Development of 76 GHz Single Chip MMIC High Frequency Unit

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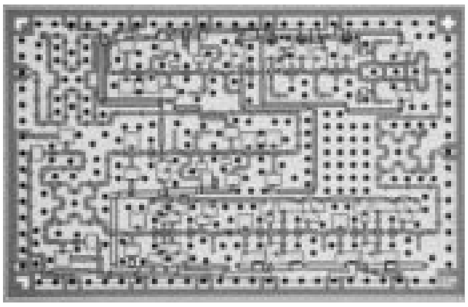

In recent years, various automotive manufacturers have focused attention on in-vehicle millimeter wave radar as a key component for ACC (adaptive cruise control) systems.

We have developed the millimeter wave unit core-component of the radar system to make the product more attractive, following on 76 GHz millimeter wave radar development in 2000.

Specifically the unit is composed of 2 MMIC (monolithic microwave IC) modules one of which integrates into a single chip MMIC 4 out of the previous 5 MMIC modules, thus rendering the unit more compact, lower cost and better suited to mass production.

This paper discusses this 2 module millimeter wave unit incorporating the single chip MMIC unit.

1 Introduction

The millimeter wave automotive radar is resistant to natural weather like fog, rain, and snow conditions in addition to having higher positional accuracy. This is why in recent years, automotive radar has been brought to attention as a key component for collision prevention warning and adaptive cruise control. And in order to use the system in automobiles, smaller size and lower cost becomes a high priority.

Our entire Fujitsu group has been collaboratively working on developing a smaller, low cost millimeter wave radar over the years, and has succeeded in developing a single antenna millimeter wave radar of 60GHz in 1997, and a 76GHz system in 2000.

In order to make the millimeter wave unit; the heart of the radar system more attractive as a product, several MMIC (Monolithic Microwave IC) modules were integrated into 1 chip to reduce size and lower cost.

The features and the major technology behind the newly developed millimeter wave unit incorporating the integrated MMIC modules are mentioned below.

2 Overview of millimeter wave products

The term "millimeter wave" generally refers to waves with extremely short wavelengths (1 to 10 mm), in the 30 to 300 GHz frequency band.

The reason that the 76 GHz band is utilized for our millimeter wave radar, is because bandwidth allocations are regulated and determined by the government in Japan, United States, and Europe, which are our major markets.

Millimeter wave radar systems currently in use employ the FM-CW (frequency modulated continuous wave) radar method, which has a simple configuration while making it possible to measure distances to targets and their relative velocities.

2.1 System configuration

A block diagram of the millimeter wave radar system's configuration is shown in Fig. 1.

This system is composed of an antenna unit, millimeter wave unit, scanner unit, analog circuit unit and digital signal processing unit.

The exterior view of the radar system is shown in Fig.2, and its major data are shown in table 1.

Fig.2 76 GHz millimeter wave radar

Table 1 Major data of millimeter wave radar

Item	Data
Radar method	FM-CW
Center frequency	76-77 GHz
Transmission power	No more than 10 mW
Antenna polarized wave characteristics	45 °Linear polarized wave
Beamwidth	Horizontal 2.7 °, vertical 3.9 °
Maximum sensing distance	Approx. 120 m
Velocity determination range	± 200 km/h
Processing speed	100 msec
Weight	No more than 700 g
Dimensions	110 (W) × 89 (H) × 90 (D) mm

