Active Antenna Using Multi-Layer Ceramic-Polyimide Substrates for Wireless Communication Systems

Tomohiro SEKI, Hideki YAMAMOTO, Toshikazu HORI, and Masashi NAKATSUGAWA

Nippon Telegraph and Telephone Corporation, Japan

1-1 Hikari-no-oka, Yokosuka, Kanagawa 239-0847, Japan

Abstract This paper proposes an active antenna structure for high-speed wireless communication systems that is constructed with multi-layer alumina-ceramic and polyimide substrates. This antenna structure incorporates a transmitter/ receiver amplifier and time division duplex switch circuits that are mounted on a Monolithic Microwave Integrated Circuit (MMIC) chip and a low-pass filter circuit. A prototype active antenna at 25 GHz is presented and the measured total gain for both transmission and reception of more than 21 dB is achieved with the directional gain of approximately 11 dBi.

I. INTRODUCTION

System studies and hardware investigations of indoor high-speed wireless communication are being conducted at millimeter and quasi-millimeter-wave frequencies [1], [2]. Such systems must offer data transmission rates of 10 Mbps or more, thus making anti-multipath and anti-shadowing techniques necessary. One solution is to narrow the beam width of the base station and personal station antennas by about several tens of degrees [3], [4]. However, when phased-array or sector antennas are employed in order to track the beams, the loss of the phase-shifter and the beam-switching circuits cannot be ignored at these frequencies. Therefore, it is difficult to compress the noise figure of the system. Consequently, it is necessary to connect the radiation element directly to the Monolithic Microwave Integrated Circuit (MMIC) chip including the low-noise receiving amplifier and the power amplifier to avoid loss of the beam tracking circuits and the feeding cables. Active antenna technology has been investigated for radar applications that achieve beam tracking and the spatial power combining functions. In recent years, active antenna technology has been the topic of investigations to find a way to adopt this technology into high-speed wireless communication systems in order to secure wideband characteristics since the frequency is increasing. However, there are only a few examples in which the active antenna was designed to incorporate the sharing of transmitting and receiving functions. Moreover, to construct a practical module for wireless communications and utilize transmission diversity, time division duplex (TDD) switches are required. A filter must also be inserted at the front of these amplifiers to suppress unwanted higher harmonics and images. Some active antenna schemes were previously proposed in which the radiation elements were directly connected to low noise amplifiers, mixers, and oscillators [5]-[7]. However, these active antennas were not entirely satisfactory because they did not achieve the aforementioned functions.

At millimeter and quasi-millimeter-wave frequencies, the size of the active array antennas is more than several centimeters. This is especially so when constructing an entire array antenna on one GaAs MMIC substrate, which is very costly. To address this problem, we propose a three-dimensional active antenna integrated with a microstrip antenna (MSA) array, individual MMIC chips including amplifiers for transmission and reception, TDD switches, and a filter to suppress unwanted harmonics and images on the multi-layer alumina-ceramic / polyimide substrate. Furthermore, we describe the prototype active antenna at 25 GHz, and present the characteristics of this antenna.

II. MULTI-LAYER CERAMIC-POLYIMIDE SUBSTRATE STRUCTURE

Effectively mounting active devices on both sides of a planar antenna substrate is difficult. Employing a multi-layer substrate to construct an active antenna with multiple active devices is especially useful because the circuit structure of the control bias and the power supply is complicated. Therefore, a multi-layer alumina-ceramic substrate is well suited to this purpose. Creating a high-density circuit structure is difficult when constructing the alumina-ceramic substrate by sintering at high-temperature, because the substrate thickness must be greater than 100 μm and the minimum line spacing is limited. Therefore, we utilize multi-layer polyimide substrates with a high level of processing accuracy that adhere to strict substrate thickness tolerances. Figure 1 shows the schematic of the multi-layer alumina-ceramic/polyimide substrates. Here, the substrate is constructed based on a four-layer alumina-ceramic substrate ($\varepsilon r = 9.0$, $\tan\delta = 0.001$ at 10 GHz, thickness = 0.25 mm) and a four-layer polyimide substrate ($\varepsilon r = 3.2$, $\tan\delta =$

