3-3 Wireless Access System

3-3-1 Design and Performance of a Millimeter-Wave Video-Transmission System using 60-GHz Band for Indoor BS Signals Transmission

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The design and performance of a millimeter-wave video transmission system using 60-GHz band for indoor broadcasting-satellite (BS) signals transmission is presented. This system can transmit multiple video signals such as broadcasting signals and user-oriented signals to a television set indoors. To minimize the local oscillator's frequency offset and phase-noise effects, the system uses a self-heterodyne scheme. Based on the concept, the system is developed to meet required carrier-to-noise-power-ratio (CNR) and 3rd-order intermodulation (IM). The BS transmission was experimentally done by using the transmitter and receiver setup. The results are very promising and show the feasibility of the system.

Keywords
millimeter wave, broadcast, BS, television, intermodulation, CNR, experiment

1 Introduction

Many systems using millimeter-wave (MMW) bands have recently been developed in the United States, Europe, and Japan. They include home-use wireless-link systems (home links), fixed wireless access systems (FWA), multi-point video distribution systems (MVDS), and wireless local area networks (W-LAN)[1]~[8]. In particular, the 60-GHz band is considered suitable for short-range wireless applications such as home-links under high atmospheric attenuation[9]. These systems use the 60-GHz band to achieve high bit-rate transmission across a wide frequency band. The Telecommunications Technology Council of the Ministry of Public Management, Home Affairs, Posts and Telecommunications (formerly, the Ministry of Posts and Telecommunications) was set up in Japan to introduce systems using the 60-GHz band, and regulations concerning this band were published in August 2000. A MMW video-transmission system[8] was earlier proposed by the Council as a potential system using the 60-GHz band.

The MMW video transmission system is an alternative to the feeder line that can connect outdoor broadcasting reception antennas with indoor television set (TV). The video signals (multiple broadcasting signals) are transmitted on the MMW band in the system. This system can effectively reduce the amount of electrical wiring that is used in portable and wall-mounted TVs. Such a reduction is an advantage since these devices are becoming more and more popular. The MMW band appears to be especially suitable for wide-band systems because broadcasting signals require a wide frequency band[15].

When designing the MMW link for the system, it must be ensured that the local oscillators of both the transmitter and receiver have high frequency stability and low phase noise, because the system uses the oscillators for the frequency conversions. The transmitter converts the input signal (source signal) into an MMW band, and the receiver converts it the regenerated source signal. To minimize the degradation of the transmission quality in this conversion process, a self-heterodyne scheme, in which the local tone of the transmitter is multiplexed into a transmission signal and is used in the receiver with the help of a square-law detector, was earlier developed[10][11][17]. This scheme could sufficiently eliminate the degradation from the phase noise and frequency offset.

One of the critical parameters in the MMW link is the carrier-to-noise-power-ratio (CNR) margin at a specified transmission distance, that is, the allowable transmission loss in the MMW link. This margin mostly depends on the effective isotropic radiated power (E.I.R.P.), reception antenna gain, and noise figure (NF) of the reception amplifier. In addition, the carrier-to-interference-power ratio (CIR) of the MMW link is of great interest, because signals composed of multiple carriers will be strongly affected by the 3rd-order intermodulation (IM3) distortion due to the non-linearity of the power amplifier of the transmitter[12].

Several wireless transmission systems[4][5] and RF devices[7] for video transmission using a MMW band have been developed. However, to the best of our knowledge, the systematic design and application of these systems, especially that using the self-heterodyne scheme, have not yet been fully clarified.

In the next section, the concept of the MMW video transmission system with some assumptions is described. Next, the design of the system based on the CNR link-budget and IM3 distortion for BS (Japanese broadcasting-satellite) signals transmission is introduced, in which the remote-heterodyne scheme is used. After that, the hardware setup and the characteristics of the transmitter and receiver are described. Next, to obtain the required CIR for the BS signals transmission, the experimental CIR by using an amplifier is reported. We also discuss the experimental results obtained using the developed transmitter and receiver. Finally, we conclude with a brief summary. Hereafter "BS" is used as a reception BS signals on the intermediate-frequency (IF) band (BS-IF).

2 System Concept

The conceptual image of the MMW video transmission system is illustrated in Fig.1. The feeder lines connected to the outside antennas such as BS antenna, communication-satellite (CS) antenna and terrestrial broadcasting antenna are fed into one room in the house. These broadcasting signals are multiplexed and transmitted on a MMW band from a wall-mounted transmitter. The receivers on the TV sets receive the MMW signal. Each separated broadcasting signal is obtained after de-multiplexing. Other signals, such as a cable-television (CATV) and user-oriented signals (a video-output signal from a video-tape player, for example) may be simultaneously multiplexed at the transmitter.

The room shown in the figure has an area of 19.4 m^2 (3.6 × 5.4 m) with a diagonal of 6.5 m (this size corresponds to the size of a 12-tatami-mat Japanese room). For this room, a propagation distance of 10m (including a 3.5-m margin) is enough for the MMW link. When the transmission loss due to the inside wall in the house is small, the radiated MMW signal can go through the wall into the next room. Therefore, a direct propagation is basically assumed, the propagation across the wall can also be considered for such a condition.

Hereafter it is assumed that the transmitter and receiver can change the frequency band by using frequency converters. That is, the transmitter converts the signal into an MMW band, and the receiver converts it back into an original one. The transmission quality in the conversions may degrade as a result of the MMW-link-margin reduction, the frequency offset between the transmitter and receiver, the

