3-5 Ka-band High Power Multi-port Amplifier (MPA)

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Ka-band High Power Multi-port Amplifier (MPA) is developed and will be demonstrated through the communication experiments for the future satellite communication systems by multi-beams in the WINDS program. In the conventional satellite communication systems by multi-beams, it is designed that transponder configuration set for each transmit power amplifier that is connected to its exclusive antenna beam, so if a port’s power condition for communication have some margin, its surplus power can’t be distributed to other port's. On the other hand, WINDS has MPA and its control system by ground terminal, total output power of the MPA is shared among all communication ports, and it is possible to assign required output power in several antenna beam efficiently within total output power. MPA for WINDS have 8 input/output ports, frequency band is 17.7-18.8 GHz, and total output power is more than 280 W.

Keywords
WINDS, MPA, Multi-port Amplifier, Ka-band, High power amplifier

1 Introduction

In the field of satellite communications, researchers and engineers are conducting research and development of the Ka band, pursuing broadband communications and cultivation of new frequency bands. Wireless communications in the Ka band also require countermeasures against attenuation due to rain — a vexing problem in the Ka band. To overcome these issues, the satellite needs to feature sufficient transmission power to provide the link availability required in the communication links as well as to include functions for appropriately controlling the satellite transmission power required to establish links in regions with temporarily increased connection demands.

In particular, for a satellite communication system that provides communication services to multiple locations (i.e., multi-beam services), the system may be advantageously designed in terms of satellite resources by coordinating the satellite transmission power for all communication ports (beams) and setting and distributing this power among the beams according to the communication environments (e.g., rain conditions and communication demands) in the regions to which the communication services are provided, instead of preparing power separately for each communication port.

For the Wideband InterNetworking engineering test and Demonstration Satellite (WINDS)[1], which can simultaneously provide fixed communication links to eight locations both within and outside of Japan, we have developed an 8-port multi-port amplifier (MPA), and plan to demonstrate its performance in orbit through a range of communication experiments.

2 Features of MPA

A conventional multi-beam satellite communication system that assigns a separate power amplifier for each beam needs to equip each port with the satellite transmission power required for establishing a communication link in each service area. Particularly when considering satellite communications in the Ka band, we also need to consider compensation for RF signal attenuation caused by rain. As the number of the multiple beams increases, the effect of this attenuation on the satellite system resources becomes correspondingly greater.

On the other hand, clear weather generally occurs far more often than rain. Thus, it is more efficient in terms of satellite system design to share the transmission power of the satellite among the beams and to distribute it appropriately according to communication environments and communication demands, as opposed to setting satellite resources for each port to provide the power required in rainy conditions.

The MPA developed for WINDS has a maximum satellite transmission power of approximately 280 W, and is capable of distributing this power to eight beams at the same time.

3 Functions and performance of the WINDS onboard MPA

3.1 Structure

Figure 1 shows the external appearance (photograph) of the WINDS onboard MPA.

Figure 2 shows a functional block diagram of the same. This MPA consists of an input multiplexer (INMTX), which divides signals; an output multiplexer (OUTMTX), which combines signals; driver amplifiers (D-AMPs), which finely adjust the phase and amplitude of the signals to improve the RF performance of the MPA; traveling-wave tube amplifiers (TWTAs); and waveguide switches (INSW and OUTSW), which switch ports in the event a TWTA fails to operate.

A signal input to an arbitrary port is divided into eight blocks in the INMTX and input into the TWTAs through the D-AMPs. The signal blocks are then amplified in the TWTAs (up to approximately 50 W) and input to the OUTMTX and output to a specific port. (In the case of one-to-one communication, the signal input in X in Fig. 2 is output to Y.)

Figure 2 is an example of one-to-one communication. The MPA also supports N-to-N (N = 1 to 8) communications. In addition, the functions of the D-AMP make it possible to provide 1-to-N amplification (N = 2, 4, 8) and to change the relationship between the input and output ports.

Overviews of each component are listed below.