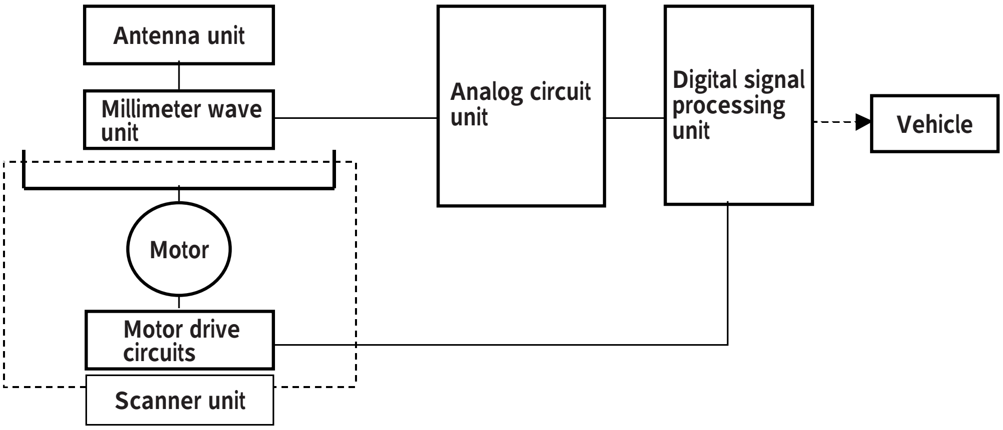

Fig.1 Block diagram of radar system

In this millimeter wave radar system, the planar antenna and millimeter wave unit are connected by a waveguide tube, and scanning is implemented laterally via an actuator. The signal processing unit performs AD conversion of the radar beat signals, analyzes their frequencies in the DSP circuit, and identifies the obstacle location by calculating data of distances, relative velocities and angles.

The sensor is required to detect instantaneously at any time of day or night and in all weather conditions, the positions and velocities of various kinds of objects, ranging from small motorbikes to large trucks. For this purpose, the antenna and millimeter wave unit is required to have a dynamic range capable of picking up large and small obstacles, and be sufficiently compact for in-vehicle installation, and to reduced scanning loads.

2.2 Overview of current millimeter wave unit

Fig. 3 shows a block diagram of the current millimeter wave unit. This unit is composed of 5 MMIC modules, a hybrid and antenna circuit board, and a IF signal amplifying unit and MMIC drive circuit board.

The MMIC modules installed in the current unit are sealed in airtight packages to assure reliability. They consist of a voltage controlled oscillator ("VCO") module, a frequency multiplier ("MULT") module, a mixer ("MIX") module and 2 amplifier modules ("AMPs" - 1 for transmission and 1 for reception). Thus there are 5 modules of 4 different types.

When triangular waveform modulated signals are input to the VCO module, the module will output FM-modulated signals. These signals are then multiplied up to the 76 GHz band by the MULT module, and amplified by the AMP module.

The local signal from the MULT module, and the faint signal reflected from the targets which have been amplified by the AMP module, are input to the MIX module, which mixes the two signals and outputs IF signals as results.

Furthermore, because the radar is a single antenna type, switching between reception and transmission is carried out by turning the individual amplifiers on or off, and the transmitted/received signals are separated by the hybrid board.

The current unit consists of 5 MMIC modules. By developing the new integrated MMIC module, the number of modules were reduced, thereby reducing the amount of installation space required for the MMIC module, the part cost, as well as the number of assembly processes.

3 Overview of newly developed millimeter wave unit

The newly developed millimeter wave unit consists of 2 modules, and we were successful in integrating 4 MMIC (MULT, MIX, AMPx2) modules excluding the VCO, and the hybrid circuit board, into a single MMIC chip. Fig. 4 shows the configuration of the newly developed unit.

The structure of the new millimeter wave unit is the same as that of the current unit, but by developing the single integrated MMIC module chip, the unit is now 75% in volume and weight in comparison to the current model. The single chip MMIC module also reduces the number of connections between modules and the number of bias connections for driving the MMIC modules, thus making its manufacturing simple and improving stability of its performance.