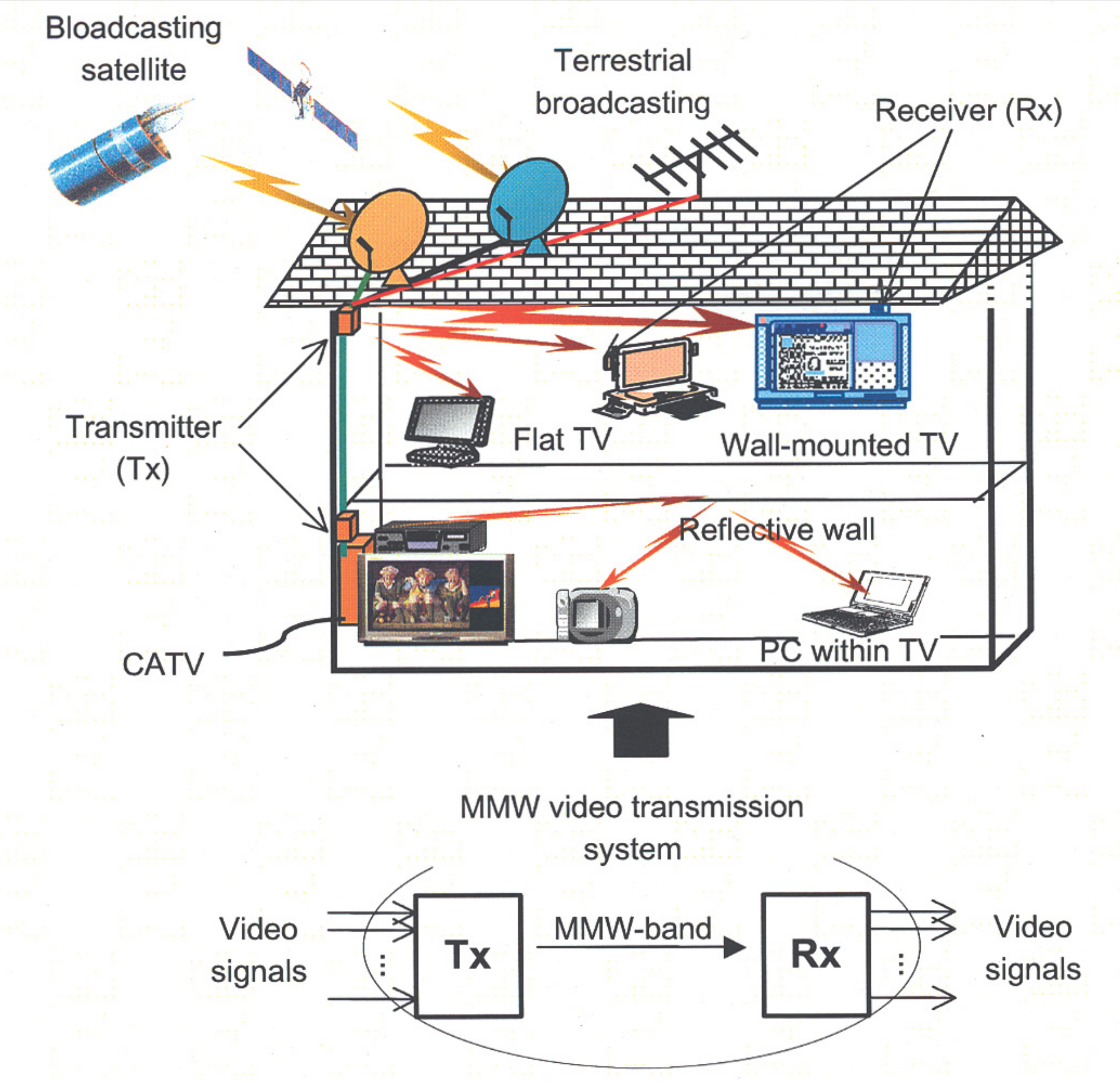


Fig. 1 Conceptual image of MMW video transmission system

phase noise of the converter, and the IM3 distortion.

3 System Design for BS Signals Transmission by the Millimeter-Wave Self-Heterodyne Scheme

The system design for BS signals transmission is given here. To determine the requirements for phase noise and frequency offset, the desirable performance parameters of a typical BS converter installed on a parabolic antenna are listed in Table 1[13][14]. As shown in the table, the output signal of the BS converter has a frequency f_0 plus a frequency offset lower than 1.5 MHz (this means that $f_1 = f_0 \pm 1.5$ MHz, where f_1 is the frequency of the signal). In contrast, a desirable capture range of a typical BS tuner's automatic-frequency-control (AFC) is $f_1 \pm 1.5$ MHz (shown as a digital-integrated-receiver-decoder's (DIRD's) desirable performance[14]). The allowable frequency offset on the MMW link must therefore be within ±1.5 MHz, which corresponds to a 25 ppm deviation at 60 GHz.

The frequency converters of the transmitter and receiver must have low-phase-noise characteristics. Because a converter usually consists of a mixer and a local oscillator, the transmission quality can degrade as a result of

Table 1 *Required performance of a BS converter*

	Modulation	Bs converter of parabolic antenna			
		Phase noise [dBc/Hz]			Allowable frequency offset
		@1kHz offset	@5kHz offset	@10kHz offset	
BS analog	FM (Frequency modulation)	Not specified			± 1.5MHz
BS digital	8PSK (8-ary phase-shift keying)	− 52	− 70	− 80	± 1.5MHz

the phase noise of the local oscillator. To meet the low-frequency-offset and low-phase-noise requirements, a self-heterodyne scheme[10][11][17]is used. In this scheme, the local tone is multiplexed into an MMW BS signals at the transmitter. The local tone and the MMW BS signals are mixed in the square-law detector, and the MMW BS signals are thus down-converted at the receiver. Under this scheme, the degradation of MMW transmission occurred from the inferior phase noise or frequency offset can be almost eliminated[10]. To show the effectiveness of the scheme, the phase-noise performance is listed in Table 2.

Table 2 *Phase-noise performance*

Frequency offset [kHz]	5	10	100
IF Input signal [dBc/Hz]	-98	-104	-117
Local tone [dBc/Hz]	-45	-49	-80
IF output signal [dBc/Hz]	-97	-103	-117

Fig.2 (a), (b), and (c), respectively, shows the BS-IF frequencies, the channel allocation for Japanese BS broadcasting[15], and the frequencies of the MMW band. From Fig.2 (b), there are eight signals (channels) on the IF. The BS digital broadcasting is assigned to BS-1, -3, -13, and -15. The BS-IF frequency with a range from 1.035 to 1.335 GHz (the center frequency is 1.185 GHz) is up-converted to the MMW band, and the signal in the MMW band is down-converted to an IF signal. To convert the BS-IF frequency to the MMW band, the band-pass filter (BPF) of the transmitter suppresses the undesired side-band signal without the local tone (shown as Lo in Fig.2 (c), in which the lower side-band is eliminated). When a single frequency converter is used in the transmitter for hardware simplicity, the RF in Fig.2 (c) becomes to be the local tone's frequency plus 1.185 GHz.

The output CNR at the receiver has previously been analytically derived[10], that is, the power ratio of a detection signal (which is made up of the product of local tone and the BS signals) to a detection noise (which is made up of the product of local tone, BS signals, and thermal noise) at the square-law detector is calculated. The result is given by

$$CNR \cong \frac{Pr}{8kTBF}, \qquad (1)$$

where Pr, k, T, B, and F are, respectively, the total reception power including the local tone, Boltzmann's constant (1.38×10^{-23} J/K), the ambient room temperature (typically, 300 K), the sum of equivalent bandwidth for all BS signals, and the noise figure. The scheme gives the best CNR performance when the transmission power of the BS signals equals that of the local tone, because the detection power of the signal is maximized. Equation (1) means that the CNR using the MMW remote-heterodyne scheme is 9 dB worse than that using the usual down-conversion type detection scheme. Although the 9 dB penalty has to be paid in the scheme, it is very attractive that an inexpensive MMW local oscillator device with inferior phase-noise and frequency-stability performances can be used in home-use systems such as the MMW video-transmission system. In addition, the local oscillator is not needed at the receiver.

