Wide-Band Millimeter-Wave/Optical-Network Applications in Japan

Nobuaki Imai, *Member, IEEE,* Hiroshi Kawamura, *Member, IEEE,* Keizo Inagaki, *Member, IEEE,* and Yoshio Karasawa

***Abstract*—This paper describes work on wide-band millimeter-wave (MMW)/optical-network applications in Japan—in particular, projects being pursued at the Advanced Telecommunications Research Institute (ATR). Digital-signal transmission at 118 Mb/s was tested. Results of the experiments demonstrate that high-speed digital-signal transmission, with a total carrier-to-noise ratio (C/N) degradation of less than 1.2 dB from a modem at a BER of 10^{-6}, is feasible. Similarly, analog FM-signal transmission with a weighted *S/N* of more than 45 dB is also feasible at a signal bandwidth of 18 MHz and FM carrier frequency of 43.75 GHz. Based on these results, a demonstration system was constructed, and the feasibility of the system was confirmed. Several key technologies for system construction such as an MMW optical modulator and an MMW high-speed p-i-n detector and some related technologies are also described. In addition, an advanced system considered suitable for future high-speed mobile communications is proposed. This system employs an optical signal-processing multibeam antenna, where the direction of each sharp beam can be adaptively controlled.**

***Index Terms*— Beamforming network, millimeter wave, millimeter wave/optical interaction, millimeter-wave subcarrier system, mobile communication system, optical signal-processing antennas.**

I. Introduction

A RAPID increase in the number of people using mobile/personal communication systems in Japan has pushed the capacity of all channels to their limit, and the problem will become even more severe with the implementation of high-speed data and/or video transmission services. Therefore, there is an urgent need to develop systems that use millimeter-waves (MMW's). Such systems have several attractive features beyond those offered by microwave or UHF-wave systems [1], [2].

First, they have a wide frequency bandwidth; therefore, a large transmission capacity can be obtained. This solves the frequency bandwidth shortage problem faced by existing systems when high-speed mobile communications are considered. Secondly, they have large penetration losses through walls and diffraction losses. This results in compact and well-defined cell boundaries. Micro/pico cellular or wireless local area network (LAN) systems, in particular, benefit from this characteristic. Finally, the small wavelengths allow miniaturize of the size of components—such as antennas. Miniaturized components are very important for portable sets as well as base-station (BS) facilities, which need to be readily installed.

To date, several papers have been published about the performance of MMW optical transmission systems [3]–[6]. This paper describes wide-band MMW fiber-optic technologies being developed in Japan for subcarrier transmission systems to be used in future mobile systems, in particular projects being carried out at the Advanced Telecommunications Research Institute (ATR) [7]–[10]. The construction of a wide-band MMW/optical network for future high-speed mobile communications is described. Moreover, experimental results of the system are reported. Digital-signal transmission at 118 Mb/s was tested. Results of the experiments demonstrate that high-speed digital-signal transmission, with a total carrier-to-noise ratio (C/N) degradation of less than 1.2 dB from a modem at a BER of 10^{-6} is feasible. Similarly, analog FM-signal transmission with a weighted *S/N* of more than 45 dB is also feasible with a signal bandwidth of 18 MHz and FM carrier frequency of 43.75 GHz.

Based on these results, a demonstration system was constructed. The system is composed of two zones and signals are transmitted both ways (up and down links) simultaneously, proving the validity of the system concept. Other related research in Japan, such as a new optical transmission scheme for MMW signals using a time-division multiplexing (TDM) technique and an intelligent antenna for MMW/optical-network systems [11]–[22], is also reviewed.

However, some problems still need to be addressed. Due to large propagation losses, in this MMW/optical-network system, large transmission power is required to cover the wide area of cell zones. In addition, the effect of the multipath becomes serious when the signal bandwidth is wide. To cope with these problems, we propose an advanced MMW/optical network which employs an intelligent multibeam antenna where the direction of each sharp beam can be adaptively controlled. An intelligent antenna that enables beam control is one of the key components in this MMW/optical-network system.

For this purpose, we proposed earlier an optical signal-processing array antenna which has a simpler circuit configuration than conventional antennas because it uses RF phase

Manuscript received April 25, 1997; revised August 15, 1997.

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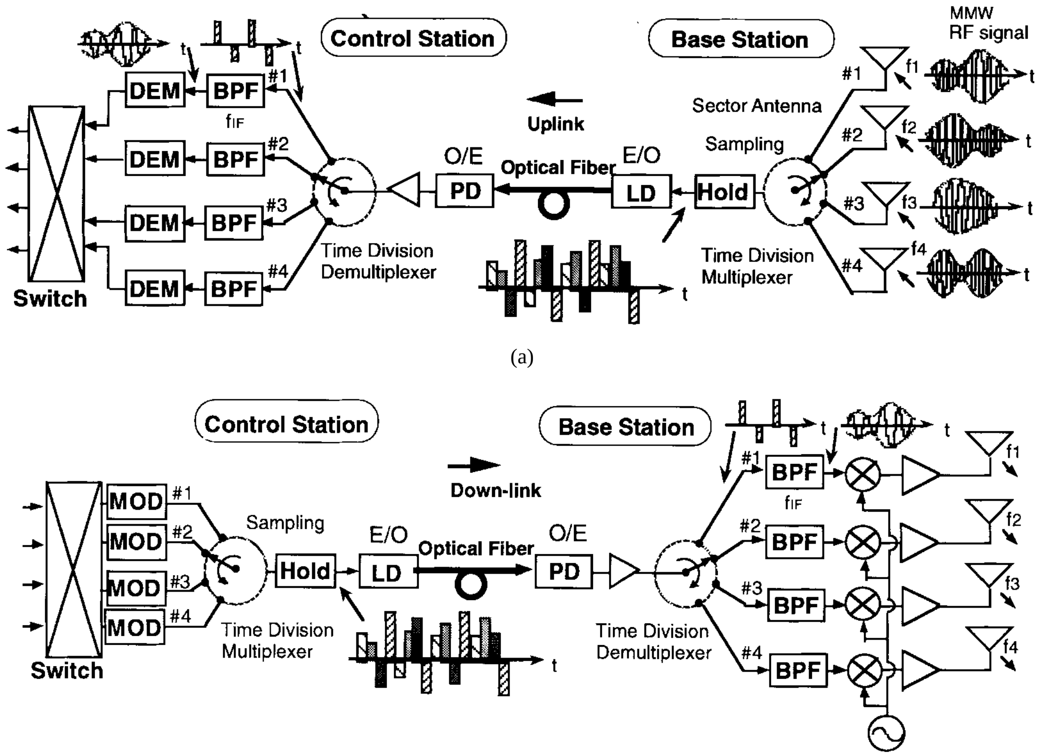
Publisher Item Identifier S 0018-9480(97)08362-2.