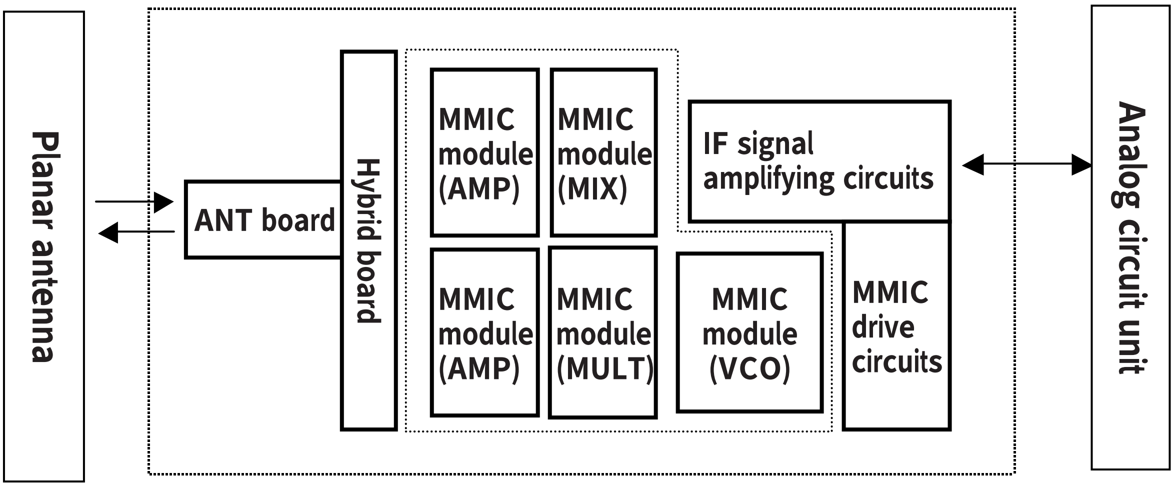

Fig.3 Block diagram of current millimeter wave unit

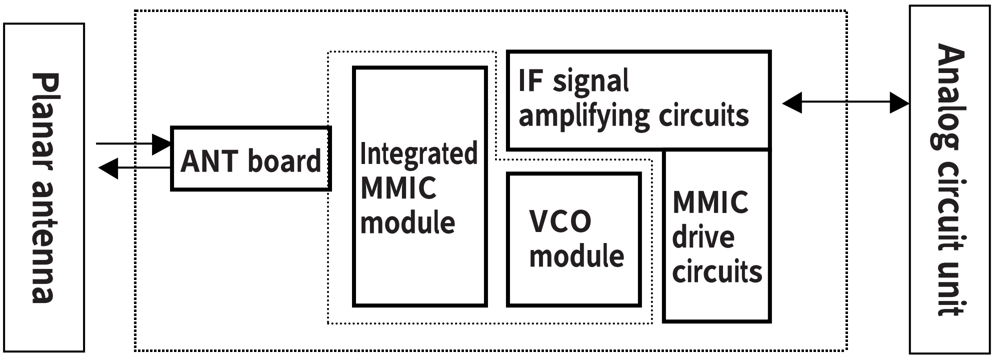

Fig.4 Block diagram of newly-developed millimeter wave unit

4 Construction of the integrated MMIC module

A cross section view of the integrated MMIC module is shown in Fig. 5. The following are noteworthy factors in the development:

①Bonding of MMIC chip and ceramic circuit board (flip-chip packaging)
②Hermetic seal
③Direct measurement by means of RF probes
④MMIC chip utilizing the HEMT (high electron mobility transistors) process

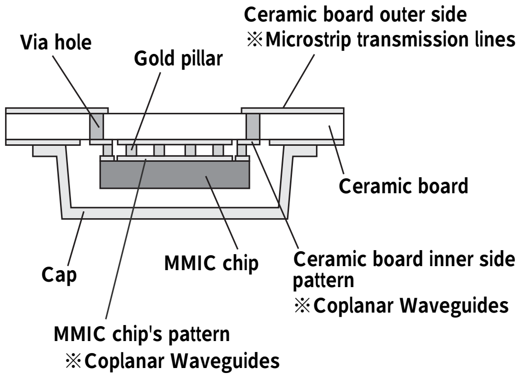

Fig.5 Construction of MMIC module

4.1 Bonding of MMIC chip and ceramic circuit board

4.1.1 Flip-chip packaging

The MMIC chip has been bonded to the 0.2 mm thick ceramic circuit board using an assembly process known as a "flip-chip." The standard method for chip assembly involves wire bonding connections onto a die-bonded chip. However, when assembling of terminals operating at extremely high frequencies such as 76GHz, chip characteristics will differ significantly depending on the loop shape of the wire and deviations in lengths, and is hard to gain stable operation characteristics. In order to control the wire bonding to obtain the required characteristics, it would be necessary to control the permissible deviation of wire bonding to be within only a few tens of microns.

As an assembly process to replace of wire bonding, we have adopted a flip-chip packaging technique using gold pillars.

Flip-chip assembly is generally used to install multi-pin chips such as LSI. The positional alignment, connection and forming is normally performed by means of printed solder bumps, utilizing the surface tension of solder. However, to obtain high performance with extremely high frequencies, it is necessary to eliminate mismatch of impedance at the connection, to suppress transmission loss. In other words, not only is the precision required for positional alignment higher than what solder connections can provide, but also a structure that can simulate high frequency characteristics which can be reproduced in manufacturing, is required. Therefore we have selected a configuration where several cylindrical gold pillars, 40 microns in diameter and 20 microns in height are formed on the trace side of the MMIC chip, and the MMIC chip is flip chip assembled onto the inner side of the ceramic board.