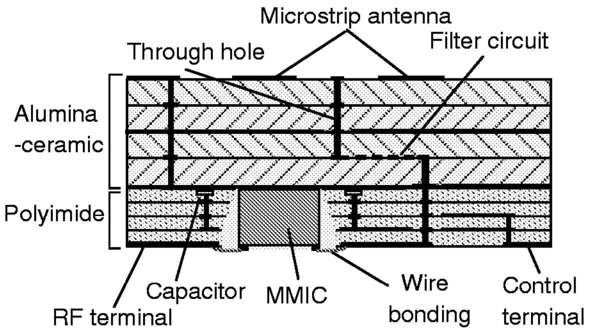

Fig. 1 Schematic diagram of proposed 3D active antenna

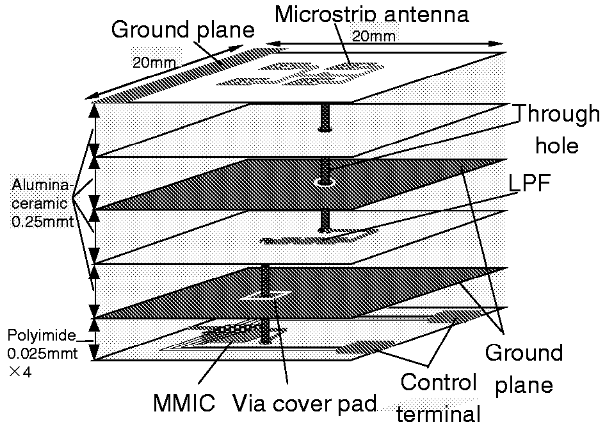

Fig. 2 Structure of proposed active antenna

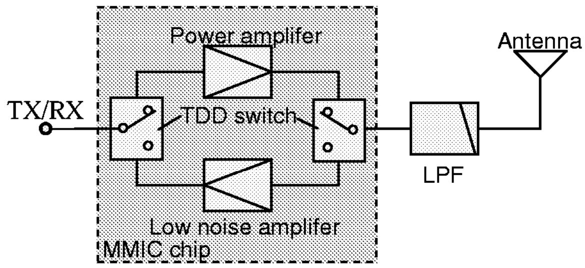

Fig. 3 Function block diagram

0.002 at 10 GHz, thickness = 0.025 mm) structure. The substrate size is 100 mm X 100 mm.

III. Design Concept of Proposed Active Antenna

Figure 2 shows the target structure of the three-dimensional active antenna, and Fig. 3 shows the function block diagram. An MSA array is placed on the multi-layer alumina-ceramic substrate. The individual MMIC chips integrated with amplifiers for transmission and reception, TDD switches, a filter, antenna feeding circuits, and other RF/IF functional circuits such as beam switching circuits are mounted on the multi-layer polyimide substrate. The substrate has a simple multiple layer structure, and it easily achieves the level of precision of several micrometers needed for the transmission lines and high-frequency circuits. A lower-cost technology has been developed for three-dimensional connections between layers using via-holes [8], [9]. This technology also enables the construction of filter and antenna feeding circuits on an alumina-ceramic substrate. The features of this active antenna structure are described below.

(1) The losses of the beam forming and feeding circuits do not influence the NF.
(2) It is possible to lower cost because the required GaAs substrate area can be reduced.
(3) The wiring of the RF/IF circuit and DC bias can be accomplished in a simple manner.
(4) It is possible to dissipate the heat load of the MMIC chips through the alumina-ceramic substrate, which has a high level of thermal conductivity.

Generally up to now, the MSAs of an active antenna were placed on a substrate at a lower level of permittivity to take into consideration the radiation efficiency and the bandwidth. However, in most cases this does not pose a practical problem in the construction of MSAs on a high permittivity substrate. This influences the characteristics of the MSAs with respect to the manufacturing process accuracy. Moreover, employing a restricted-size alumina-ceramic substrate does not pose a problem because a large antenna is not required in wireless communication systems employing the quasi-millimeter and millimeter-wave frequency band.

Next, the proposed prototype active antenna is presented. The operating frequency of 25 GHz was selected to simplify measurement. This prototype antenna is configured such that the planar antenna is situated on the uppermost layer of the alumina-ceramic substrate and is connected to a low pass filter circuit based on the strip line structure constructed on the inner alumina-ceramic layer (Fig. 2). The MMIC chip and the control line are mounted on the multi-layer polyimide substrates. A 2x2 planar array antenna structure is constructed using the same process as the one-side fed microstrip antenna in which the antenna is constructed using only the surface layer which is the most accurately produced. The selected antenna substrate size is 20 mm x 20 mm. The array space of the horizontal plane and vertical plane is 0.43λ and 0.48λ, respectively. The low-pass filter circuit which must be downsized is constructed with the strip line on the inner alumina-ceramic substrate that has a high dielectric constant in order to avoid design problems between the high frequency circuit and control circuit. The purpose of this filter circuit is to suppress the unwanted frequency component, because the circuit causes an increase in the loss and the noise figure is inferior. Therefore, we select the four-stage low-pass filter circuit structure with an insertion loss of less than 1.0 dB. We use the GaAs MMIC chip for the active device incorporating the transmitting and receiving amplifier, which is constructed based on a three-stage structure, and a switching circuit for switching between the transmission and reception functions. This amplifier achieves a gain of more than 16 dB and a reflection level of less than -16 dB at 25 GHz.

