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A 60 GHz-Band 3-Dimensional System-in-Package Transmitter Module with Integrated Antenna

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SUMMARY A low cost, ultra small Radio Frequency (RF) transceiver module with integrated antenna is one of the key technologies for short range millimeter-wave wireless communication. This paper describes a 60 GHz-band transmitter module with integrated dipole antenna. The module consists of three pieces of low-cost organic resin substrate. These substrates are vertically stacked by employing Cu ball bonding 3-dimensional (3-D) system-in-package (SiP) technology and the MMIC's are mounted on each organic substrates by using Au-stud bump bonding (SBB) technique. The planer dipole antenna is fabricated on the top of the stacked organic substrate to avoid the influence of the grounding metal on the base substrate. At 63 GHz, maximum actual gain of 6.0 dBi is obtained for fabricated planar dipole antenna. The measured radiation patterns are agreed with the electro-magnetic (EM) simulated result, therefore the other RF portion of the 3-D front-end module, such as flip chip mounted IC's on the top surface of the module, does not affect the antenna characteristics. The results show the feasibility of millimeter-wave low cost, ultra small antenna integrated module using stacked organic substrates.

key words: *module, RFIC, MMIC, antenna integration, millimeter-wave, SiP, stud bump*

1. Introduction

60 GHz-band short range wireless communication has been focused as high speed data transmission system for consumer use. For popularization of millimeter-wave wireless terminals, low cost and small size wireless terminals have the strongest demand. Millimeter-wave CMOS MMIC's/RFIC's technology is one of the solutions which enable the reducing cost and size of millimeter-wave circuits [1], [2]. From the view point of whole transceivers, integration of external circuit components and antennas should be considered as the next step. There are mainly three approaches to integrate these elements, i.e., on-chip (MMIC/RFIC chip) integration [3], Low Temperature Cofired Ceramics (LTCC) module integration [4], [5] and organic substrate module integration [6], [7]. Since the dielectric constant of organic substrate is the lowest among these solutions, a module using organic substrates is preferable for antenna integration [7].

In this paper, an antenna integrated transmitter module using organic substrates [8], [9] is described. To reduce the size of the module, stacked substrates with flip-chip mounted MMICs configuration [10], [11] is employed. Au stud bump is used for MMIC flip-chip mounting on an organic substrate, and Cu ball interconnection is used for stacking the organic substrates vertically [12]–[14]. On the top substrate, a planer dipole antenna [15] is fabricated. Designed and measured results of the integrated antenna performances are described and discussed.

2. Transmitter Module Configuration

Figure 1 shows the block diagram of 60 GHz-band transmitter module with integrated antenna. Input IF signal is 5 GHz-band and is up-converted to 65 GHz by using an even harmonic mixer. Then it is amplified up to 10 dBm by a driver amplifier and a power amplifier. Since the LO signal of 7.5 GHz is used, x4 multiplier is required for the 60 GHz-band even harmonic mixer. All of active circuits are fabricated by GaAs MMIC technology. At antenna input, $P_{1\,\mathrm{dB}}$ (output power at 1 dB gain compression point) of 6.2 dBm and P_{sat} (saturated output power) of 12 dBm are obtained. The output spurious level is 40 dB lower than that of desired signal. The detail of these circuit blocks except antenna and their performances are described in Ref. [11].

Figure 2 shows the structure of antenna integrated transmitter module. The module consists of three sheets of Any Layer Interstitial Via Hole (ALIVH) substrate and GaAs MMIC's. The ALIVH substrate is produced by Panasonic Electric Industrial Co., and is an non-woven organic multilayered substrate. It's relative permittivity is 3.47 and dielectric loss tangent is 0.032. The top substrate is RF substrate which handles 60 GHz-band RF signal. Mixer, Driver amplifier and power amplifier GaAs-MMIC chips are mounted on the substrate and an planar antenna are integrated in the substrate. The second top substrate is LO substrate which generates 30 GHz LO signal for the

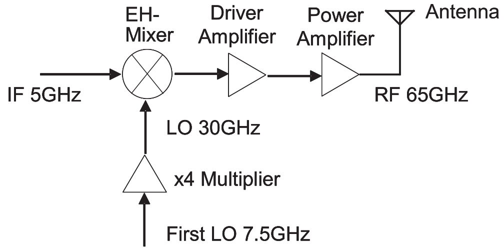

Fig. 1 Block diagram of 60 GHz-band transmitter module with integrated antenna.