3.1 CNR Margin in the Link-Budget Analysis

The system analyzed here is a relay link between the satellite broadcasting link and the MMW link. To evaluate the feasibility of the system, the CNR margin must be estimated by using Equation (1). For the cutoff CNR, CNR_{cutoff}, at the output of the relay link, 14 dB for BS analog transmission and 11 dB for BS digital transmission[13] are used.

Table 3 lists the specifications and

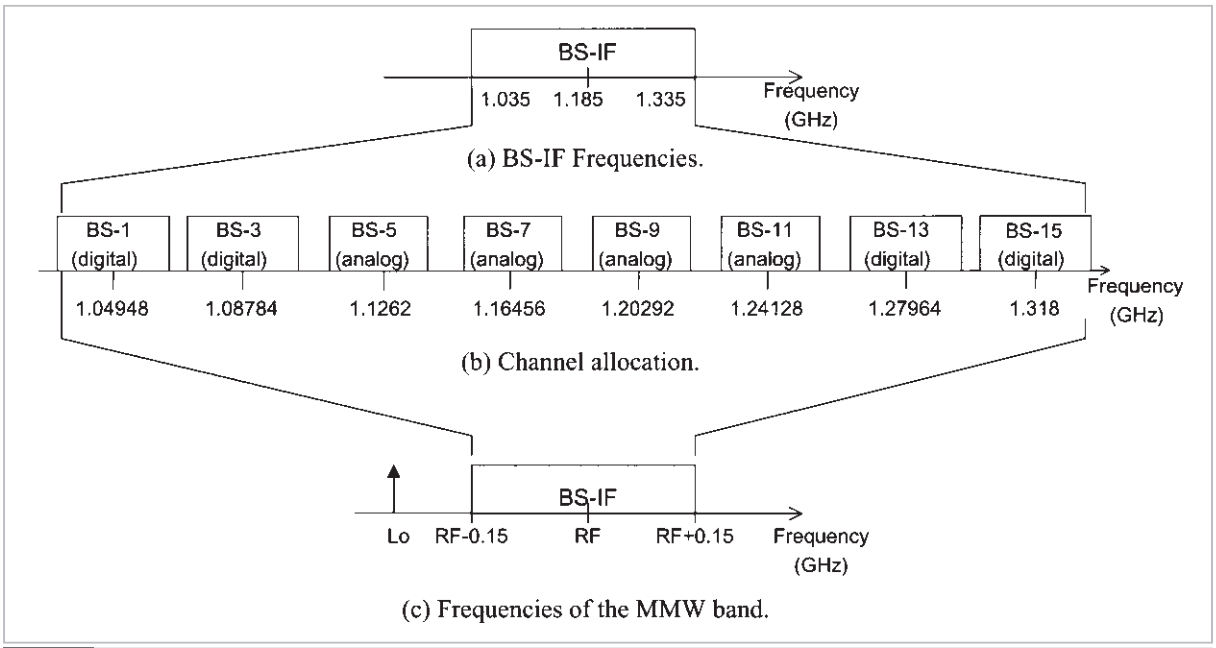


Fig.2 *BS-IF frequencies, channel allocation, and frequencies of MMW band*

obtained CNR margin for the satellite broadcasting and MMW links. The calculated 10 dBm transmission power of the MMW transmitter with a 5 dBi antenna, and the calculated 6 dB noise figure of the MMW receiver with a 30 dBi antenna, are 24.2 dB of the total CNR value including that of the MMW link for each BS signal. The CNR margin, which is

Table 3 *Specifications and obtained CNR margin*

Parameters		Values: BS analog	Values: BS digital
CNR at input of transmitter (CNR_{sat})		25 dB	
Number of channels		4	4
Modulation		FM	8 PSK
Bandwidth/channel		27 MHz	34.5 MHz
Transmitter	Total power	+ 10 dBm (Local tone: + 7 dBm, BS − IF: − 2 dBm/channel)	
	Antenna gain	5 dBi	
Propagation path	Transmission distance	10 m	
	Path loss@ Free-space loss	88.0 dB@60 GHz	
Receiver	Antenna gain	30 dBi	
	Total reception power(Pr)	− 43 dBm	
	Noise figure	6 dB	
	Detection thermal noise($8kTBF$)	− 74.9 dBm	
CNR for MMW link (CNR_{MMW})		31.9 dB	
CNR at output of receiver (CNR_{total}), $CNR_{total}=\frac{1}{\frac{1}{CNR_{sat}}+\frac{1}{CNR_{MMW}}}$		24.2 dB	
CNR_{cutoff}		14 dB	11 dB
CNR *margin*		10.2 dB	13.2 dB

defined as $CNR_{total} - CNR_{cutoff}$, for BS analog signal is 10.2 dB and that for BS digital signal is 13.2 dB. This margin enables the transmission distance to be increased and MMW links to be established in buildings with inner walls made of wood, paper, plaster, and clay, such as those in a typical Japanese house.

3.2 Analysis of Intermodulation Distortion for BS Signals Transmission

The MMW video transmission system must transmit multiple carriers through an amplifier. As a result, in addition to the thermal noise, additional IM noise due to the transmission of multiple carriers will occur. It is a significant factor in the overall performance of the system and has been analyzed in a study on satellite communication systems[12], where the distribution of the IM products is derived for uniformly spaced multiple-carriers with the same amplitudes. Because BS signals transmission involves eight carriers, the system generates the same IM products as those generated in satellite communication systems. However, in terms of modulation, BS signals transmission is different because there are two types of carriers in the BS frequency-band and they are spaced uniformly. One is FM with a bandwidth of 27 MHz for analog broadcasting, and the other is 8 PSK with a bandwidth of 34.5 MHz for digital broadcasting. Therefore the measuring of the IM distribution becomes difficult.

If the several signals go through a non-linear amplifier, new frequency products are generated that are harmonically related to the input-signal frequency. Many of these products are outside of the frequency band of interest; that is, some are higher-order products that are at such low level that their analysis is of little importance. Normally, the IM products of interest are those of the lower order, such as 2nd- and 3rd-order or those that exist in the pass-band of the system. In particular, IM3 products generate signals that are very close to the original signals, thereby degrading the original signals when the system transmits signals with more than two carriers in their bands. Therefore, because the system processes BS signals, which have eight carriers in their band, it should be designed to take into account the IM3 products.