(a)

(b)

Fig. 1. Configuration of the TDM fiber-optic link.

shifters when the element number is increased [23]–[26]. After some system evaluations, this antenna was found to be suitable for the above advanced system [27]. Based on this consideration, the configuration of an advanced MMW/optical network employing an optical signal-processing array antenna is proposed. Several key technologies needed to construct subcarrier transmission systems are also described.

II. Research on MMW Optical-Network Systems in Japan

Wide-band and low-loss characteristics of an optical-fiber link can most effectively make full use of the advantages of MMW's [3]–[6]. Several approaches exist to produce a fiber-optic link for MMW's:

1) directly sending the MMW over fiber (MMW-over-fiber) by using an optical carrier;
2) sending a low-frequency signal on an optical carrier for up-conversion at the receiver end;
3) optical generation and fiber-optic transmission of MMW signals such as with an optical heterodyne scheme using two coherent laser sources.

The first approach is the simplest method. The second approach requires more components, excluding it from being used to construct compact BS's. The third approach is more complex and expensive to implement using conventional technologies.

Considering these aspects, we considered that an MMW-over-fiber system would be the best, although each approach has its own features. As is described in the following section, external optical modulators (EOM's) and photodiodes which can be operated in the MMW frequency band have recently become easily available. At ATR, we have already proposed an MMW-over-fiber system that transmits an MMW signal over a fiber-optic link [28]—the first of its kind in Japan—and have constructed a demonstration system. The details are given in the following section.

Osaka University has proposed a new optical transmission scheme for MMW signals using a TDM technique [11], [12]. Fig. 1 shows the configuration of the proposed system. Fig. 1(a) shows the up-link configuration and Fig. 1(b) shows the down-link configuration. In the proposed system of Fig. 1(a), amplitude modulated MMW signals received by several sector antennas from several subscribers are sampled (i.e., bandpass sampling) and transformed to pulse trains of the TDM format in the hold circuit, which then modulate the laser diode (LD). The amplitude of the MMW signals are preserved. After transmission over the fiber, these signals are detected and then divided into individual signals by the time-division demultiplexer. After being bandpass filtered, these signals are demodulated. In contrast, in the down link shown in Fig. 1(b), as in the case of Fig. 1(a), output signals of the modulators are sampled and transformed in the hold circuit to pulse trains with the TDMA format. These pulse trains then modulate the LD. After transmission over the fiber, these signals are detected and then divided into individual signals by the time division demultiplexer and the bandpass filter. They are then up-converted to MMW signals and transmitted to each subscriber station.

The main feature of this method is that it is free from the effects of intermodulation because only one signal is applied

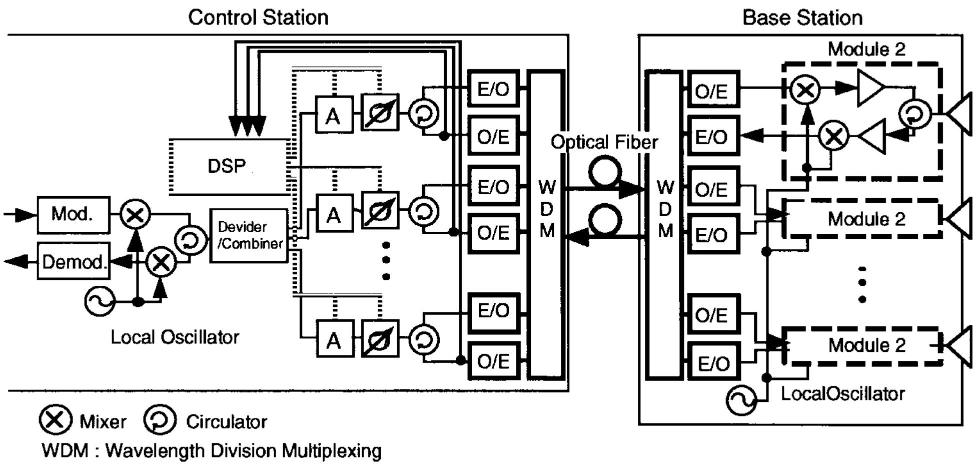


Fig. 2 Configuration of an intelligent antenna for millimeter-wave/optical-network systems.

at a time and direct modulation of the LD is possible because the speed of the sampled signal is much lower than that of the MMW signal. The routing technology based on theoretical considerations for optical-network systems is of great interest for Osaka University researchers [13].

The Communications Research Laboratory (CRL) in Japan, proposed the first intelligent antenna for MMW/optical-network systems [14]. Intelligent antennas are expected to solve the problems of large propagation losses and multipath fading in MMW. They also proposed a technique for application of radio-on-fiber to an MMW intelligent antenna. By using this technique, the configuration of users can be simplified because the radio-on-fiber technique can centralize all information about the users.

Fig. 2 shows the configuration of the system in which adaptive circuits for the beamforming (attenuators and phase shifters) modulator and demodulator are centralized in the control station (CS). In this case, a wavelength-division multiplexing (WDM) technique is used to decrease the number of fibers between the CS and the BS. However, in the system, a low-frequency signal is transmitted over the fiber for up-conversion at the BS. Therefore, a local oscillator is necessary at the BS, but as mentioned above this is not feasible for making compact BS's. They have also studied an adaptive distributed antenna. By combining and equalizing the signal from the different path, the transmission performance under the shadowing and frequency selectivity fading can be improved. The effectiveness of this antenna has been theoretically confirmed [14].

As another approach to MMW/optical-network systems, the optical generation of an MMW signal using a coherent multifrequency light source has been studied, and their transport over an optical frequency-division multiplexing fiber-optic network has been proposed [15]. Experimental results have demonstrated 61-GHz MMW generation and 40-km-long transport.