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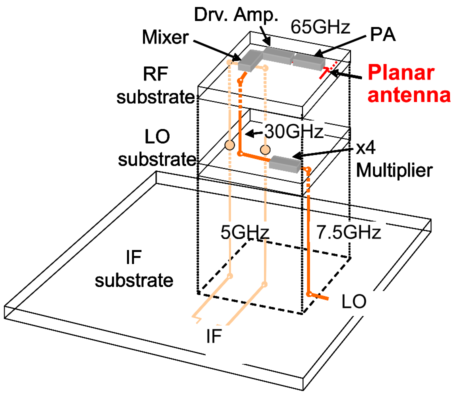


Fig. 2 Configuration of 60 GHz-band transmitter module with integrated antenna.

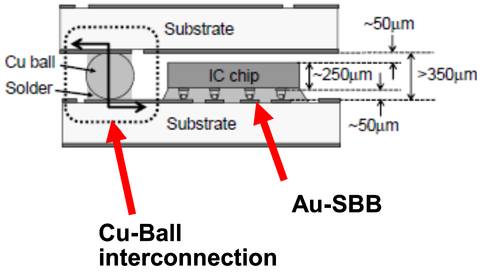
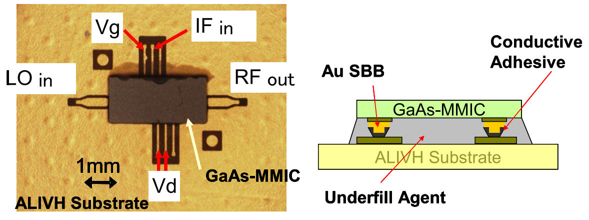


Fig. 3 Cross sectional view of interconnection section of 60 GHz-band transmitter module.



Top view (Photo) Cross sectional View

Fig. 4 Enlarged photo and cross sectional view of flip-chip mounted MMIC on ALIVH substrate.

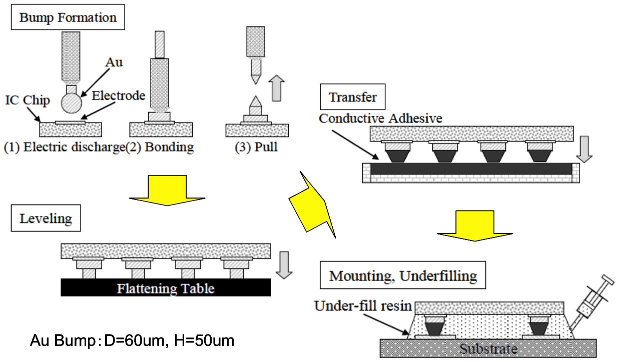


Fig. 5 Au-SBB flip-chip process flow.

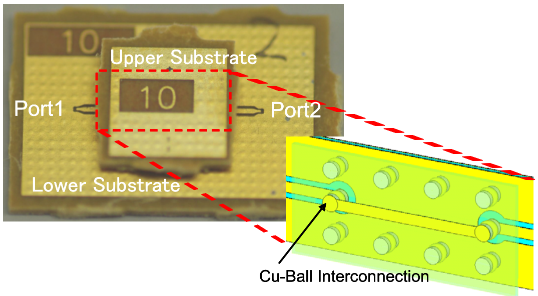


Fig. 6 Test sample of vertically stacked ALIVH substrates for Cu-ball interconnection evaluation.

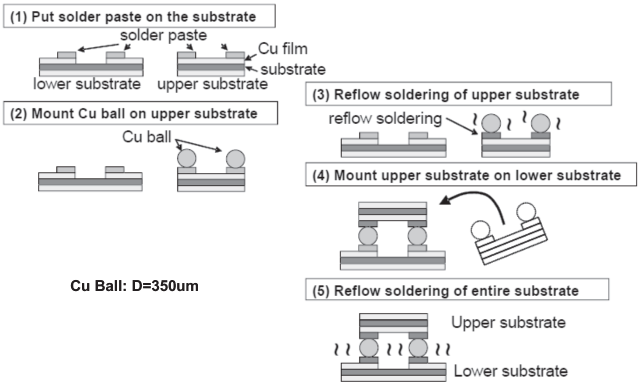


Fig. 7 Process flow of Cu-ball interconnection for vertically stacked ALIVH substrates fabrication.

60 GHz-band even harmonic mixer, from a 7.5 GHz LO signal. The bottom substrate is IF substrate which provides 5 GHz IF signals and 7.5 GHz LO signal to RF/LO substrates. Since the IF substrate requires RF/D.C. connectors to supply IF/LO signals and D.C. power to the transmitter module, the IF substrate size becomes larger than the transmitter module. The effective size of the transmitter module is same as that of RF substrate.