The IM3 products can be classified into two main categories: two-tone ($2f_1 - f_2$) type products and three-tone ($f_1 + f_2 - f_3$) type products. The two-tone and three-tone products are harmonically generated and are related to two and three input signals, respectively. When we assume that N carriers (f_1, f_2, . . . , fN) are input into an amplifier and the frequency interval of each carrier is the same, the number of two-tone and three-tone products that fall in the k-th carrier can be given by equations (2) and (3), respectively[12][16].

$$D_2(N,k) = \frac{1}{2}\left[N - 2 - \frac{1}{2}\left\{1-(-1)^N\right\}(-1)^k\right] \qquad (2)$$

$$D_3(N,k) = \frac{k}{2}(N-k+1) + \frac{1}{4}\left\{(N-3)^2 - 5\right\} - \frac{1}{8}\left\{1-(-1)^N\right\}(-1)^{N+k} \qquad (3)$$

Table 4 shows the number of IM3 products that fall on the transmitting channels calculated by using the above two equations.

Table 4 *Number of IM3 products that fall on the transmitting channels*

Channel	BS-1	BS-3	BS-5	BS-7	BS-9	BS-11	BS-13	BS-15
Number of IM3 (2-tone)	3	3	3	3	3	3	3	3
Number of IM3 (3-tone)	9	12	14	15	15	14	12	9

From the point of power of the IM3 products, the power of the three-tone products is four times larger than that of the two-tone products[12]. The relationship between the CIR and the 3rd-order intercept-point (IP3) of the device is expressed by the following equation:

$$IP3 = \frac{Spl_3}{2} + P_{out}\,(\mathrm{dBm}), \qquad (4)$$

where P_{out} is the output power per channel of each signal and suppression level Spl_3 can be expressed as

$$Spl_3 = CIR + 10\log_{10}\{D_2(N,k) + 4\times D_3(N,k)\} \quad (5)$$

Equations (4) and (5) give the CIR as follows.

$$CIR = 2\times(IP3 - P_{out}) - 10\log_{10}\{D_2(N,k) + 4\times D_3(N,k)\} \quad (6)$$

When an amplifier with a known IP3 amplifies BS signals with the same power, required CIR is obtained from Equation (6) by substitution of the signal's power, P_{out}, at the output of the amplifier when the video signal's quality becomes worse. Then IP3 can be obtained from Equation (4) and (5) at a designed P_{out} using the required CIR.

4 Hardware Description

Based on the analytical link-budget shown in Table 3, a transmitter and receiver set that uses a new microwave-monolithic-integrated-circuit (MMIC)-based RF module for the MMW self-heterodyne scheme was developed. The built-in module of the transmitter has a flat antenna. To ensure the gain of the antenna of the receiver is high, a circular waveguide array antenna with an inexpensive plastic base was used. For performance comparisons, a structurally similar antenna with an aluminum-base is also developed. The MMW video-transmission system specifications are summarized in Table 5.

Table 5 MMW video-transmission system specifications

Local tone (Lo)		59.010 GHz
RF frequency (RF)		60.195 GHz
Transmitter	**Total power**	10 dBm
	Local oscillator's phase noise (measured value)	-45 dBc/Hz@5 kHz -49 dBc/Hz@10 kHz -80 dBc/Hz@100 kHz
	Antenna gain	5 dBi
Receiver	**Noise figure**	6 dB
	Local oscillator	Unnecessary
	Antenna gain	30 dBi

4.1 Transmitter

Fig.3 shows a block diagram of the transmitter, including the RF module and a DC-power-supply circuit. The up-converter of the module consists of a double-balanced FET mixer, a gain-controlled amplifier, a doubler, and a dielectric-resonant-oscillator (DRO). A gate-bias voltage is applied in the FET mixer and is made from V_{GG} inside the module (the voltage can be controlled at adjustment point 1). Fig.4 shows the up-converter output power for the RF signal and the local tone against the gate-bias voltage under IF input power of −15dBm and the IF frequency of 1.1 GHz. The figure shows that the gate-bias voltage can control the output power for the RF signal and the local tone. This is because the balanced point and the conversion loss of the mixer are changed. To leak the local tone, the mixer is used as an "un-balanced" point. From the figure, we can see that an equal power distribution between the RF signal and the local tone can be obtained when the gate-bias voltage is −0.4V. The power of the RF signal and that of the local tone as a function of the local input power (the power can be controlled at adjustment point 2) is also shown in Fig.5, which shows that the up-converter output power for the RF signal and local tone can be linearly controlled by the local input power. Thus −0.4V is set as the gate-bias voltage.

The RF module in the transmitter (package size: 50×23×6.5 mm) is shown in Fig.6. A patch antenna (planar-antenna, 1.60×1.13 mm) with linear polarization is mounted within the module. The window is made of a borosilicate-opaque glass and is hermetically sealed.

The IF-input power vs. RF output power of the transmitter is shown in Fig.7. When the IF input power is −15 dBm, the RF output power and the local tone's power are equal, and each RF output power is 7 dBm. In this case, the compression level of the image signal (that corresponds to the lower side-band) is −22 dBc when the IF input power is −15 dBm.

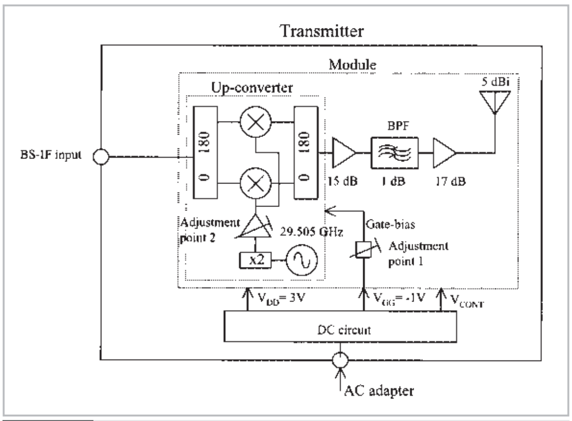


Fig.3 *Block diagram of transmitter*

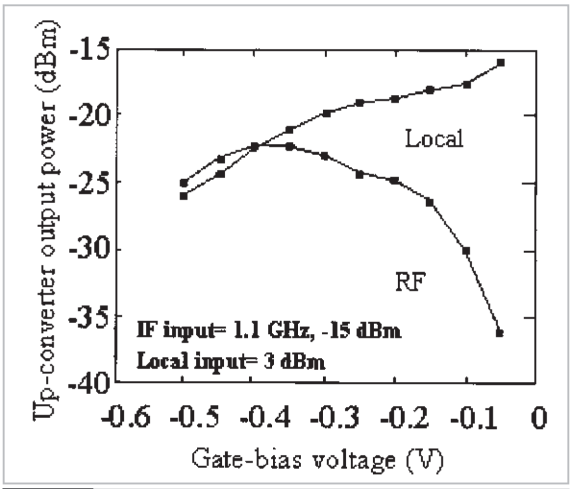


Fig.4 *Gate-bias voltage vs. up-converter output power applied in the balanced mixer*