Coplanar waveguides are used for the trace on the MMIC chip and inner side of the ceramic board, which are flip-chip connected via gold pillars. Fig. 6 shows the structure of the coplanar wageguide route and Fig. 7 shows the microstrip route. The coplanar wageguide route is a route in which the signal line and ground line are positioned in parallel. It is representative of high frequency circuits, in the same manner as the microstrip (MSW) lines having a signal line parallel to the ground line on the other side of the PCB. The standard quasi-millimeter wave MMIC chip often uses the proven microstrip route, and in order to narrow the pattern width, the chip needs to be made thin or it is necessary to connect the chip pattern surface to chip bottom ground surface using via holes.

On the other hand, the coplanar waveguides used in the present development only has signal lines and ground lines on the chip pattern surface, and the chip thickness direction has no effect to the characteristics. Also, it is not necessary to connect the chip pattern surface ground and the chip bottom surface ground. This allows the omission of the back surface grinding process and the via hole processes required in the production of a standard millimeter wave MMIC chip, leading to a reduced number of processes as a whole.

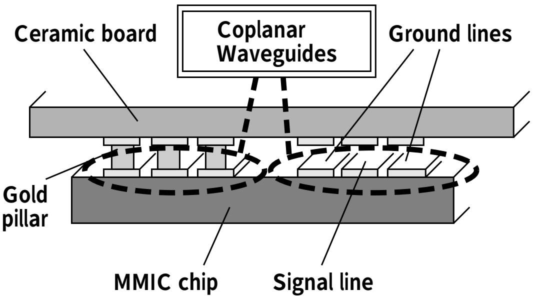

Fig.6 Coplanar waveguide

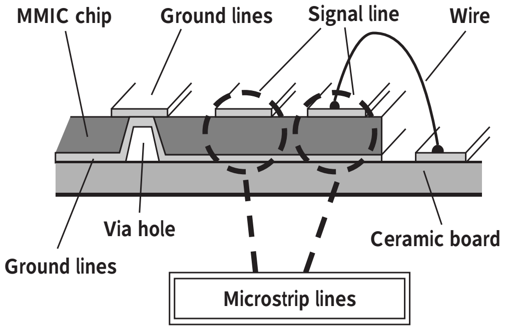

Fig.7 Microstrip line

Furthermore, the signal and ground lines being on the same side permits the use of minimal-length gold pillars for connecting the MMIC chip pattern side to the ceramic board inner pattern side, thus making it possible to keep the impedance variation small, which in turn yields stable characteristics. Another benefit is that the HEMT and other active devices are grounded through the pillars, leading to lower parasitic impedance constant than a typical one which is ground through via holes. Manufacturing control is performed by using a height monitor in the plating process, to keep the height within the range of designed pillar height.

Fig. 8 shows the high frequency characteristics of connections between the ceramic board and the MMIC chip (i.e. of the gold pillar section). Since the actual construction of the unit faithfully reproduces the design, it achieves transmission loss (S_{21}) and reflection loss (S_{11}) values of 0.3 and 15 dB respectively at 77 GHz. These loss values are superior compared to the expected losses for standard wire connections (transmission loss 0.6 and reflection loss 10 dB). The height deviation occurring at the flip-chip connection is kept down to approximately ±2 microns, resulting in low deviation characteristics at the connections.

Incidentally, even if 20 micron high pillars have a deviation of ±5 microns, the characteristic impedance of the coplanar waveguides on the MMIC chip would vary only by ±2Ω. Thus the MMIC is designed with ample tolerance for deviations that may occur in production (wafer processing and assembly).

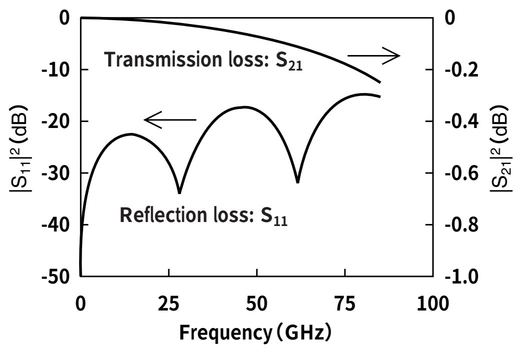

Fig.8 High frequency characteristics of gold pillar portions

4.1.2 Parallel plate mode

In this section we describe certain problematic phenomena resulting from the integration of the 4 MMIC chips into a single MMIC chip, and relevant countermeasures.