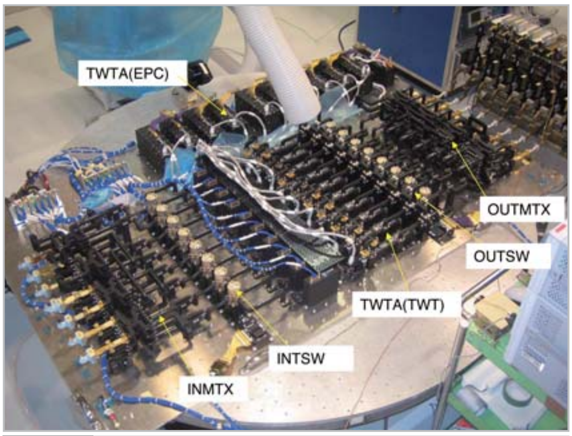

Fig. 1 *Configuration of MPA (PFM)*

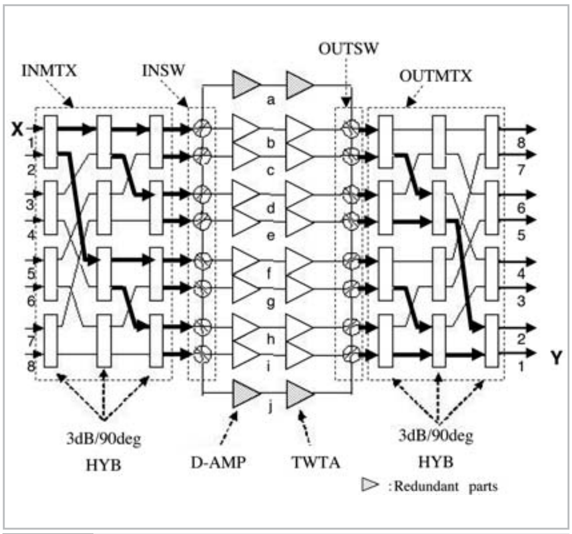

Fig.2 *Block Diagram of MPA*

(1) Power division and combination (INMTX/OUTMTX)

The 8-port MPA must divide the input signal into eight equal power blocks and input these blocks into the TWTAs (power dividing). With the reverse mechanism, the MPA also needs to combine eight signal series amplified in the TWTAs into a single signal series (power combining). The INMTX divides the power, and the OUTMTX combines the power.

This division and combination of the RF signals are performed in the INMTX and OUTMTX units, respectively. The INMTX and OUTMTX each consist of 12 waveguide hybrids (HYBs: two inputs and two outputs each) and the E/H bends that connect them.

A signal is distributed to eight TWTAs by allowing the signal to pass through three HYBs. The signals output from the eight TWTAs pass through the OUTMTX, where the signals are routed through three HYBs via the reverse mechanism of the INMTX to be phase-combined; the resultant signal is then output to a specific port.

(2) Traveling Wave Tube Amplifier (TWTA)

The RF signal is divided into eight blocks by the INMTX, sent to the TWTAs via the D-AMPs, amplified to 50 W at maximum, and sent to the OUTMTX.

The TWTA used in MPA is based on conventional technologies, and its design is optimized according to the frequency, bandwidth, and output requirements of WINDS communication. The TWT was designed based on a 120 W-class TWT[2] under development by a manufacturer selected when the WINDS project was initiated.

The TWTAs installed on WINDS feature 90 W-class saturation power. Figure 3 shows the input and output characteristics of the 10 TWTAs installed on WINDS. The operation of the MPA takes into account the effect of the intermodulation product due to non-linear amplification, and the MPA is operated in a region backed off by approximately 2.5 dB, where linear amplification can be assumed.

Figure 4 shows the external appearance (photograph) of the TWTA flight model.

(3) Adjustment of amplitude and phase (D-AMP)

To improve the RF performance of the MPA, it is important to equalize the amplitude and to synchronize the transmitted phase between the divided signal series in the step directly before these signals are input to the TWTAs. The driver amplifiers (D-AMPs) are used to effect this adjustment. With a command from the earth, the phase can be set in steps of 1 degree and the amplitude can be set in steps of 0.5 dB.