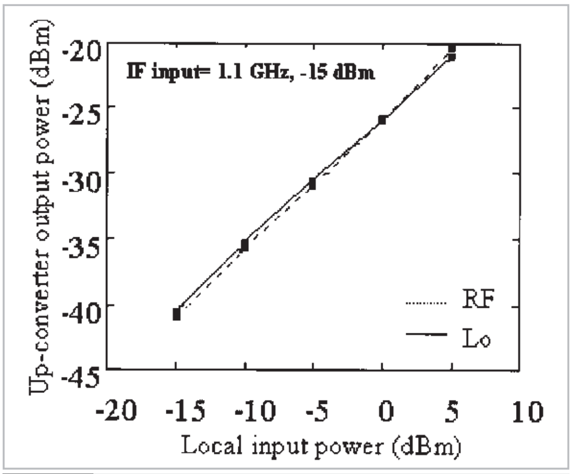


Fig.5 *Local input power vs. up-converter output power*

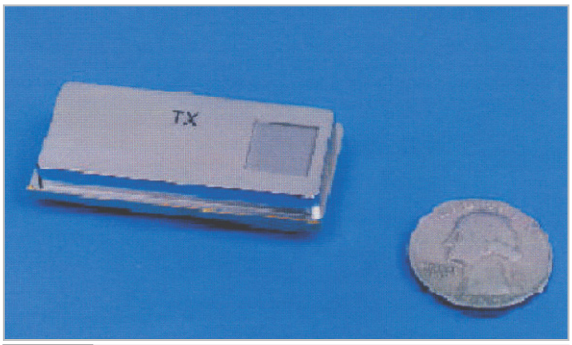


Fig.6 *RF module in transmitter*

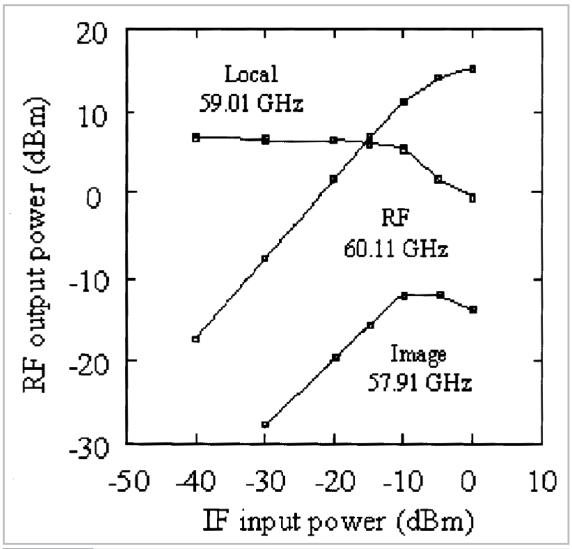


Fig.7 *IF input power vs. RF output power of transmitter*

4.2 Receiver

Fig.8 shows a block diagram of the receiver. The receiver consists of the array antenna, the RF module, and a DC power supply circuit. The RF module consists of two amplifiers, a single-ended FET mixer, and a band-pass filter. The mixer is used as a square-law detector. The appearance and the package dimensions of the receiver are the same as those of the transmitter except for the V-band connector (shown in Fig.9). Fig.10 plots RF input power vs. IF output power of the receiver. The RF input power is equivalent to total reception power including RF signal power and local tone power. Two MMW tones with 59.01 GHz (local tone) and 60.11 GHz, and the same power are fed into the module. According to the figure, when the total reception power is −53 dBm, IF output power is about −46 dBm. This means that the conversion loss of the module is about 10 dB when the reception signal power is 3 dB below the total reception power. The measured phase-noise characteristics of the receiver is shown in Table 5. It is clear that the phase-noise power is less than −100 dBc/Hz at 10 kHz frequency-offset.

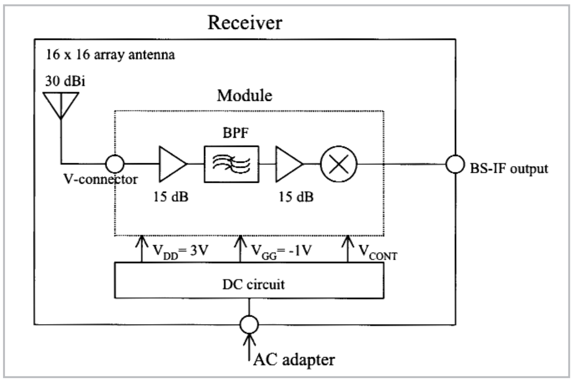


Fig.8 Block diagram of receiver

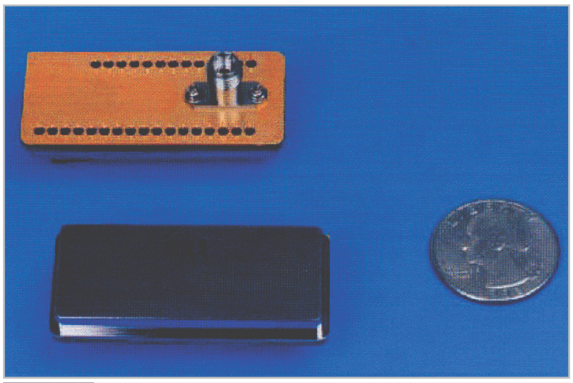


Fig.9 RF module in receiver (face and back)

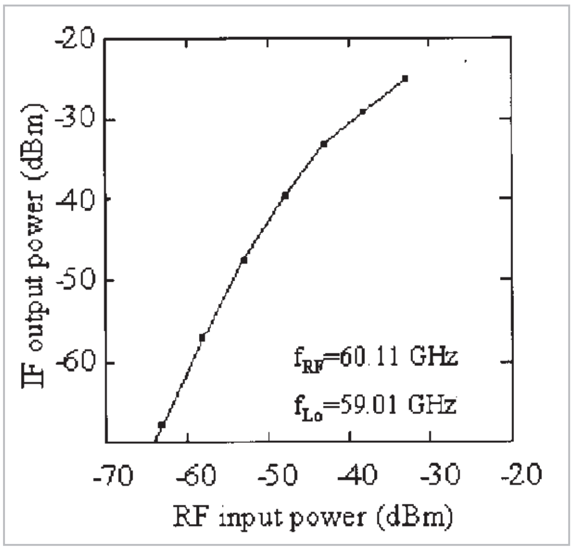


Fig.10 RF input power vs. IF output power of receiver

4.3 Reception Antenna

Fig.11 and 12, respectively, show the schematic structure and a photograph of the developed 16 × 16 circular-waveguide-array antenna. Each element of the array is distributed using a strip-line. Two antennas, with the same structure and shape but with bases made of plastic (a syndiotactic-polystyrene with gold plated) and aluminum, were fabricated. The syndiotactic-polystyrene base can be made by injection molding in order to reduce the cost.