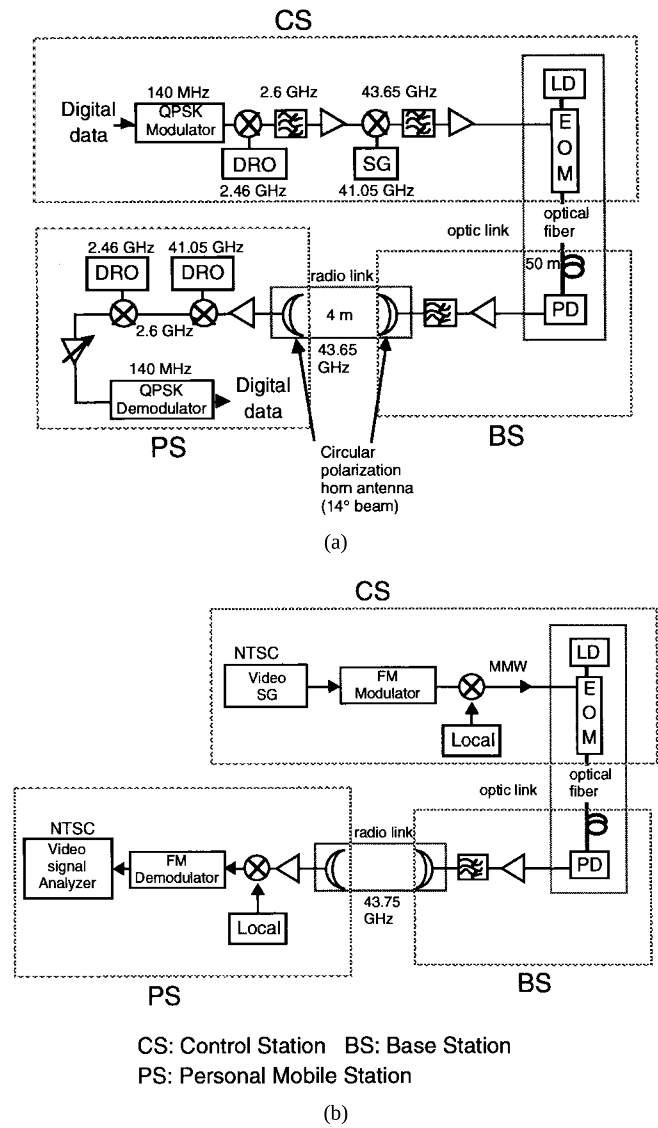


Fig. 3. Block diagram of an MMW fiber-optic link.

III. MMW/Optical Network System Developed at ATR

Fig. 3 shows a fundamental block diagram of an MMW fiber-optic link developed at ATR. Fig. 3(a) shows the case where a digital signal is transmitted, and Fig. 3(b) shows the case where an analog FM signal is transmitted. This system distributes MMW signals from a CS to a BS over a fiber. At

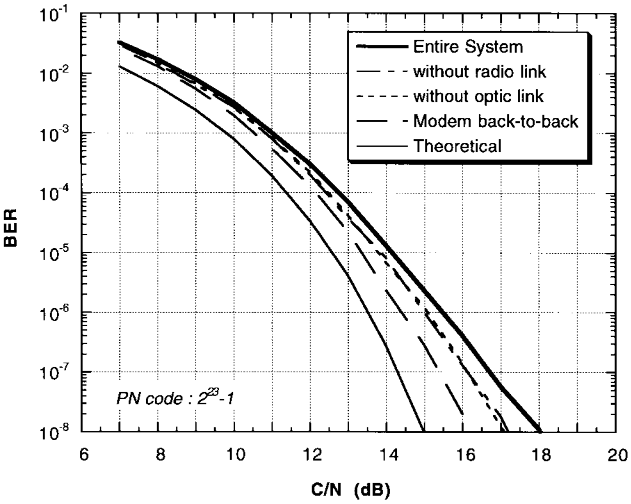


Fig. 4. Measured BER characteristics of the system shown in Fig. 3.

the BS, the optical signals are translated to MMW signals. This means that no frequency conversion is required at the BS. The configuration allows us to achieve simple, small, and low-cost radio BS's because there is no need for frequency converters.

The standard frequency for MMW applications in Japan is 60 GHz. Note, however, that 43.65 GHz has been used in experiments due to restrictions on the characteristics in the optical modulator. The characteristics of the optical modulator are described in Section IV. The optical frequency bandwidth exceeds 30 GHz. However, it deteriorates above 50 GHz. The transmission rate of the signals was 118 Mb/s and QPSK modulation was employed. In the case of digital-signal transmission, a short radio path (4 m) and narrow beamwidth (14°) horn antennas were employed to measure BER transmission characteristics, and to avoid other effects such as multipath propagation.

Fig. 4 shows the system's measured BER characteristics. The measured C/N, which achieves a BER of 10^{-6}, was 15.5 dB. This means the degradation in the BER characteristics of the whole system from the characteristics of the modem was approximately 1 dB. The characteristics were obtained without an optic or radio link. They were almost identical to the total system's BER characteristics. These results show that the feasibility of digital-signal transmission at 118 Mb/s with a total C/N degradation from a modem at a BER of 10^{-6} is less than 1.2 dB, and analog FM-signal transmission with a weighted *S/N* of more than 45 dB was confirmed with a signal bandwidth of 18 MHz and FM carrier frequency of 43.75 GHz.

The C/N degradation in the system [shown in Fig. 3(a)] mainly occurs in two sections: the radio and optic links. If it is assumed that both links have the same C/N, and the C/N in both links has to be kept higher than 18.5 dB to satisfy the total C/N of 15.5 dB. If we consider that a 0.5-dB margin is necessary for the system margin, a C/N of more than 19 dB is necessary. Based on this C/N value, the received power can be calculated as a function of the propagation distance with the parameter of antenna gain [7].

The equivalent input noise power $P_{\rm n}$ is calculated by

$$P_{\rm n} = kTBF \tag{1}$$

where

- k Boltzman's constant (1.38×10^{-23} J/K);
- T absolute temperature (~300 K);
- B bandwidth (Hz);
- F noise figure (NF) of the receiver.