Figure 3 shows the cross sectional view of interconnection section of the module. A GaAs MMIC chip is flip-chip mounted on an ALIVH substrate by using Au Stud Bump Bonding (SBB) with underfill agent. Au bump (height of 50 μm) is fixed on a organic substrate by conductive adhesive. Figure 4 shows the enlarged photo and the cross sectional view of flip-chip mounted MMIC on ALIVH substrate. Figure 5 shows the Au-SBB flip-chip process flow.

Since the ALIVH substrate has a MMIC on it's surface, the distance between the vertically stacked ALIVH substrates should be more than the thickness of GaAs MMIC (around 300 μm.) To obtain the required height of more than 300 μm, Cu-ball interconnection technology is employed which has been widely used in ball grid array (BGA) packaging. In this case, the diameter of Cu-ball was selected as 350 μm. By using EM simulation, ground (GND) pattern and Cu-ball arrangements (number and location) are optimized. Figure 6 shows the test sample of vertically stacked ALIVH substrates for Cu-ball interconnection evaluation. The measured loss of interconnection is less than 1 dB at 60 GHz. Figure 7 shows the process flow of Cu-ball interconnection.

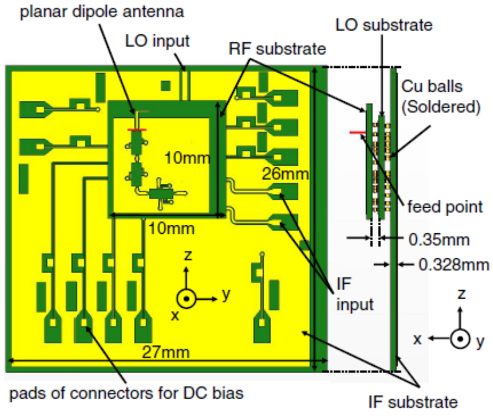
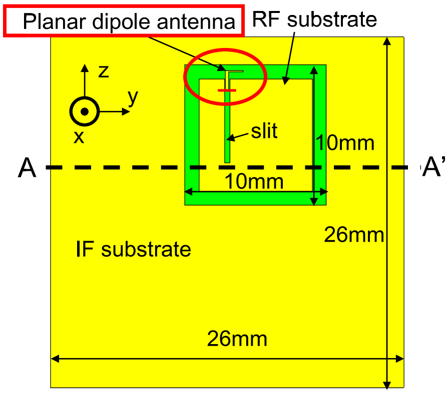
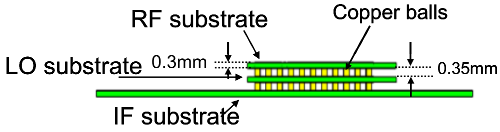


Fig. 8 Actual substrate pattern of 60 GHz-band antenna integrated transmitter module with IF substrate.



(a) Top view



(b) Cross sectional view (A-A' cut)

Fig. 9 EM simulation model of 60 GHz-band transmitter module for antenna design.

3. Antenna Design

Figure 8 shows the actual substrate pattern of 60 GHz-band antenna integrated transmitter module with IF substrate. Figure 9 shows the EM simulation model of the transmitter module which is used for antenna design. A planar dipole antenna is located on the top ALIVH substrate (RF substrate.) In order to simplify the EM simulation, the top metal of IF and RF substrates is considered as GND except antenna element, antenna feed circuit and surrounding area of RF substrate. This means the connectors and MMIC's mounted on the surfaces of IF/RF substrates can be ignored in antenna design. Figure 10 shows the detailed structure and the dimensions of the planar dipole antenna. A pair of radiators; dipole antenna is patterned on the top-side and on the back-side of the top ALIVH substrate. Since the dielectric constant of organic substrate, such as ALIVH, is lower than ceramics or semiconductors in general cases, it is suitable to configure the antenna having wider frequency bandwidth.

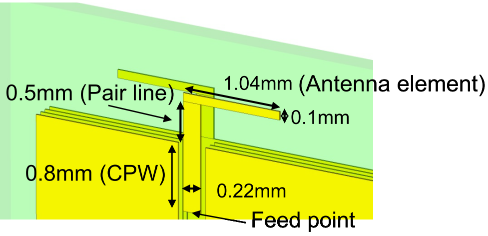


Fig. 10 Detailed structure and dimensions of integrated planar dipole antenna on the top organic substrate.