The circular waveguide of the antenna (diameter: 3.5 mm) has only a single mode at the V-band. Its cutoff frequency for TE11mode is 50.2 GHz and that for higher-order modes is 65.6 GHz. The aperture size of the antenna is 71 × 71 mm. For power distribution, strip-line parallel feed with a quarter-wavelength transformer is used. PTFE (a polytetrafluoroethylene) is used as a dielectric substrate. For the connection from the circular waveguide to the strip-line, and from the strip-line to the coaxial line, the size is optimized using an electromagnetic simulator. We also made the output port of the antenna a V-band connector.

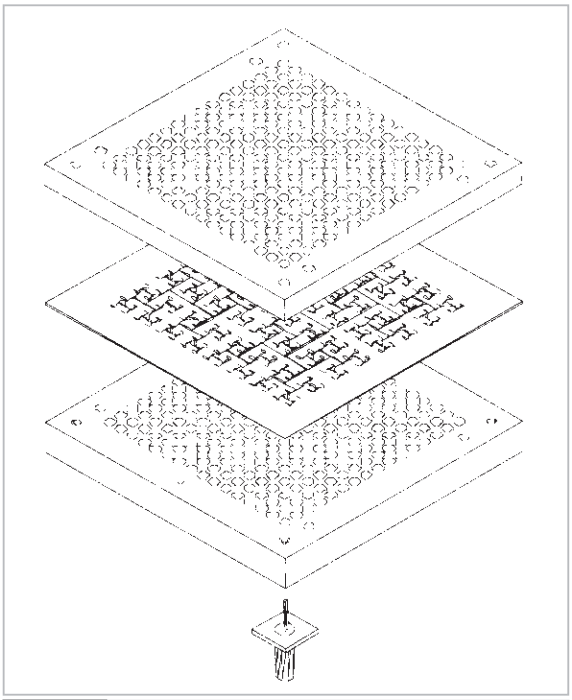


Fig.11 Schematic structure of 16×16 array antenna

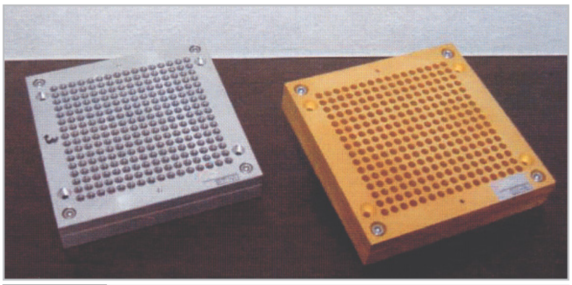


Fig.12 Photograph of 16×16 array antenna (left: aluminum-base, rigit: plastic-base)

Measured far-field patterns of the plastic-base antenna for the E- and H-planes at 60 GHz are shown in Fig.13(a) and (b), respectively. A near-field method[18] is used in the measurement. As a power of each element is uniformly distributed, the sidelobe level is about −11dB. The full beam width at half maximum of gain for this antenna is around 3.7 degrees for E- and H-plane.

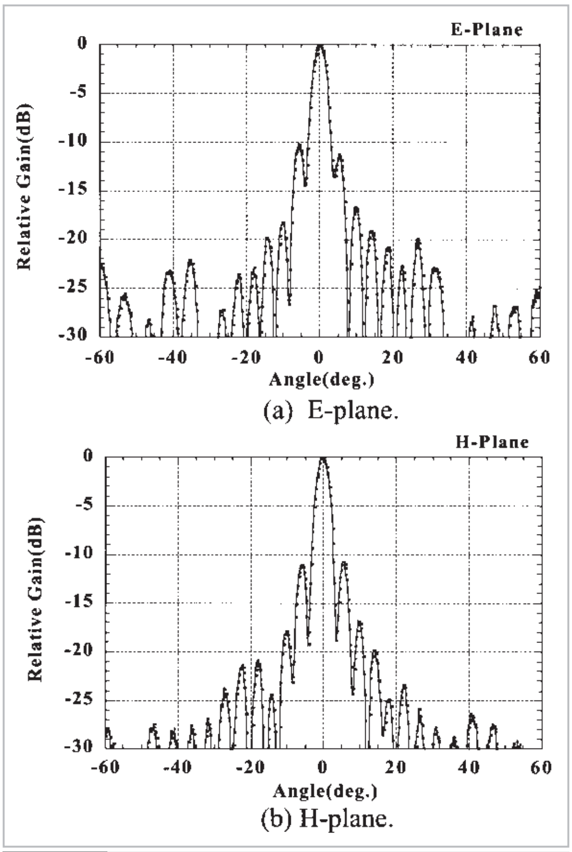


Fig.13 Far field pattern of 16×16 array antenna

To measure the gain of this reception antenna on the frequency, a standard horn antenna with a known gain is measured for various frequencies. Next, the gain of the reception antenna is also measured for various frequencies. The gain can be obtained as compared with these two gains. The near-field method is also used in the measurement. The measured gains of both antennas are shown in Fig.14 as a function of frequency. As the interface of the antenna is the V-band connector while that of the near-field measurement system is the waveguide, a waveguide-to-coaxial adapter was used in the measurement. The measured antenna gain shown in the figure includes the loss (within 0.5 dB) of the adapter. We can see that the measured gains of both antennas are almost the same. The obtained gain of the plastic-base antenna is around 30 dBi for 58 GHz at maximum, and around 27 dBi at 55 GHz and 64 GHz. Therefore the flatness within 3 dB is obtained for 9 GHz band. This bandwidth is 15% at 60 GHz.

The efficiency, η, is calculated from the following equation,

$$G=4\pi(A/\lambda^2)\,\eta, \qquad (7)$$

where G, A, and λ are, respectively, an antenna gain, an aperture size, and a free space wavelength. The efficiency of the antenna is calculated to be 37%. Such a wide bandwidth (9 GHz) shows that this planar antenna structure is suitable for wide-band applications such as our system. The plastic- and aluminum-based antennas have almost the same antenna gain as well as other characteristics such as a reflection property and a radiation pattern.