Assuming a 59-MHz bandwidth and a 4-dB NF for the receiver, the $P_{\rm n}$ becomes −92.1 dBm. To achieve a C/N of 19 dB, the received power must be higher than −73 dBm. The signal power $P_{\rm s}$ is calculated from a theoretical equation of the propagation

$$P_{\rm r} = P_{\rm t} G \left(\frac{\lambda}{4\pi d} \right)^2 \tag{2}$$

where

- Pt transmitting power (W);
- G Total gain of the transmitting and receiving antenna;
- λ wavelength (m);
- d propagation distance (m).

By using this equation, the received power can be calculated as a function of the propagation distance with the antenna gain parameter. To transmit more than 50 m, the total antenna gain, which is the sum of both the transmitting and receiving antennas, must be higher than 16.2 dB, assuming a 10-dBm transmitted power at 43.65 GHz. To transmit more than 100 m, the total antenna gain must be higher than 22.2 dB.

Characteristics when an analog FM signal is transmitted have also been evaluated by the system shown in Fig. 3(b). It was found that a weighted *S/N* of more than 45 dB can be achieved with a transmission distance of more than 50 m [29].

Based on these considerations, in order to prove the system concept, a demonstration system was constructed, having one CS, two radio BS's, and two personal mobile stations, as shown in Fig. 5. For the broad-band signal source, a moving picture was used. The signal is the National Television System Committee (NTSC), which is digitized to be 118 Mb/s by the encoder. Since an MMW fiber-optic link can transmit any modulation scheme, an FM analog video signal and a QPSK digital signal were simultaneously transmitted. It was demonstrated that the moving picture could be transmitted with good quality, as was shown in Fig. 4, and the system concept was proved. Fig. 6 shows a view of the experimental setup.

IV. Key Components for Building a MMW Optical Network

To build the system shown in Fig. 3, an MMW optical modulator [16] and an MMW high-speed p-i-n detector [17] were employed as key components. These components are commercially available. The MMW optical modulator described in [16] is available from Sumitomo Cement Company, Ltd., Funabashi, Japan, and the MMW high-speed p-i-n detector (described in [17]) is available from NTT Electronics Company, Ltd, Atsugi, Japan.

Fig. 7 shows the frequency characteristics of the EOM which was used to build the system. The characteristics

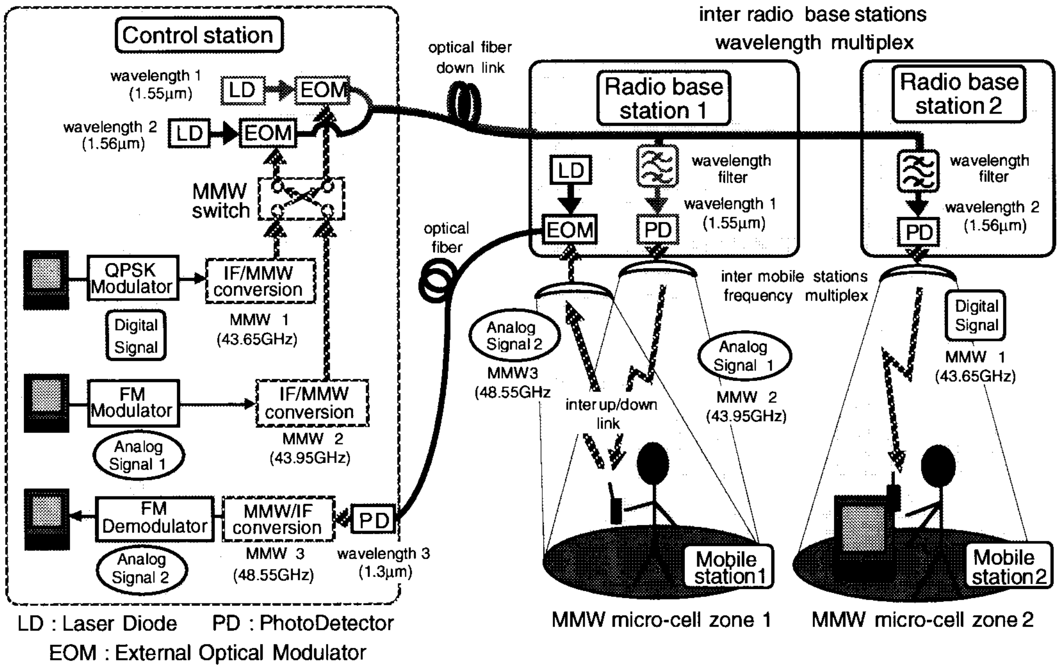


Fig. 5. Block diagram of the demonstration system.

Fig. 6. A view of the experimental setup.

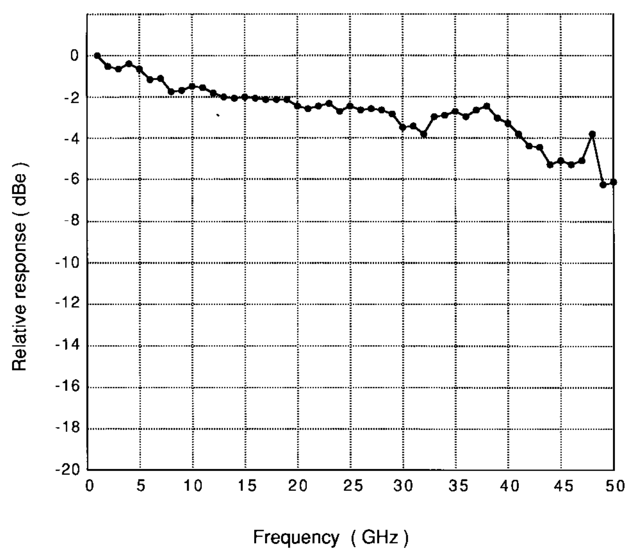
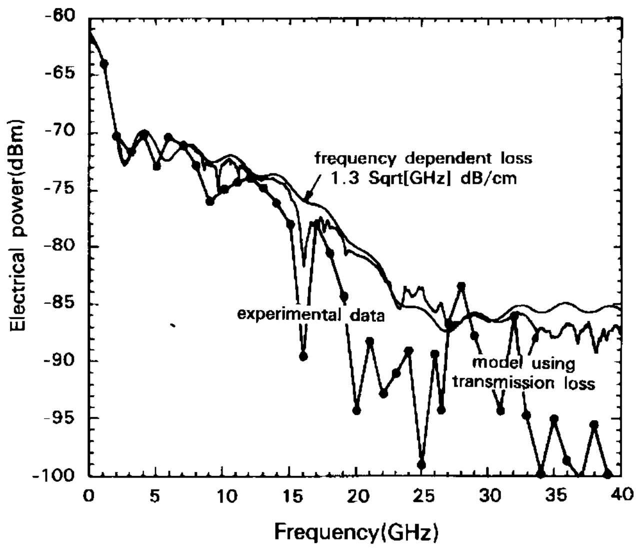


Fig. 7. Frequency characteristics of the EOM that was used to build the system.