Because the MMIC chip handles 76 GHz high frequency waves, current of several 10s of mA flows through it. In order to dissipate the heat that the chip generates as a result of this current, a ceramic board provided with grounding metal is used beneath the chip; for heat dissipation, the chip and the board must be brought as close together as possible. Bringing the MMIC chip and the ceramic board close together however gives rise to a form of propagation known as "parallel plate mode". This results in unwanted radiation in various circuits formed on the chip, causing decrease in gain and other problems. To avert excitation of parallel plate mode, we deployed multiple grounded gold pillars on the MMIC chip. The relation between the number of gold pillars and excitation of parallel plate mode was analyzed by means of 3-D electromagnetic field simulation.

The results of the 3-D simulation are shown in Fig. 9. The simulation consisted of 2 metal plates positioned 20 microns apart, and a row of 40 micron diameter gold pillars positioned perpendicular to the wave diffusion direction. It was found from the simulation that the parallel plate mode was suppressed as the number of gold pillars were increased (as the spacing between the pillars decreased). To obtain maximum gain of 10 dB, it was necessary to hold parallel plate mode down to 18 dB; therefore we determined a maximum pillar spacing of 300 microns and deployed pillars uniformly over the entire area of the MMIC chip according to that spacing.

Another issue was the values of the coplanar waveguides. The basic design values of coplanar waveguides are 20 microns for width and 20 microns for spacing. Smaller values than these for the width and spacing of the lines result in increased damping; on the other hand they prevent the electromagnetic field from being spread into the MMIC chip or the atmosphere. Because of this merit we have employed coplanar waveguides with 10 micron width and 10 micron spacing, despite the entailing loss increase. Thus, although impedance variation occurs due to the proximity of the ceramic board to the MMIC chip, spread of the electromagnetic field is averted through the use of coplanar waveguides with smaller width and spacing than the design values.

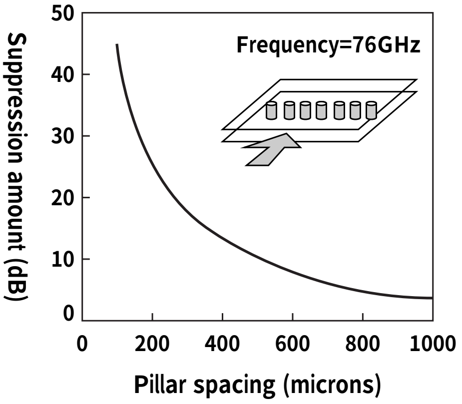

Fig.9 Simulation of parallel plate mode electromagnetic field

4.2 Hermetic seal

In order to secure its reliability, the MMIC chip connected via flip-chip to the ceramic board is hermetically sealed with a cap (refer to Fig. 10). Since the side of the ceramic board on which the chip is mounted is almost fully metalized with grounding metal, an electromagnetically shielded construction is achieved by brazing on a metal cap that would mask the chip.

The coplanar waveguides on the ceramic board are connected to the microstrip lines on its opposite side by means of via holes. The via hole sections are also metalized to make it airtight, while enabling it to efficiently transmit very high frequency waves of 76GHz.

Furthermore, by making the inside of the ceramic board be the coplanar wageguide route, and the outside to be the microstrip route, the ground surface is shared and variations in transmission mode are minimized. And use of a thin ceramic board having a thickness of 0.2 mm limits loss at the via holes and enables the cutoff frequency for the microstrip lines to be set higher than 80GHZ.

