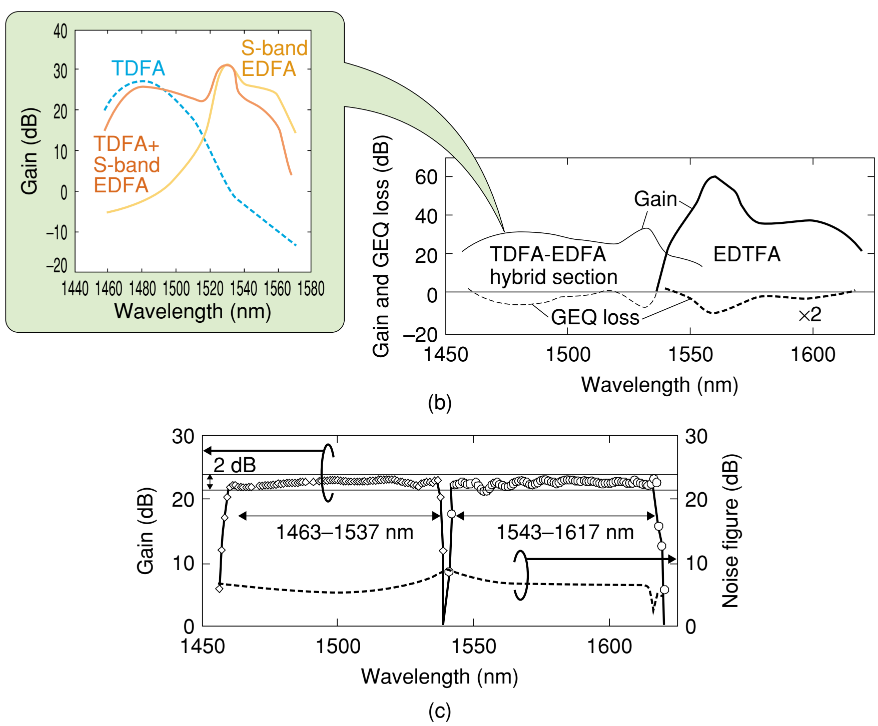

Fig. 6. Amplification characteristics (b) without GEQ and (c) with GEQ.

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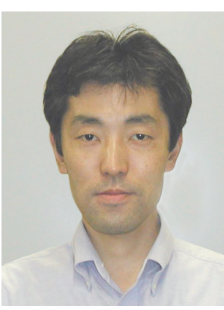

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