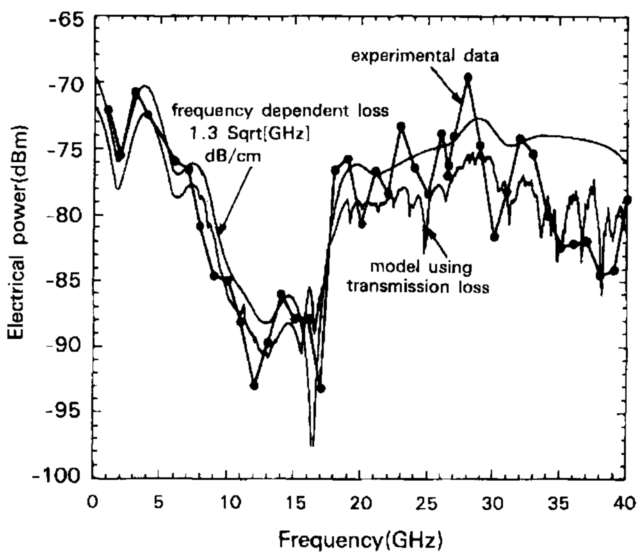
were measured by an HP83467C component analyzer. The optical frequency bandwidth exceeds 30 GHz. The optical insertion loss and half-wavelength voltage $V\pi$ of this EOM are 5.4 dB and 5.0 V, respectively. This EOM features the use of a conventional coplanar waveguide from a practical manufacturing point of view, and is packaged in a rectangular block. A high-frequency response up to the MMW band can be achieved by optimizing the circuit pattern in the input of the coplanar waveguide.

As an MMW optical modulator capable of being operated at higher frequency bands, a ridged-type optical modulator has been reported [18]. Such optical modulators have been proposed which utilize thin (0.6-μm) SiO_2 layers and thick (29-μm) coplanar waveguide electrodes to obtain both a low drive voltage and low conduction losses under the velocity-matching condition. With this configuration, EOM's whose optical frequency bandwidth exceeds 100 GHz with a $V\pi$ of 5.1 V, and EOM's whose optical frequency bandwidth is 45 GHz with a $V\pi$ of 3.3 V could be achieved. The optical insertion losses and the extinction ratios of both types of EOM's were 5–6 dB and more than 20 dB.

Specified frequency bands in the MMW band are being allocated for MMW subcarrier systems. Accordingly, components employed for these systems should have a high responsivity at the specified frequency bands. Based on this concept, several components have been developed, which achieve better performance than conventional ones by optimizing the circuit at the specified frequency bands. For example, an MMW optical modulator was proposed that employs an inverted slot



(a)



(b)

Fig. 8. Measured frequency response of a phase-reversal-type EOM.

line to achieve perfect velocity matching at the specified band and to achieve deep modulation [19], [20].

As another approach, band-operated light modulators, which can reduce the drive power at the expense of narrowing the bandwidth, have been reported [21], [22]. Still another approach is the use of a phase-reversal-type EOM [30].

Fig. 8(a) shows the obtained experimental results for the straight-electrode optical modulator. This figure also show theoretical calculation curves for when the transmission loss of the electrode is included. In the calculation, two assumptions for the transmission loss were made: the transmission loss is proportional to 1.3 $\sqrt{f(\mathrm{GHz})}$, which was experimentally obtained, and the measured transmission loss is included [8]. The dip caused around 15 GHz is due to the dip in the transmission loss itself, which is probably caused by the imperfectness of the coplanar/coaxial transition section.

Fig. 8(b) shows the experimental results obtained for the phase-reversal-type optical modulator, along with the calculated estimation. As was expected, a higher frequency response compared with that of a straight-electrode optical modulator could be achieved around the 30-GHz band. The frequency response of the phase-reversal-type EOM is enhanced by 10 dB compared with that of the straight-electrode-type EOM. The measured and modeled responses fit well at low frequencies. At higher frequencies, the experimental response has a large ripple and a fall in response above 30 GHz compared with the prediction. The likely cause of the problem is deterioration of the electrode return-loss response at high frequencies.

The p-i-n photodetector reported in [17] is of the edged-coupled waveguide type. In conventional p-InP/i-InGaAs/n-InP edge-coupled photodetectors, the thickness of the undoped InGaAs layer determines the coupling efficiency as well as the bandwidth; a tradeoff exists between the coupling efficiency and bandwidth. This originates from the fact that the InGaAs layer functions both as a light-absorption/carrier-transit layer for the photodetector and as a core layer for the waveguide.

To overcome this tradeoff relationship, the optical field distribution was enlarged by adding doped InGaAsP intermediate-bandgap layers between the InGaAs layers and the InP layers. The bandwidth went up to 110 GHz and the efficiency became 50%. However, the p-i-n photodetector employed for the demonstration system described in the previous section could only operate up to 50–60 GHz and at an efficiency between 65% and 80%.

An impedance-matched transimpedance amplifier was also studied. Fig. 9(a)-(i) shows equivalent circuits of the metal–semiconductor–metal (MSM) photodetector used in the simulation. A 50-fF capacitance was chosen for the photodetector [31]. When the input resistance of the transimpedance amplifier is high, the relative response at lower frequency band improves, but the frequency response degrades, as is shown in Fig. 9(b). The response in the lower frequency band was improved proportionally to the input resistance of the transimpedance amplifier. However, the frequency response in the higher frequency band proportionally degraded to the input resistance.