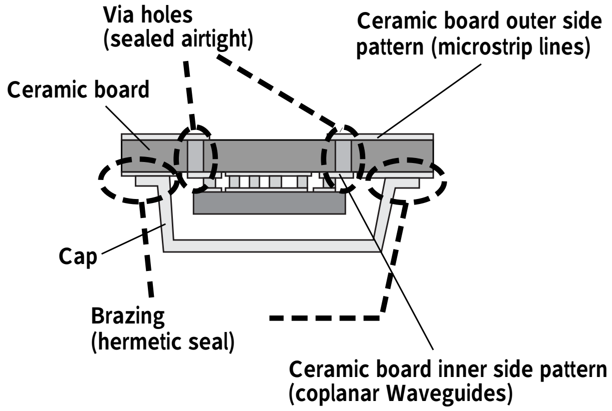

Fig.10 Hermetic seal

4.3 RF probe pads

The exterior of the newly developed integrated single chip MMIC module is shown in Fig. 11. The module has 2 RF probe pads, located at opposite ends of the ceramic board. One is a port for 38 GHz input signals and the other is a port for 76 GHz I/O signals. A magnified view of the probe pad is shown in Fig. 12. Conventional RF signal I/O ports were of microstrip construction, and inspection was performed after converting the MMIC module from the microstrip route to the coplanar wageguide route (Fig. 13). The newly developed probe pads possess both characteristics of the microstrip and the coplanar waveguide. These pads make it possible to inspect the MMIC module via the RF probes directly, without transmission line conversion jigs, and thus reduces the number of inspection steps. These pads also permit usage of wires or ribbons for connections to other lines, as in conventional modules.

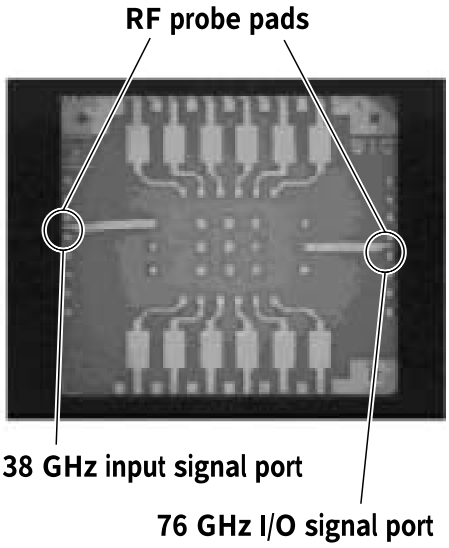

Fig.11 Exterior view of MMIC module

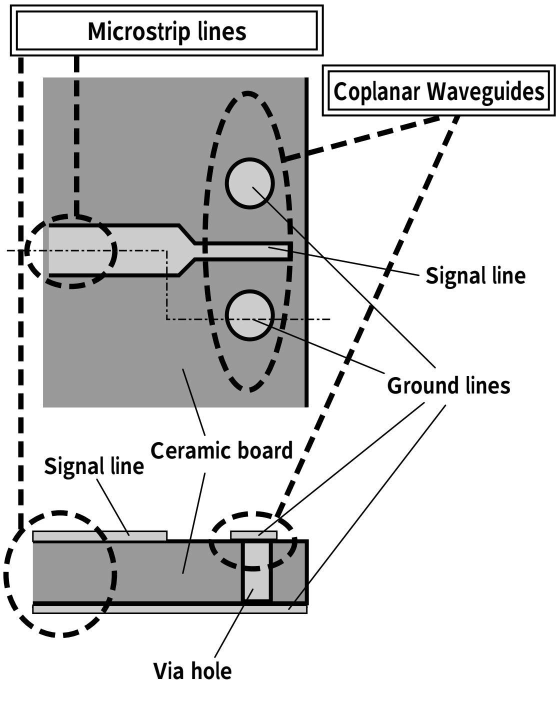

Fig.12 Enlarged view of probe pad

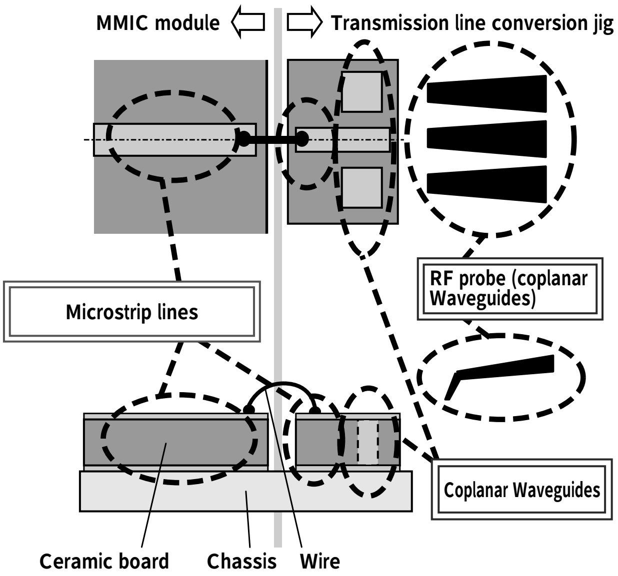

Fig.13 Former inspection method

4.4 Circuit operation of the integrated MMIC module

A block diagram of the integrated single chip MMIC module is shown in Fig. 14. As mentioned earlier, this module integrates 4 MMIC chips into a single chip.