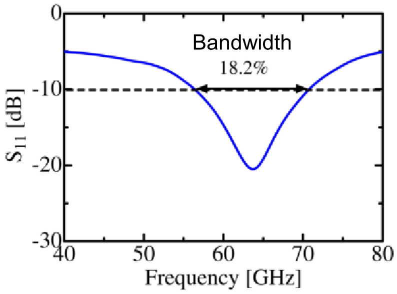


Fig. 11 Simulated return loss of integrated planar dipole antenna.

Figure 11 shows the simulated return loss of planar dipole antenna. Bandwidth of 18.2% is obtained in 60 GHz-band. Figure 12 shows the simulated antenna pattern at 63 GHz. Actual gain of 6.8 dBi is obtained. Due to the effect of GND of IF substrate, the direction of main beam becomes theta = 60 degrees.

4. Fabrication and Measurements

Figure 13 shows a photograph of the fabricated 60 GHz-band transmitter module with integrated antenna. The size of RF substrate is 9 mm × 10 mm. On the top of RF substrate, three GaAs-MMIC's (mixer, driver amplifier and power amplifier) are flip-chip mounted. Since the I/O connectors are mounted on the IF substrate, the size of IF substrate becomes 26.5 mm × 27 mm, but it's effective area is just the same as RF substrate.

Figure 14 shows the transfer characteristic of fabricated transmitter module. The output power was measured at the antenna feed. $P_{1\,dB}$ of 6.2 dBm and P_{sat} of 12 dBm are obtained at 63 GHz. Undesired signals, i.e. LO leakage and image signal are suppressed by the image rejection type even harmonic mixer. LO leakage is less than −34 dBm and image rejection ratio (IRR) is 55 dB.

Figure 15 shows the measured antenna pattern of fabricated transmitter module. Actual gain of 6.0 dBi is obtained and agrees with designed value of 6.3 dBi. The measured antenna pattern is in agreement with the simulated results and this means that the top of the RF substrate and IF sub-

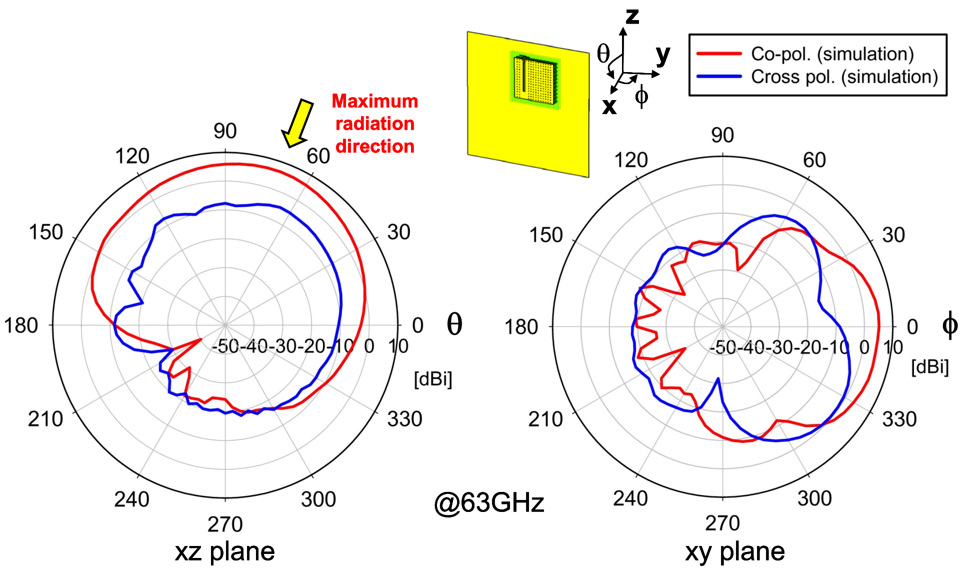


Fig. 12 Simulated antenna pattern [9].

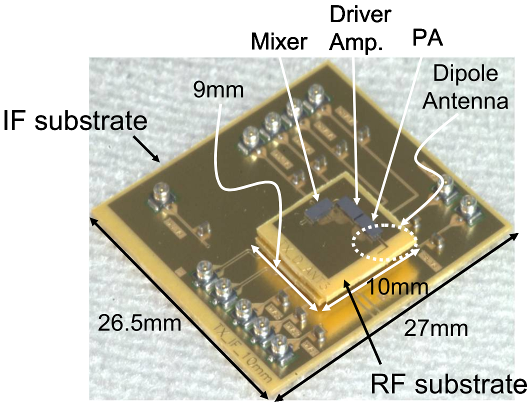


Fig. 13 Photograph of fabricated 60 GHz-band transmitter module with integrated antenna [9].