The bandwidth limit of the photodetector was proportional to $1/2\pi\ RC$; therefore, as can be seen, the response degrades 6 dB/octive beyond the bandwidth. A shunt inductance, which is shown in Fig. 9(a)-(ii), was used to improve the response beyond the bandwidth of the photodetector. Fig. 9(c) shows the inductance dependence of the relative response. The input resistance of the amplifier was assumed to be 5 kΩ in this case. A 20-dB improvement, which has been expected at low frequency, could be obtained at frequencies beyond the bandwidth limit of the photodetector.

Based on this concept, a monolithic heterojunction FET (HFET)/MSM OEIC receiver for optical signals was designed and fabricated. Fig. 10(a) shows the circuit configuration of the OEIC receiver. The OEIC receiver has three stages that use HFET's having a 100-μm gatewidth and a 0.2-μm gate length. Fig. 10(b) compares the frequency response of the fabricated OEIC receiver and that of the MSM photodetector itself. The receiver gives more than a 15-dB improvement over the MSM photodetector itself in the frequency range of between 45–50 GHz.

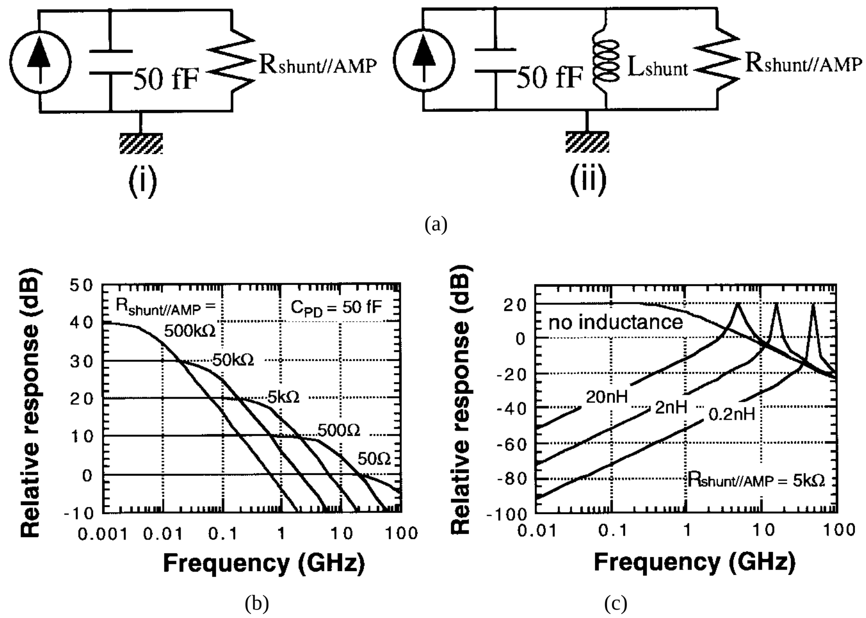


Fig. 9. Equivalent circuits of the MSM photodetector and their frequency responses.

V. A Novel Optical Bi-Phase Modulator for MMW Subcarrier Systems

A novel optical modulator for an MMW subcarrier optic link is reviewed in this section [10]. The modulator enables the bi-phase modulation of MMW subcarriers. It simplifies the optic link by unifying such functions as IF modulation, up-conversion to MMW, and optical modulation, which are separately equipped in a conventional system.

Fig. 11 shows system block diagrams of optical modulators employed as MMW bi-phase modulators. Fig. 11(a) illustrates a conventional configuration and Fig. 11(b) illustrates a configuration based on our proposal. In the conventional scheme, a data signal modulates an intermediate frequency signal, is up-converted to the radio-frequency band, filtered, amplified, and applied to the optical modulator. In contrast, in the new scheme most of these circuits are eliminated and the data signal is directly applied to a Mach–Zehnder modulator, together with an unmodulated radio-frequency wave. By performing several functions, the optical modulator allows a very simple transmitter configuration to be achieved.

The principle of the proposed bi-phase modulator [shown in Fig. 11(b)] can be explained as follows. During operation, the bias voltage and RF drive voltage are simultaneously applied to the EOM. The bias is equivalent to a phase-shift term, which defines the operating point of the EOM. Additionally, we apply a binary data voltage of magnitude $\pm V\pi/2$, which shifts this operating point by $\pm\pi/2$.

Fig. 12 illustrates the operation of the EOM as a bi-phase modulator. As can be seen from this figure, switching between the maximum positive and negative in the slope of the EOM response causes the phase of the radio-frequency term to reverse, while the dc term is constant.

By employing the EOM as a 40-GHz optical subcarrier bi-phase modulator, a differential phase-shift keying (DPSK) signal was transmitted and the BER performance of the system was evaluated [10]. The bit rate of the input data is 10 Mb/s, and is multiplied by a spreading sequence using an exclusive or (XOR) gate at a nominal chip rate of 100 Mb/s. The result was compared with that of an all-electrical configuration using a standard MMW mixer as a phase-shift keying (PSK) modulator. It was found that the measured performance of the system using an optical subcarrier bi-phase modulator is almost identical to that of an all-microwave system The degradation of the SNR at a BER of 10^{-6} was less than 0.4 dB. The proposed configuration was found to simplify the system configuration without degrading the electrical performance.

The EOM can also be used as a frequency-doubling subcarrier bi-phase modulator. For nonlinear operations, the EOM is biased at either the maximum or minimum in the bias voltage versus optical output power response of the EOM.

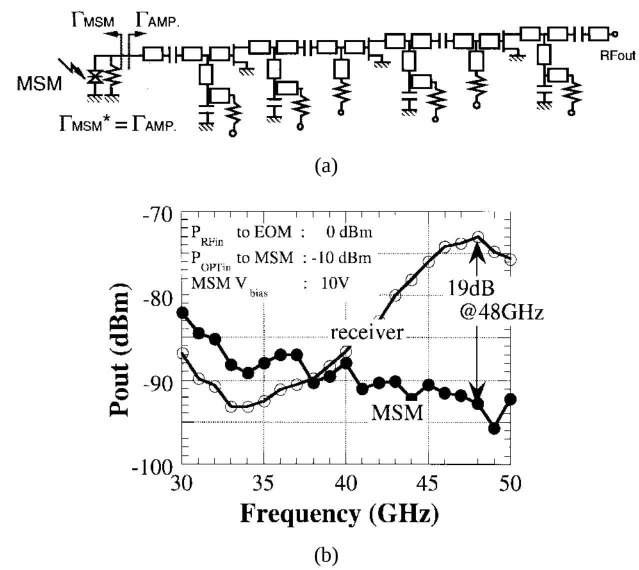


Fig. 10. Frequency response of the OEIC receiver and MSM photodetector.