IV. Experimental Results

A. Directional Characteristics

Figure 4 is a photograph of the prototype antenna. The photograph to the left shows the radiation element side of this antenna, and the photograph to the right shows the MMIC and the control circuit pattern size. The jig in the photograph is used to mount the RF connector which is needed to perform measurements with this antenna, but the influence of this jig on the radiation characteristics is unavoidable. The following is a description of the radiation pattern of the antenna. The horizontal plane radiation pattern and vertical plane radiation pattern are given in Fig. 5 and Fig. 6, respectively. The solid line represents the transmission results and the dashed line represents the reception results in these figures. These figures were generated based on the calculated results using the finite difference time domain (FDTD) method. When the bias voltage of the drain was 3.0 V, the bias voltage of the gate was 0.25 V and the current of the drain was 47 mA. Figure 5 shows that the dispersion of the main lobe is very small, and the back lobe level and the unwanted radiation level are adequately suppressed. From these results, we considered that the unwanted radiation levels from the wire-bonding mounting the MMIC and from the high-frequency circuit are adequately suppressed for the antenna feeding circuit. It is clear that both the measured and calculated results agree well and the transmission and reception horizontal radiation patterns are in good agreement. Next, the vertical radiation characteristics are presented. Figure 6 shows that there is a difference between the measured and calculated results in the main lobe. One of the main reasons for this is that diffraction occurs due to the jig. However, these results show that both the transmission and reception radiation patterns are in good agreement and that the back lobe level is adequately suppressed. This prototype antenna adequately suppressed the unwanted radiation levels from wire-bonding and the control circuits.

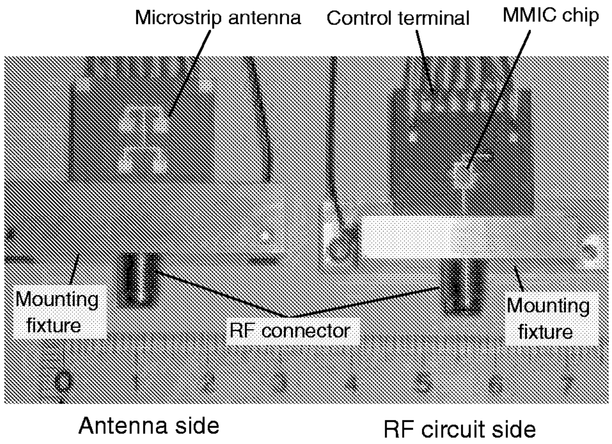

Fig. 4 Photograph of prototype active antenna

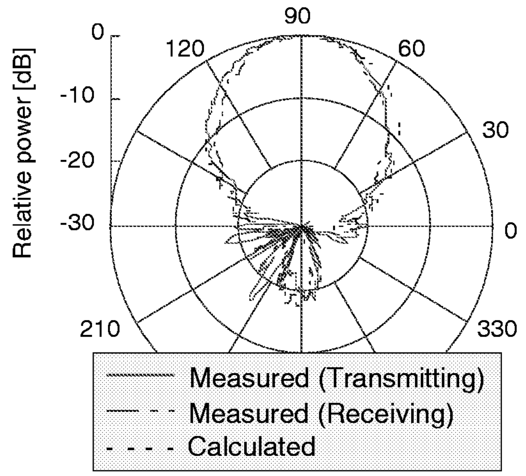

Fig. 5 Measured H-plane radiation patterns

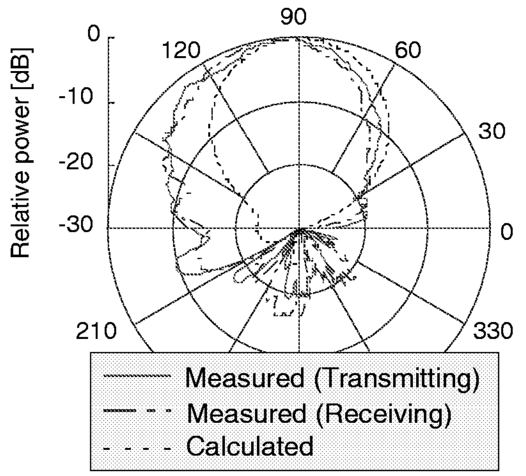

Fig. 6 Measured E-plane radiation patterns

Moreover, the radiation characteristics for transmission and reception are in good agreement, and this antenna operates in the same propagation environment for both transmission and reception.