The D-AMPs can also set the phase in steps of 90 degrees (four values: 0 degrees,

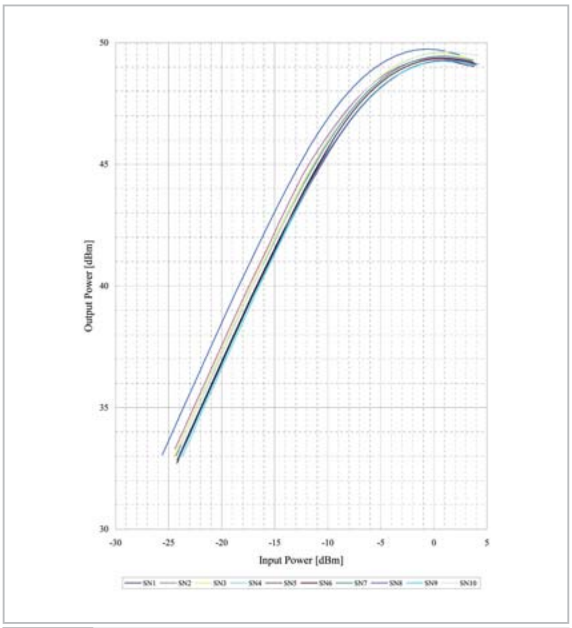

Fig.3 *Input and output characteristics of TWTA (flight model)*

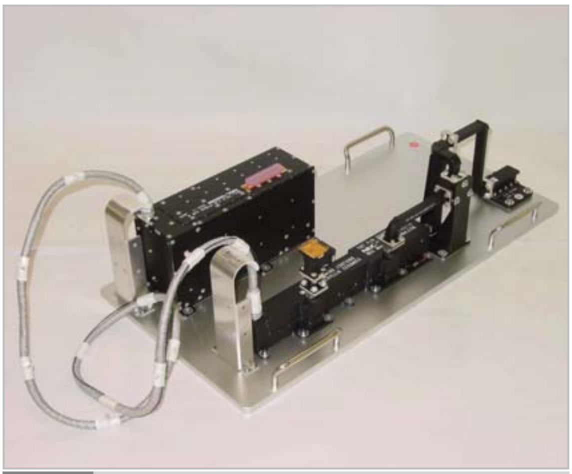

Fig.4 *External appearance of TWTA (flight model)*

90 degrees, 180 degrees, and 270 degrees; this function is referred to as the “bit phase function” below), can change the route (the relationship between the input and output ports), and can support 1-to-N amplification (N = 2, 4, 8). [See **3.3** (3)]

(4) Configuration of redundant system (INSW/OUTSW)

To enable the WINDS onboard MPA to handle failures in the D-AMPs or the TWTAs, the configurations of the D-AMPs and the TWTAs need to provide the same electrical lengths between INSW and OUTSW as those stipulated under the structural characteristics for the 8-port MPA. For this reason, an even number of D-AMP and TWTA (D-AMP+TWTA) sets is required. We have prepared 10 sets for the MPA.

Figure 2 shows the currently assumed structure of system operation, employing Ports b through i. (Ports a and j are off.) If the D-AMP or the TWTA in a specific port fails, the MPA continues operation by changing the configuration, effected by turning off one of the adjacent ports.

For example, if Port c should fail, the D-AMP and the TWTA in Ports b and c or in Ports c and d are turned off. If Port a should fail, the D-AMP and TWTA in Ports a and b or in Ports a and j are turned off. In other words, two supplementary ports can respond to a failure in a single port. (Naturally, the redundant system can handle the failure of two adjacent ports.)

3.2 Major specifications

Table 1 shows the major specifications of the WINDS onboard MPA.

3.3 Functions and performance

Major functions of the WINDS onboard MPA are as follows.

(1) The input signal is amplified to a maximum of 280 W and then output.

(2) The MPA can accept different signals in up to eight ports. While maintaining the spectrum of each signal, the MPA outputs the signals within the range in which the sum of the power outputs in all ports does not exceed 280 W.

(3) The bit phase function of the D-AMPs enables 1-to-N amplification (N = 2, 4, 8) and route modification. (Figure 2 illustrates the case in which all D-AMP bit phase shifters are set to 0 degrees.)