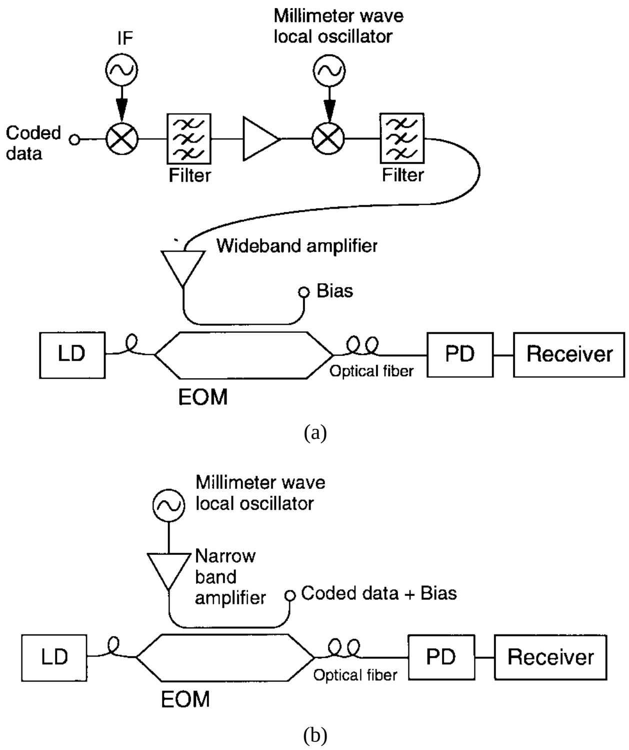


Fig. 11. Block diagram of an optical modulator as an MMW subcarrier bi-phase modulator.

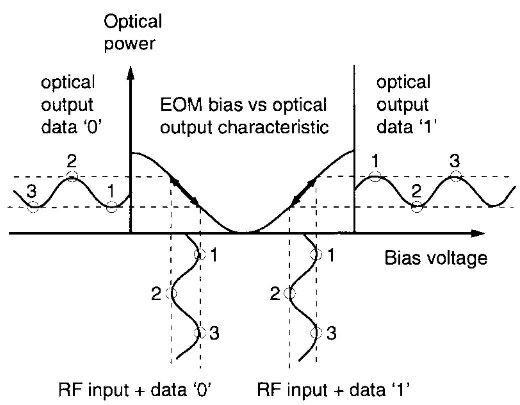


Fig. 12. Operational principles of the EOM as a bi-phase modulator.

Fig. 13 illustrates the operation of the EOM as a frequency doubling bi-phase modulator. Operating in a nonlinear region produces an intensity modulation at twice the frequency of the applied RF signal, and switching between the maximum and minimum results in a phase reversal of the RF component of the detected optical signal [10].

VI. An Advanced MMW Optical Network Employing Optical Signal-Processing Multibeam Antennas

In Section III, the fundamental signal transmission characteristics of an MMW-over-fiber system were examined and the feasibility of this system was confirmed. However, some problems still need to be addressed. For instance, the system suffers from large propagation losses and multipath fading due to structural reflections.

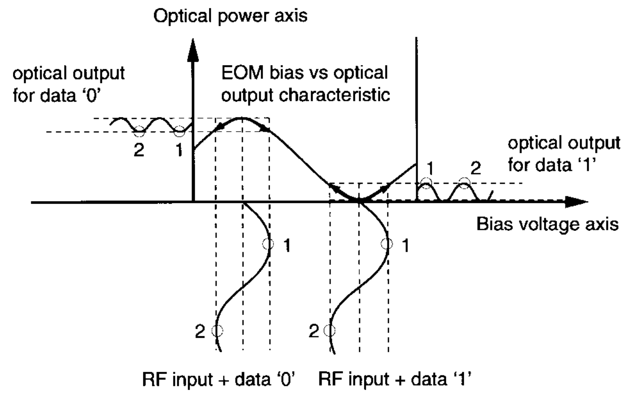


Fig. 13. Operational principles of the EOM as a frequency-doubling bi-phase modulator.

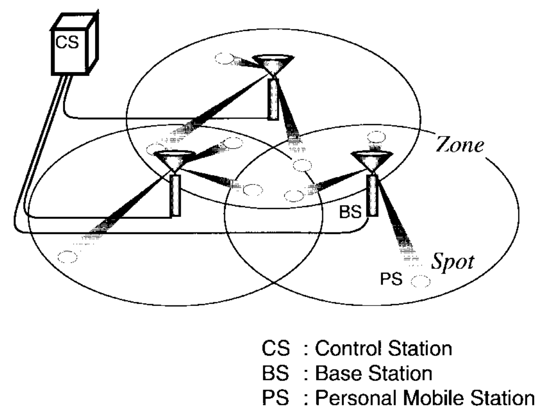


Fig. 14. Advanced multiple spotbeam system.

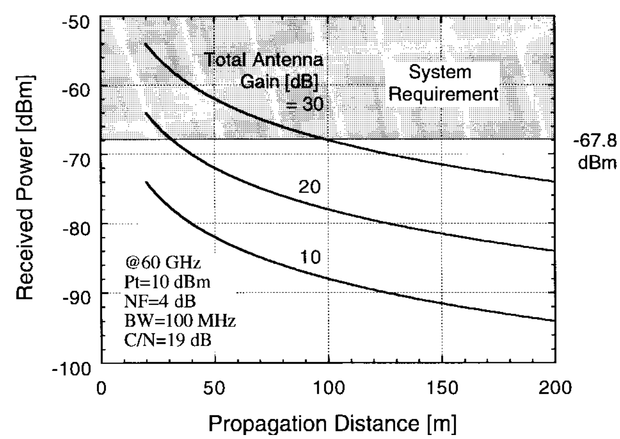


Fig. 15. Received power versus propagation distance characteristics as a function of the total antenna gain.

To cope with these problems, we propose an advanced MMW optical network employing optical signal-processing multibeam antennas. The system configuration is characterized by the combination of an optical-fiber feed system and optical signal-processing multibeam antennas having total optical compatibility [27].