The integrated MMIC module has a port for input of 38 GHz VCO signals from the exterior, an I/O port for 76 GHz signals, and 2 IF signal output ports. The signal routes can be broadly divided into local signal, transmission signal and reception signal routes. In the transmission mode the reception component is turned off, and in the reception mode the transmission component is turned off. Switching between transmission and reception is performed by varying the drain bias voltage of the transmission component amplifier and the reception component amplifier in turn.

Signals from external VCO are separated into 2 streams by a 38 GHz branch-line hybrid circuit. One of the separated signals is supplied to the local port of the 76 GHz mixer as a local signal after being amplified by a 38GHz amp, going through the multiplier and then again being amplified by a single stage amp.

The other signal stream is amplified by a 38 GHz amp, goes through the multiplier, and amplified further by another amp, then output as a transmission signal from the 76GHz I/O port through a 76GHz branch line hybrid.

Received signals enter from the 76 GHz I/O port, goes through a branch-line hybrid circuit, then is amplified in a amplifier, down-converted at the 0-180 degree hybrid circuit by a pair of single-end mixers, and output via the IF signal output port.

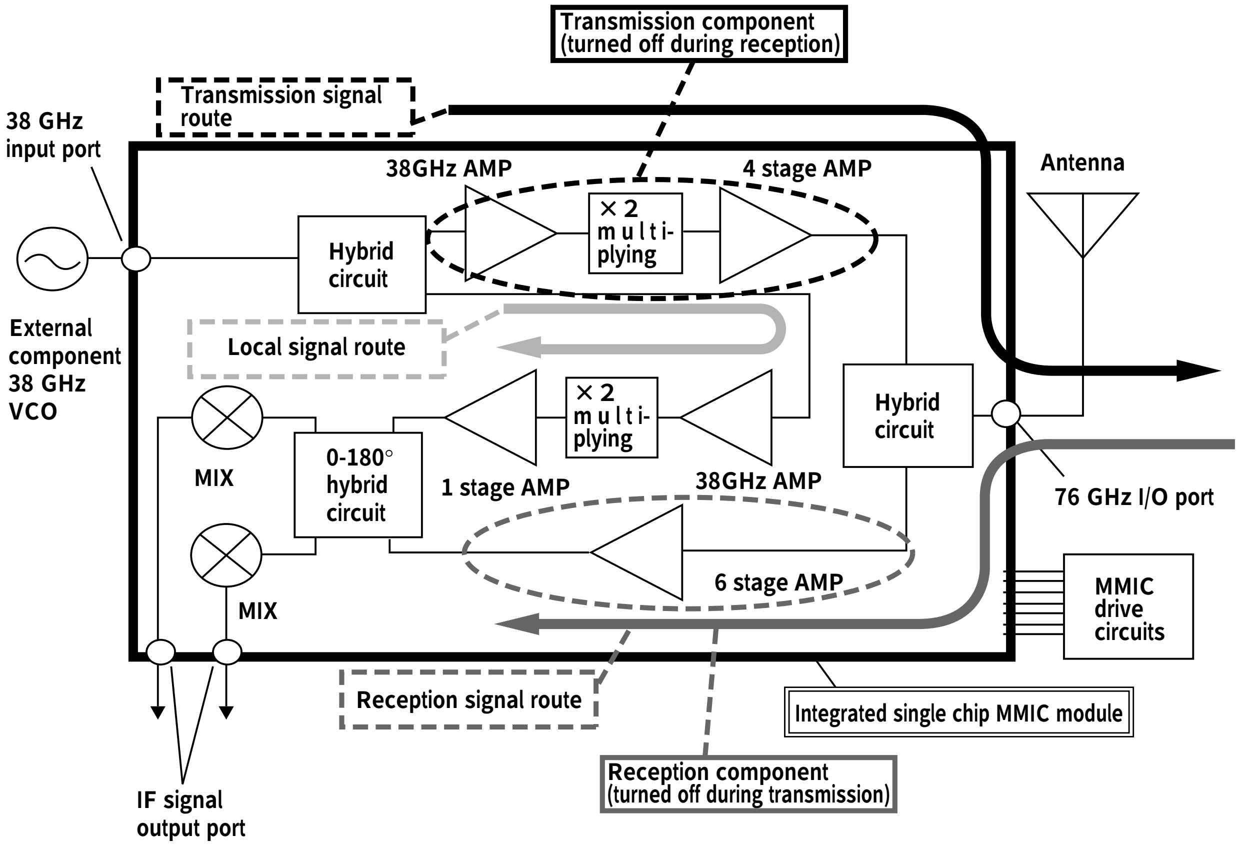

Fig.14 Block diagram of the integrated single chip MMIC module

A level diagram was determined during the development in order to give the single chip millimeter wave unit comparable characteristics to the current unit. The hybrid circuits are configured within the chip for cost reduction and miniaturization. Furthermore, the bias voltage required to drive the MMIC has been cut down to bare minimums, while making it possible to adjust applied voltage to control its characteristics.