Figure 5 shows an example of this function. When the signal is input in X and the bit phase shifters in Ports b through i are set as [b = 0, c = 180, d = 0, e = 180, f = 0, g = 180, h = 0, i = 180], the signal is output at Z. Alternatively, if the signal is input in X, and the bit phase shifters in Ports b through i are set as [b = 0, c = 270, d = 90, e = 0, f = 270, g = 180, h = 180, i = 90], the signal is output from the four ports marked M. The bit phase function can set the configuration of the redundant sys-

Table 1 *Major specifications of WINDS onboard MPA*

Item	Performance
Frequency range	17.7 to 18.8 (GHz)
Range of input power	-8 to -22 (dBm/port)
Max. input power for MPA(in all port)	-8dBm
Total Output power at linear operation	More than +54.5 (dBm) [about 280(W)]
Inter port isolation	More than 25 (dB)
Power Consumption	Less than 1385 (W)
mass	About 65kg
TWTA-output power	Max. 90 (W) [saturation] Operation:50 (W)*1
D-AMP’s Gain variable range / step	Range : 0 to 3 (dB) Step : 0.5 (dB)
D-AMP’s Phase variable range / step ①for adjustment function ②for one to N(=2,4,8) connection	① Range : 0 to 45(degree) Step : 1 (degree) ②Range : 0 to 360 (degree) Step : 90 (degree)

*1: MPA for WINDS operates in linear range

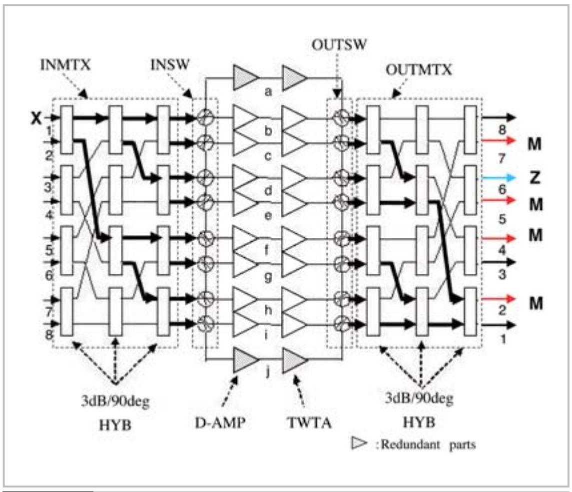

Fig.5 *Explanation of output port change by D-AMP’s Bit-shift function*

tem and provide 1-to-N amplification (N = 2, 4, 8). WINDS can switch among these modes at intervals of 2 msec, in synchronization with the TDMA time slot.

4 Major technologies

Listed below are the key technological issues in providing or improving MPA performance in the development of the WINDS onboard MPA.

(1) Design of INMTX/OUTMTX

Improving the maximum transmission power requires reducing loss in the INMTX and OUTMTX. While we designed the HYB based on a system with proven track records in other satellites, we increased its bandwidth, introduced high isolation in its design, and shortened the E/H bend length for connecting the waveguides, as well as shortened the bend length between any two HYBs to reduce the loss as much as possible.

Securing inter-port isolation requires equalizing the total electrical length of all ports and reducing the differences in phase and amplitude to the full extent possible among the ports. To equalize the INMTX/OUTMTX route length in all ports, the design takes into account the number of bends, the direction of bending, and the number of E/H bends used.

We performed an evaluation test using prototypes[3][4] and determined the designs of the HYB and the INMTX/OUTMTX. Table 2 shows the results for the HYB prototypes.

Using these HYB prototypes, we built the INMTX/OUTMTX prototypes and confirmed the prospect of building a flight model featuring loss of 1.15 to 1.26 (dB) and inter-port isolation of 29.6 (dB).

Table 2 *HYB prototype results*

Item	Result of BBM Test
Insertion Loss	3.18 (dB)
VSWR(return loss)	28.3 (dB)
Insertion loss unbalance between port	Within 0.13 (dB_{p-p})
Phase unbalance between port	-1.35 to +1.05 (degree)
Isolation	27.8 (dB)

※the number of samples under test are 24

(2) D-AMP and TWTA characteristics

It is difficult to produce individual examples of the D-AMP and the TWTA with equal frequency amplitude characteristics and phase characteristics, due to individual variations in manufacturing. Thus, we evaluated the characteristics using a D-AMP and TWTA set (D-AMP+TWTA) as the unit, minimized the differences in characteristics, and made the phase characteristics as even as possible.

(3) Temperature conditions

The temperature of the MPA is expected to rise due to the heat generated in the TWTAs and the heat generated by the RF signals passing through the waveguides. On the other hand, the characteristics of the D-AMP and TWTA change significantly with temperature. As described in (2), to even out the characteristics of the D-AMP+TWTA combination, the temperature distribution within the MPA must be maintained as evenly as possible, and to ensure that the temperature difference between ports is minimal, regardless of the temperature distribution generated in WINDS operation. As noted in Reference[5], a phase difference between the ports of within 10 degrees and an amplitude difference within 1.5 can provide an inter-port isolation of 20 dB or more.