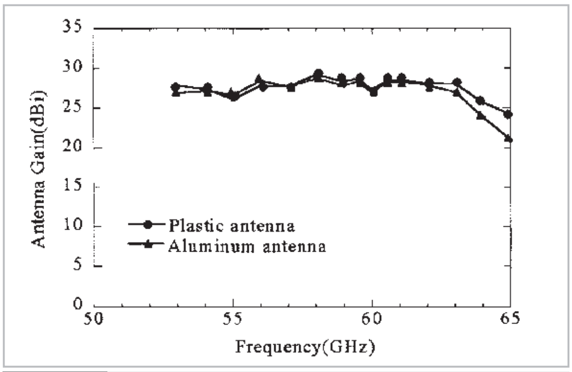


Fig.14 Antenna gain of plastic-base and of aluminum-base antennas

5 Experimental Performance of BS Signals Transmission

First, the required CIR for the BS analog and digital signals in an experiment based on subjective evaluation is calculated. Then, by using the required CIR, the required IP3 for the power amplifier of the transmitter is estimated. An experimental BS signals transmission by using the developed transmitter and receiver is also performed.

5.1 Experimentally Measured Intermodulation Products

Fig.15 shows the experimental setup for evaluating IM3 products. An actual BS reception signals are used for this experiment. An IF amplifier is used as a non-linear device that makes IM noise. In the experiment, the level of the signal input into the IF amplifier is changed by using a variable attenuator (ATT-1). When the level of the signal input is increased, the quality of the video signal on the monitor becomes worse because of the IM noise. When any degradation of the video signal's quality can be recognized from a visual inspection, the level of the signal input into the IF amplifier is measured. More IM3 products are generated in the center of the transmitting band than around the edges of the band[12]. Both the BS-7 (BS analog) and BS-3 (BS digital) signals are measured because they are the nearest channels to the center of the band. The IF amplifier with a gain of 18 dB and IP3 of 26 dBm is used.

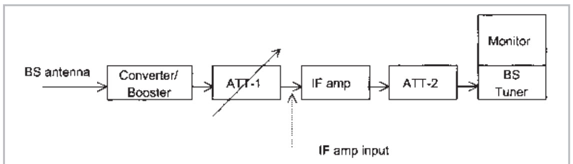


Fig.15 Experimental setup for evaluating IM3 products

Table 6 lists the level of each BS signal's input into the IF amplifier (shown as "IF amp input" in Fig.15) when a degradation (a beat pattern on the monitor) is observed in the BS-7 channel. Table 7 also shows the level of each BS channel's input into the IF amplifier when a degradation (an impulse block noise) is observed in the BS-3 channel. From these Tables, we can see the difference in level is 1.5 dB from Table 6 and 2. 0 dB from Table 7 among eight BS channels. This is because the actual reception power from the BS converter itself includes a difference.

Table 6 Level of each BS signal's input into IF amplifier when a degradation occurred in BS-7 (BS analog)

Channel	BS-1	BS-3	BS-5	BS-7	BS-9	BS-11	BS-13	BS-15
Power [dBm]	-13.5	-13.5	-13.0	-13.0	-12.0	-12.0	-13.0	-13.5

Table 7 Level of each BS signal's input into IF amplifier when a degradation occurred in BS-3 (BS digital)

Channel	BS-1	BS-3	BS-5	BS-7	BS-9	BS-11	BS-13	BS-15
Power [dBm]	-7.1	-7.1	-5.5	-5.5	-5.5	-5.5	-7.1	-7.5

By substituting $IP3$, P_{out}, $D_2(N, k)$, and $D_3(N, k)$ for Equation (6), the required CIR for BS-7 and BS-3 channels can be calculated as follows:

$$\mathrm{CIR}=2(26-P_{out})-10\log_{10}(3+4\times 15) =34-2P_{out} \quad \text{(dB), for BS-7} \tag{8}$$

$$\mathrm{CIR}=2(26-P_{out})-10\log_{10}(3+4\times 12) =34.9-2P_{out} \quad \text{(dB), for BS-3} \tag{9}$$

Although it is needed that all BS signals have the same power level in our analysis described in Section 3.2, there is a difference among BS signals. To include the difference, the maximum and minimum levels in each Table are used hereafter. In this case, P_{out} is -12.75 ± 0.75 dBm plus the amplifier's gain for BS-7, and -6.5 ± 1.0 dBm plus the amplifier's gain for BS-3. By substituting P_{out} for Equations (8) and (9), the required CIR for BS-7 and BS-3 channels can be obtained.

The required IP3 is also calculated from Equations (4) and (5) in which the transmission power for each BS channel, P_{out}, is assumed to be -2 dBm. The CIR and required IP3 are summarized in Table 8.

It is clear from Table 8 that the BS digital channel (BS-3) is around 12 dB more robust against the interference power than the BS analog channel (BS-7). The analog channel also requires a higher IP3 (around 19 dBm).

Table 8 Required CIR and IP3 for non-linear devices for BS-7 and BS-3

Channel	BS-7 (analog)	BS-3 (digital)
Required CIR [dB]	23.5 ± 1.5	11.9 ± 2.0
Required IP3 [dBm]	18.75 ± 0.75	12.5 ± 1.0

5.2 Experimentally measured CNR Performance

Fig.16 shows the experimental system setup. Fig.17 shows photographs of the transmitter and receiver. The bandwidth of the transmitter and receiver was tuned to 300 MHz in order to evaluate the performance of the BS signals transmission system.

BS signals in the 1-to-1.3 GHz band from the parabolic BS antenna were input into the transmitter. The transmitter up-converted the input signals into 60-GHz band signals and transmitted them from the 5-dBi patch antenna. The receiver, which had a 30-dBi planner array antenna, amplified the received MMW signals and down-converted them into BS-IF signals. The signals were fed into the BS tuner. To measure the CNR , the BS output signals are connected to a spectrum analyzer instead of the BS tuner. When the output power of each BS signal is measured, center frequency and bandwidth of the analyzer are set for each BS signal's center frequency and bandwidth because this system handles multi-carrier signal.