B. Gain Characteristics

Figure 7 shows the total gain characteristics for transmission and reception. The solid line represents the transmission characteristics and the dotted line represents the reception characteristics. This figure shows that the transmission gain and reception gain of 22.6 dB and 21.6 dB, respectively, is attained repeatedly. Furthermore, it is clear that a ripple occurs at 25.0 GHz. It is considered that the reason for this ripple is the differences in the frequency characteristics of each part.

The gain allocation is given in Table 1. Here, the loss of the feeding circuit and low-pass filter circuit are the measurement values. The mounting loss caused by mounting the MMIC chip is derived from the difference. Based on this table, the prototype antenna operation is reasonable.

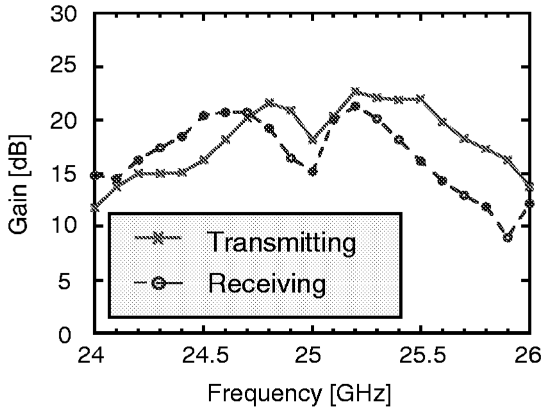

Fig. 7 Total gain characteristics

Table 1 Gain allocation

Items	Gain
Directional gain	11.3dBi
Amplifier gain	16dB
Feeding circuit loss	1.4dB
LPF circuit loss	2.5dB
Mounting loss	0.8dB
Total gain	22.6dB

V. CONCLUSION

This paper proposed an active antenna structure for high-speed wireless communication systems that is constructed based on multi-layer ceramic and polyimide substrates. This antenna incorporates a transmission/ reception amplifier and time division duplex switch circuits are mounted on the MMIC chip and the low-pass filter circuit. A prototype active antenna at 25-GHz is described and results show that the measured total gain of transmission and reception is greater than 21 dB with the directional gain of approximately 11 dBi. It is clear that the directional patterns of both transmission and reception are in good agreement.

ACKNOWLEDGMENT

The authors thank Dr. H. Mizuno, Dr. S. Kubota and Dr. K. Uehara of NTT Network Innovation Laboratories for their helpful discussions and suggestions.

REFERENCES

[1] Y. Takimoto, "Recent activities on millimeter wave indoor LAN system development in Japan," in IEEE MTT-S Int. Symp. Dig., pp. 405-408, June 1995.

[2] N. Morinaga and A. Hashimoto,"Technical trend of multimedia mobile and broadband wireless access systems," Trans. IEICE., Vol. E82-B, No. 12, pp.1897-1905, Dec. 1999.

[3] J.E. Mitzlaff, "Radio propagation and anti-multipath techniques in the WIN environment," IEEE Network Magazine, pp. 21-26, Nov. 1991.

[4] K. Uehara, T.Seki, and K. Kagoshima,"Indoor propagation calculation considering antenna patterns using geometrical optics method," Trans, IEICE., Vol.J78-B-II, No.9, pp.593-601, Sep. 1995.

[5] C. W. Pobanz and T. Itoh, "A conformal retrodirective array for radar applications using a heterodyne phased scattering element," in IEEE MTT-S Int. Microwave Symp. Dig., 1995, pp.905-908.

[6] P. Liao and R. A. York, " A high power two-dimensional coupled-oscillator array at X-band," in IEEE MTT-S Int. Microwave Symp. Dig., 1995, pp.909-912.

[7] T. Ivanov and A. Mortazawi, " Two stage double layer microstrip spatial amplifiers," in IEEE MTT-S Int. Microwave Symp. Dig., 1995, pp.589-592.

[8] T. Tokumitsu, T. Hiraoka, H. Nakamoto, and M. Aikawa, "Multilayer MMIC using a 3mm x N-layer dielectric film structure," IEICE Trans. Electron., vol. E75-C, No. 6, pp. 698-706, June 1992.

[9] T. Seki, K. Uehara and K. Kagoshima, " A Three-Dimensional Active Antenna for a High-Speed Wireless Communication Application," IEEE MTT-S Int. Microwave Symp. Dig. 1997, pp.975-978.