In the development of WINDS, we applied this information and considered that the characteristics of the TWTA and the D-AMP would require that the temperature difference between the ports be limited to approximately 11°C to arrive at a phase difference between the ports of 10 degrees or less. We placed heat pipes in the structure body under the MPA to even out the temperature among the ports.

(4) Power-handling capacity design

When all TWTAs of the WINDS onboard MPA operate in the saturated range, we expect that a maximum of 700 W of signals or more may pass through a single waveguide; accordingly, we designed the power-handling capacity of the OUTMTX waveguides to accommodate at least 1.4 kW.

5 Verification by tests

To set the routing of the D-AMPs and the TWTAs in the test, we turned Ports a and j off (main system) or Ports e and f off (one of the possible redundant system configurations) as shown in the block diagram indicated in Fig. 2, followed by measurement and evaluation of the resultant data.

In addition to normal temperature and pressure conditions, we measured various characteristics at a low temperature (approximately −5˚C) and at a high temperature (approximately +50˚C) and confirmed that performance variation due to temperature is extremely small, thus securing the targeted MPA performance.

(1) INMTX/OUTMTX direct connection characteristics (excluding D-AMP/TWTA)

Before assembling the entire MPA system, we removed the D-AMPs and the TWTAs, connected the empty space with waveguides, and evaluated the resultant isolation. Table 3 shows the results, in which we secured an isolation of 27 dB or more. We also secured 30 dB or more in 42 out of 56 routes.

(2) Input and output characteristics

Figure 6 shows the input and output characteristics for input into Port 1 (18.0 GHz, Ports a and j are turned off). When the signal is input at −8 dBm, it is output at 55.44 dBm. All ports show similar characteristics.

(3) Inter-port isolation[Note 1]

Figure 7 shows the inter-port isolation characteristics for input to Port 1. These results show that isolation of 25 dB is maintained over a bandwidth of approximately 1.1 GHz. Input to Ports 2 through 8 reveals similar characteristics.

(4) Frequency amplitude characteristics[Note 1]

Table 4 shows a summary of the results of the frequency amplitude characteristics when Ports a and j are turned off. Generally, the characteristic values in the lower side of the band are slightly larger. Nevertheless, the system ensures a performance of 1.0 dBp-p or

Table 3 Results of INMTX/OUTMTX direct connection tests (Configuration without D-AMP and TWTA)

	IN1	IN2	IN3	IN4	IN5	IN6	IN7	IN8
OUT1		30.73	33.33	33.59	32.04	33.04	33.16	28.99
OUT2	34.66		33.49	32.81	32.78	31.92	29.28	33.57
OUT3	34.21	29.50		29.31	33.65	29.19	31.71	32.53
OUT4	29.53	34.14	27.04		29.37	33.40	32.80	31.33
OUT5	31.16	30.63	33.21	29.23		27.40	35.25	36.04
OUT6	30.61	30.84	28.95	33.18	29.59		35.77	35.53
OUT7	34.30	29.06	31.23	30.56	33.78	31.19		33.98
OUT8	29.07	34.20	30.55	31.35	30.80	33.43	32.68	

※ : Table shows that when input port(column) is IN#, output signal shows each 8 port. Those 8 output value shows column IN#.

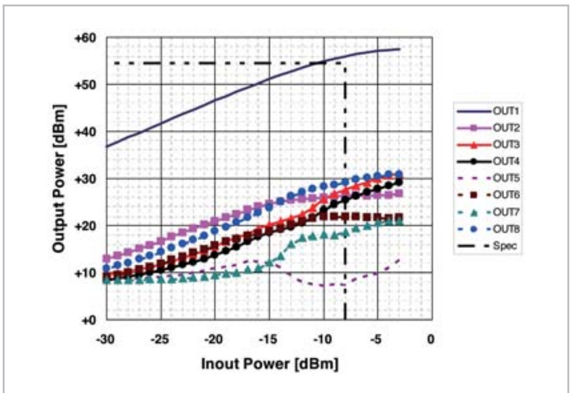

Fig.6 Input and output characteristics for input to Port 1 (18.0 GHz)