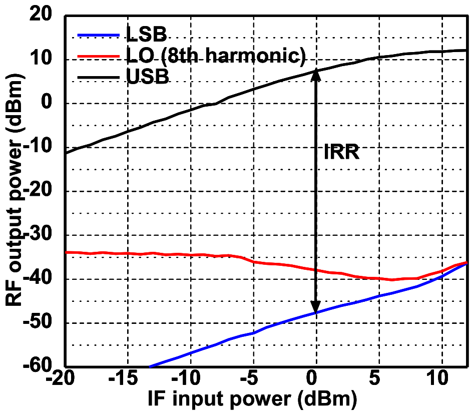


Fig. 14 Transfer characteristic of transmitter module at antenna feed. IF frequency is 5 GHz, LO frequency is 7.25 GHz and RF frequency is 63 GHz. In the figure, USB (upper side band) is desired transmit signal (63 GHz), LO is undesired local signal leakage (58 GHz) and LSB (lower side band) is undesired image signal (53 GHz.) IRR shows image rejection ratio.

strate can be considered as GND in this planar dipole antenna design.

5. Conclusions

Targeting 60 GHz-band, small, low cost wireless transceiver, antenna integrated transmitter module using 3-D SiP technology is developed. By using Au-SBB for MMIC flip chip mounting and Cu-ball interconnection for vertically stacking of ALIVH substrates, ultra-small size is feasible. By using organic substrates, such as ALIVH substrates, low cost is achievable. Since this substrate has lower dielectric constant than LTCC, it causes easy radiation from integrated antenna. Actual gain of 6.0 dBi is obtained by the measurement of fabricated antenna integrated transmitter module.

The results show that the proposed 60 GHz antenna integrated module using organic substrates and 3-D SiP technology is very promising.

As the future works, GaAs-MMIC's should be merged and replaced by a Si-RFIC to achieve higher integration/lower cost. Active phased array antenna should be also investigated to obtain higher antenna gain and beam scanning/forming functionality.

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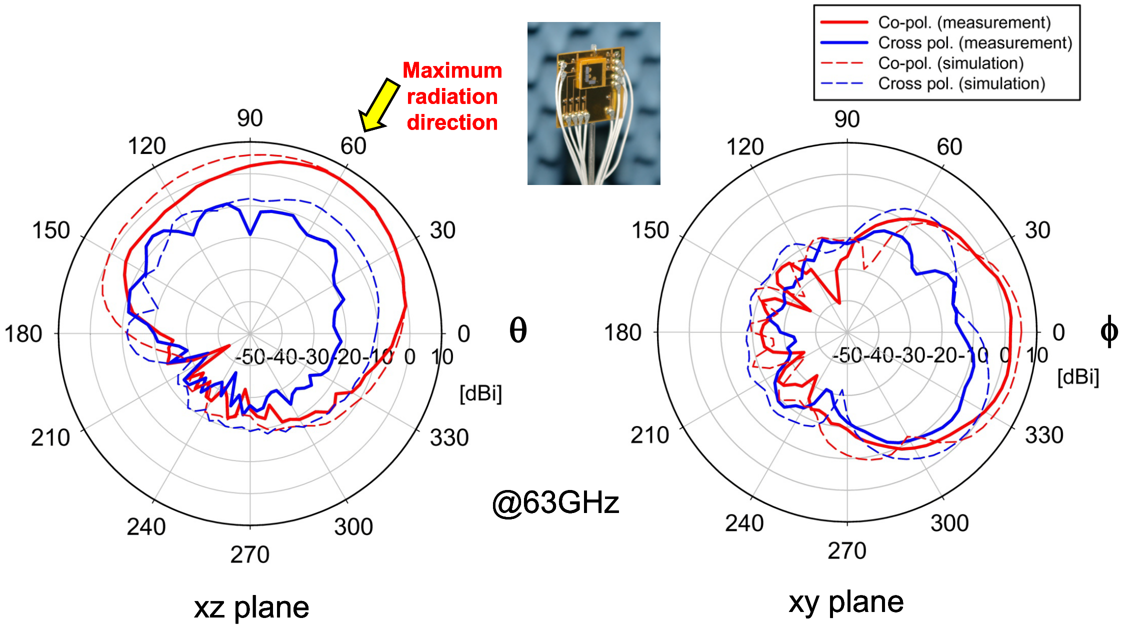

Fig. 15 Measured antenna pattern of fabricated module [9].

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