Fig. 15 is a photograph of the integrated MMIC actually fabricated. The process used is based on P-HEMT (pseudomorphic HEMT) with InGaP/InGaAs heterojunctions. The P-HEMT performance is as follows: Gate length 0.15 microns, transition frequency ft = 90 GHz, maximum frequency of oscillation fmax = 170 GHz. The capacitors are MIM (metal-insulator-metal) construction using SiN. Epitaxial active layers are used for resistance. The area of the integrated MMIC chip is 8.46 mm2, which is just 1/3 of the total area taken by the current MMIC chip. Furthermore, as can be seen from the photograph in Fig. 15, more than 250 gold pillars are positioned in the chip to prevent interference between circuits.

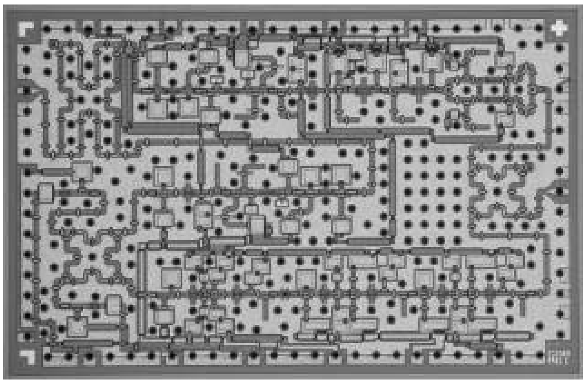

Fig.15 Photograph of single chip integrated MMIC

4.6 Performance of integrated MMIC module

Table 2 lists the performance of the integrated single chip MMIC module fabricated in the development. Its transmission performance is shown in Fig. 16 and its reception performance is in Fig. 17. Its performance is comparable to that of the conventional millimeter wave unit with the current MMIC module.

Table 2 Performance of single chip integrated MMIC

Item	Transmission performance	Reception performance
High frequency characteristics	Transmission power 7.3dBm (0dBm@38GHz in)	Gain 30.8dB (0dBm@38GHz in)
		Noise figure 11dB (@IF 1MHz)
Power consumption	$0.54W_{DC}$	$0.30W_{DC}$

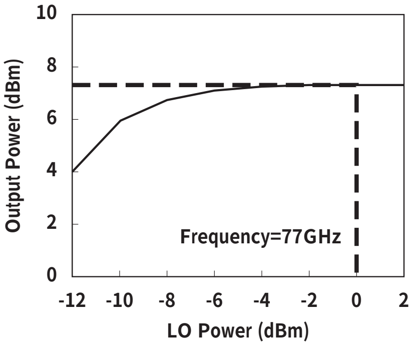

Fig.16 Output power of the integrated single chip MMIC module

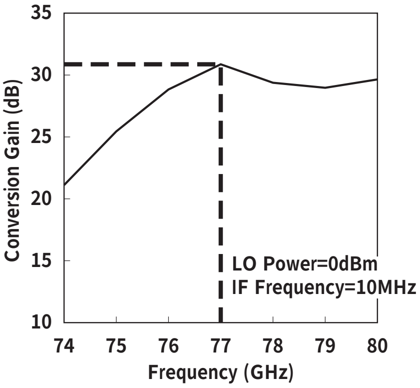

Fig.17 Conversion gain of single chip integrated MMIC

5 Conclusion

As the market for 76 GHz millimeter wave equipment expands, greater size reduction and lower cost will be required. We were able to develop a millimeter wave unit to meet those expectations. We would like to actively work in the future to mass produce the 76GHz millimeter wave radar, so that we may offer it as a product as soon as possible.

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