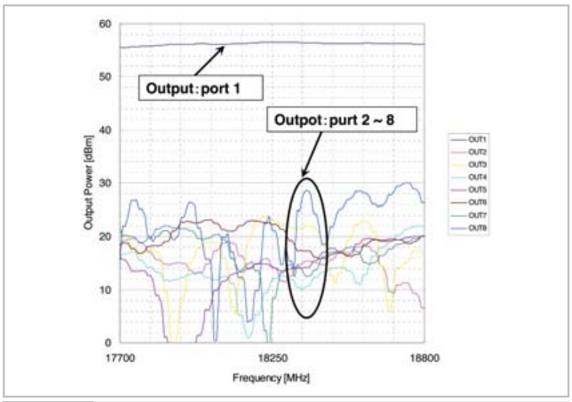

Fig.7 Inter-port isolation characteristics for input to Port 1

less in the 600-MHz band.

(5) Phase nonlinearity(Note 1)

Table 5 shows a summary of the nonlinearity results when Ports a and j are turned off. These results indicate that the initial goal of 10 degrees or less is satisfied.

(6) AM/PM conversion characteristics

Figure 8 shows the AM/PM conversion characteristics for input and output in Port 1. The specified distribution in the development of the MPA is 6.2 deg/dB or less [for input of -8 dBm]. All eight ports feature values of approximately 3.5 deg/dB.

(7) Power-handling capacity

We performed a thermal vacuum test in a vacuum chamber, setting the conditions for maximum power transmission with the MPA. We then tested to determine whether the OUTMTX waveguides are capable of handling the resultant power. The results were as follows. For the test for Port 1, input of +1 dBm yielded output of +57.77 dBm. (When input was higher than +1 dBm, the results were approximately the same; thus this +1 dBm value is considered the maximum output of the MPA.) The MPA was operated at this output power for approximately 10 minutes; no abnormal operation was observed. These results confirm the appropriateness of the power-handling capacity design of the OUTMTX.

Table 4 *Frequency amplitude characteristics of MPA (flight model)* (Note 2)

Frequency range(GHz)	Variance of response(dB_{p-p})	
	Best	Worst
17.7 -18.3	0.63(port1)	0.81(port2)
18.2 -18.8	0.13(port8)	0.35(port1)

Note2 : port# shows that input port is port#, and output port is port #.

Table 5 *Phase nonlinearity of MPA (flight model)* (Note 2)

Frequency range(GHz)	Variance of response(dB_{0-p})	
	Best	Worst
17.7 -18.3	7.91(port5)	8.98(port1)
18.2 -18.8	3.52(port4)	3.73(port3)

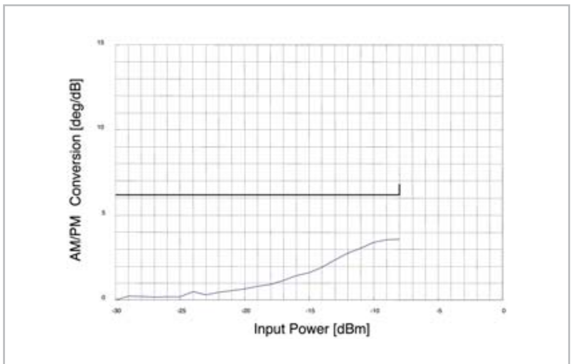

Fig.8 *AM/PM conversion characteristics (for input and output in Port 1: 18.0 GHz)*

(Note 1) Measurement was performed with an input level of −8 dBm. [Operation of the TWTA entails approximately 50 W output (Approximately 2.5 dB back-off).] As a result, output was approximately +55 dBm.

6 Conclusions

After performing a diverse range of tests, including the thermal vacuum test and the vibration test, we were able to confirm target RF characteristics and to confirm the feasibility of MPA operation in orbit.

Acknowledgement

From the outset of development of the MPA, Dr. Shunichiro Egami, a former professor of Shizuoka University, joined our development team as a visiting JAXA researcher and gave us much advice on the design of the MPA and subsequent data evaluation. We would like to take this opportunity to express our deepest thanks to Dr. Egami for his valuable assistance.

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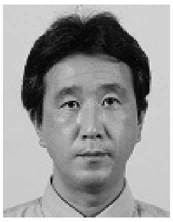

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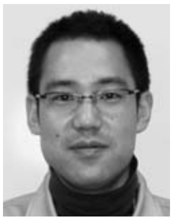

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