The system we propose (Fig. 14) is composed of a CS, several radio BS's, and many personal mobile stations (PS's). Feeder links between the CS and BS's are connected by optical fibers. Intelligent antennas installed at the BS's have access

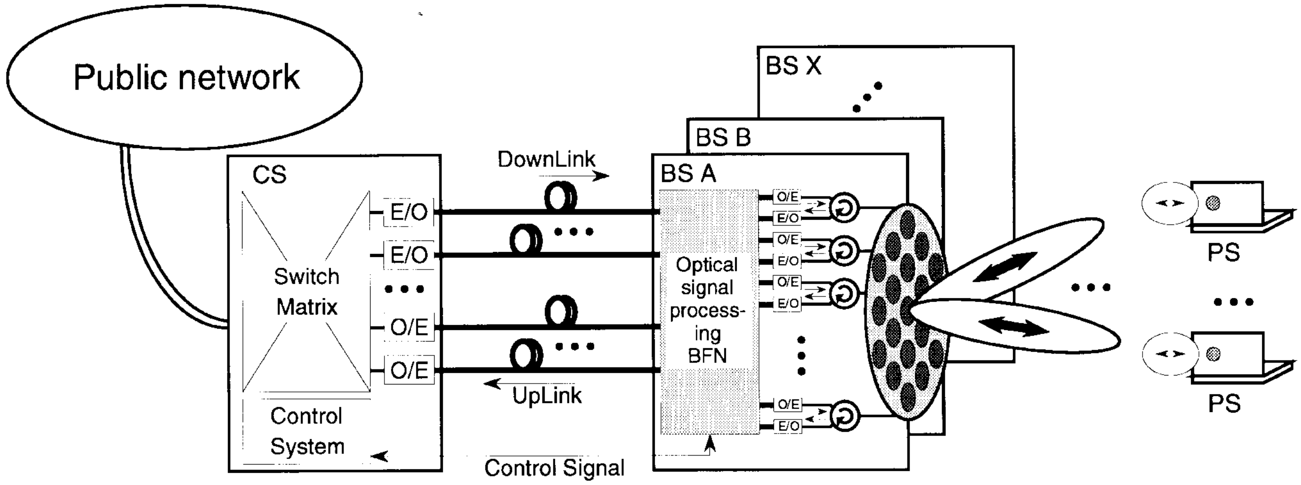


Fig. 16. Configuration of an advanced MMW/optical network employing an optical signal-processing BFN.

to a number of PS's by multiple spotbeams. The zones of the BS's overlap each other, and this causes BS diversity as a countermeasure for shadowing and maintains efficient utilization of the frequency under traffic localization [27].

The fundamental system parameter is evaluated in this section to clarify the system concept. Fig. 15 shows the received power versus propagation distance characteristics assuming a 10-dBm transmitting power at 60 GHz. The procedure for the calculation is the same as that described in Section III. The parameter different from that used in Section III is the operating frequency and signal bandwidth. Here, the standard MMW frequency (60 GHz), and a wider signal bandwidth (100 MHz) are considered for future application. From this figure, it can be seen that to propagate more than 100 m, a total antenna gain of more than 30 dB is required.

In this system, we consider that the BS should have an intelligent high-gain antenna with a sharp beamwidth, and the that PS should have a simple low-gain antenna with a wide beamwidth to enable it to see the BS. The actual gain of a single patch antenna at 60 GHz has been estimated to be around 5 dBi. In this case, the gain of the BS antenna should be 25 dBi. This necessitates a gain of 25 dBi for a BS antenna with at least 100 patch elements (array-factor gain of 20 dB). It would only be a few centimeters square in a two-dimensional (2-D) array configuration in the MMW band.

Beamforming network (BFN) technologies are essential in this system. When the antenna element number is very large as described above, an optical signal-processing array antenna is suitable [27]. An optical signal processor in a BFN generates the desired amplitude and phase distribution for each array element by means of spatial parallel-signal processing.

When a large-scale array antenna is needed in our proposed system, the complexity of the structure does not increase because of its spatial parallel-processing nature. Moreover, it has super-wide-band and RF frequency independent characteristics. Furthermore, since the parallel signal processing can be directly applied to optical signals sent from the CS, this system is highly compatible with optical-fiber systems.

Fig. 16 shows the basic configuration of an advanced MMW optical network employing an optical signal-processing array antenna. In the down link at the CS, signals are switched to a corresponding fiber. At the BS, from the optical signal BFN input, an optical signal is delivered to each optical output port with the desired phase gradients. After the optical-to-electrical (O/E) converter translates it into an MMW signal, MMW signals are radiated from each element antenna with the same phase relation. As a result, the beam is focused to the desired direction. The signal flow for the up link is the reverse process of the above.

The number of signals to be fed from the CS depends on the number of spotbeams. Achieving the desired gain necessitates at least 100 elements. However, within a zone of only 100 m, the number of users might be about ten at most. Accordingly, the number of fibers is much smaller than the number of antenna array elements. Also in this case, the number of fibers between the CS and the BS can be decreased by using WDM, as shown in Fig. 2. As was described above, the number of signals transmitted between the CS and the BS is the same as the number of beams. On the other hand, in the case of Fig. 2, the number is equal to the number of array elements. Accordingly, for the configuration shown in Fig. 16, the circuit configuration of WDM can be simplified compared to the case of Fig. 2.

VII. Conclusion

Work on wide-band MMW/optical-network applications in Japan, particularly those being pursued at ATR, have been reviewed. Results of fundamental transmission experiments have shown that the system proposed is capable of transmitting wide-band digital signals and analog FM signals with good quality, and the feasibility of this system was confirmed.

Several key technologies for system construction and some related technologies have been reviewed. In addition, an advanced system, which is considered to be suitable for future high-speed mobile communications, has been proposed. It employs an intelligent multibeam antenna and the direction of each sharp beam can be adaptively controlled. An optical signal-processing array antenna was found to be suitable for this system.

ACKNOWLEDGMENT

The authors would like to thank Dr. B. Komiyama, President of ATR Adaptive Communications Research Laboratories, Dr. H. Inomata, and Dr. E. Ogawa for their encouragement and advice. They also thank Dr. Y. Ji, O. Shibata, and Dr. H. J. Thomas for their contributions to this paper.

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