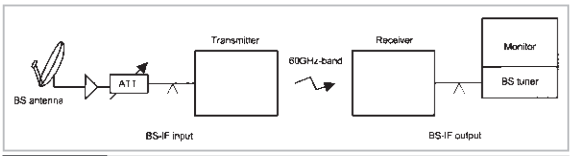
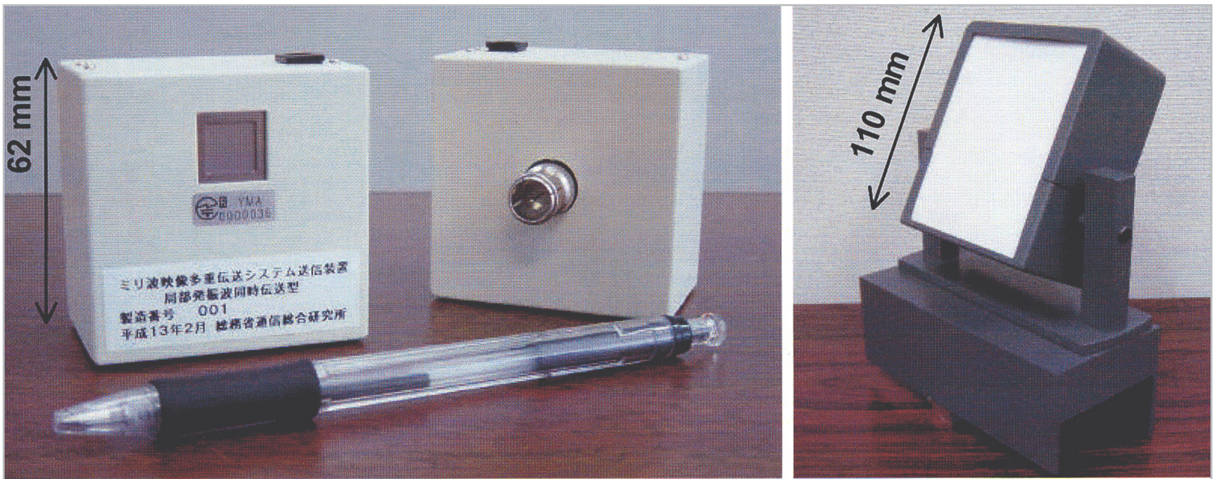


Fig.16 Experimental system setup

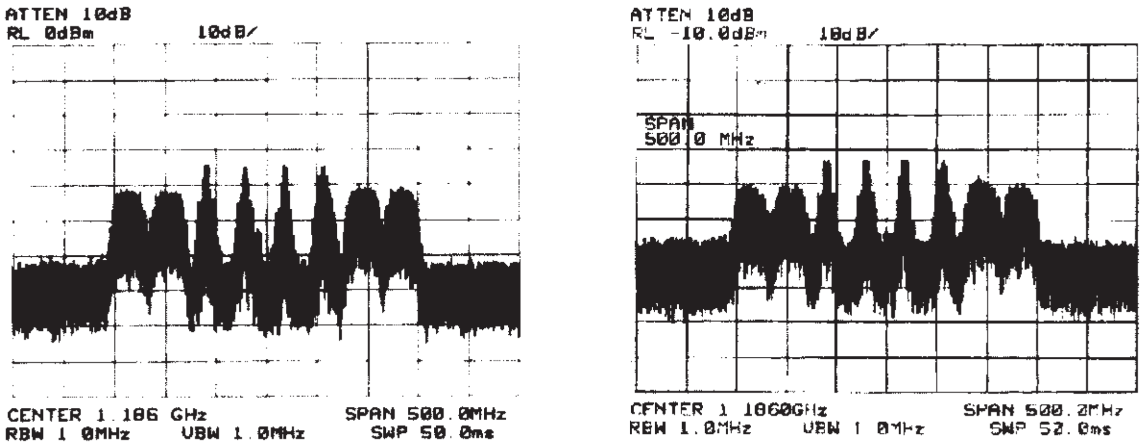
Fig.18(a) and (b), respectively, show the power spectrum of the BS input at the transmitter and that of BS output at the receiver for a transmission distance of 10 m. The lower two signals and upper two signals are BS digital channels, and the four middle signals are BS analog channels. We can recognize that the spectrum at the receiver is almost the same as that at the transmitter, and particular frequency response is not observed on the IF band.

Fig.19 shows the experimental CNR before and after the MMW transmission (10-m transmission distance). The CNR of the BS output is degraded about 1 – 3 dB compared to that of BS input. From the link-budget analysis shown in Table 2, the CNR_{total} for the BS analog and digital signals transmission is 24.2 dB when CNR_{sat} is 25 dB. This also means that the CNR of BS signals degrade 0.8 dB after the MMW link. The performance degradation in the experiment is slightly worse than



(a) Transmitter (front and back) (b) Receiver

Fig.17 Transmitter and receiver



(a) BS-IF spectrum at transmitter input.

(b) BS-IF Spectrum at receiver output.

Fig.18 *Power spectrum of BS-IF*

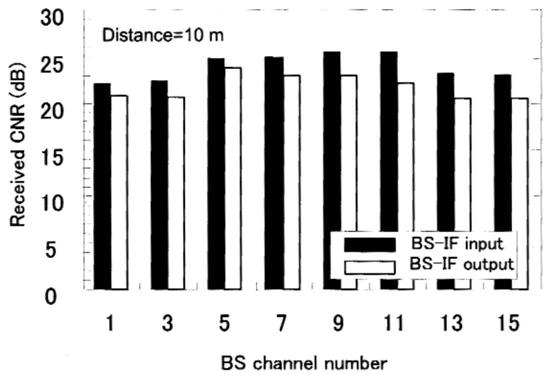


Fig.19 *Experimental CNR before and after MMW transmission*

that of the analytical value. It can be thought that the difference comes from the uneven input power of BS signals or hardware imperfections, while the uniform input power is supposed in our analysis.

CNR is more than 20 dB for MMW transmission of over 10 m, which meet the required CNR values of 14 dB for BS analog signals and 11 dB for BS digital signals. In this transmission case, we did not observe any degradation in video quality either with or without the MMW transmission link. From these results, we can conclude that our system is realistic.

6 Conclusion

This paper presents the design and performance of a MMW video transmission system using 60-GHz band for indoor BS signals transmission. A selt-heterodyne scheme is used in the system. Based on the concept, we designed the system by using a CNR link-budget and an IM3 analysis. The transmitter and receiver setup and its characteristics are also presented. To find a required CIR and IP3 of a power amplifier in the transmitter, we used an amplifier with a known gain and IP3 in the experiment based on our subjective evaluation. The feasibility of the system is experimentally verified by using a transmitter and receiver setup we developed. In the MMW transmission experiment over a distance of 10 m, CNR was more than 20 dB when the transmission power was 10 dBm, and high-quality video signals were generated.

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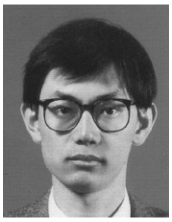

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