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On-Chip Yagi Antenna for Wireless Signal Transmission in Stacked MCP

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I. Introduction

This paper proposes wireless signal transmission using on-chip yagi antennas, which are used for stacked MCP (Multi-Chip Packaging). The features of this work are (a) multiple signal transmissions are realized by directional antennas, (b) measured directivities of on-chip yagi antennas are demonstrated, and (c) a scaling scenario of the on-chip directional antenna is presented to achieve the same signal throughput as clock frequency. The yagi antenna offers very high directivity and gain [1], so it can provide space-division multiplexing and multiple signal transmissions for intra- and inter-chip communication as shown in Fig. 1.

II. On-Chip Yagi Antenna

Figure 2 shows a micrograph of on-chip yagi antenna [1]. Each element has a zigzag structure [2], [3]. The antenna was fabricated in a redistributed layer of the wafer-level chip-scale package (WL-CSP) [4], which is processed above a Si CMOS chip as a packaging process. The process has three metal layers. Upper two-layers are copper, and a lower layer is aluminum. A dielectric material is polyimide. Thicknesses of copper and polyimide are 10 μm, and aluminum is 2 μm. The fabricated antenna has four elements including two directors, a radiator and a reflector in the top Cu layer, and the resonance frequency is 16.7 GHz. The chip area is $3 \times 3\,\text{mm}^2$. The electromagnetic wave is usually propagated in a dielectric layers in a package and Si substrate. In this feasibility study, the EM propagation in the dielectric layers is focused on, because it becomes dominant at the higher frequency.

III. Results and Discussion

Figure 3 shows the diagram of the measurement setup. The signal generator (Agilent E8257D) is used at the transmitting end, and the spectrum analyzer (Agilent 8563EC) and the power meter (Agilent E4419B+E9300A) are used to measure received power at the receiving end. The hybrid couplers are used to generate the differential signal for the Tx and Rx antennas. The low noise amplifier (LNA) is also used as a pre-amplifier, which has power gain of 23 dB and noise figure of 2.2 dB. The input power of the signal generator is 25 dBm and the frequency is 16.7 GHz. Figure 4 shows screenshots of the spectrum analyzer. The output result depends on the cable loss, the LNA, the power divider, etc. The measured data are calibrated using the thru pattern, and the parasitic loss of the measurement setup was 15.3 dB at 16.7 GHz.

Figure 5 shows calibrated transmission gain at 16.7 GHz [5] as a function of distance between two antennas x. The antenna transmission gain reduces as the distance becomes longer. At the shorter distance, near-field effect is observed [6]. Figure 6 shows the transmission gain as a function of orthogonal distance y as shown in Fig. 2.

Signal throughput T can be derived from the following equation.

$$T = k_e B \log_2(1 + SNR) \quad (1)$$

where B is band width, and SNR is signal noise ratio. The efficiency factor k_e is provided to consider efficiency of PHY, MAC, etc. In this work, k_e is calculated from the actual performance of IEEE 802.11a [7]. which realizes 54 Mbps with 20 MHz band width at 30 dB of SNR. According to Eq. (1), the antennas shown in Fig. 2 can transmit 2.27 Gbps signal with 16.7 GHz of carrier frequency and 3.34 GHz (=0.3 × carrier frequency) of band width. k_e is 0.537. The antenna distance x is 20.0 mm and y is 0 mm, and the antenna pitch is 18.0 mm as shown in Fig. 7. Adjacent antennas behaves as noise sources, and SNR is 6.62 dB.

Here, the scaling scenario is presented. The proposed scenario provides antenna structure, antenna topology, carrier frequency, and band width so that the same bit rate as the clock frequency can be obtained. The directivity of yagi antenna depends on the number of elements, which can be increased at the advanced technology node because antenna length becomes shorter. Figure 8 shows simulated directivities of (a) dipole and yagi antennas, (b) yagi antenna consisting of 4, 5, 7 or 13 elements. An antenna simulator (YSIM) is used. Table I shows the proposed scaling scenario. The local clock is taken from ITRS2005, and the throughput is the same as the local clock. The antenna width is not scaled in this scenario, and 2.66 mm of antenna width is employed in this work. The antenna length is scaled according to the wavelength. The number of antenna elements depends on the wavelength and the antenna width. The band width is assumed ±15 % of carrier frequency, and the carrier frequency is 5/2 times as high as the clock frequency because $5/2 f_c$ is easily obtained and not affected by clock noise. SNR depends on the directivity and the antenna pitch because adjacent antennas behave as noise source. The antenna pitch is adjusted to achieve the desired SNR. At the 14 nm technology node, 3 independent signals of 73 Gbps transmission are expected in a 20 mm-square MCP. Moreover, horizontal direction can be used for additional signal transmissions.

IV. Conclusions

In this paper, we propose the intra- and inter-chip wireless signal transmission using the on-chip yagi antenna. The measurement result performs high directivity, and 5.2 Gbps signal transmission is expected. According to the scaling scenario, 73 Gbps transmission for each 8.28 mm step is expected at the opposite side of 20 mm distance in 4-chip MCP. The on-chip directional antenna is indispensable for realizing the multiple signal transmissions.

Acknowledgment

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References

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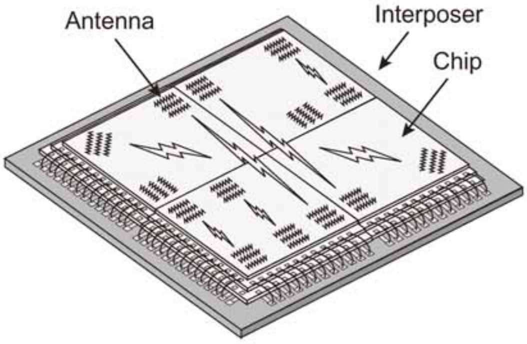

Fig. 1. Wireless signal transmission in stacked MCP.

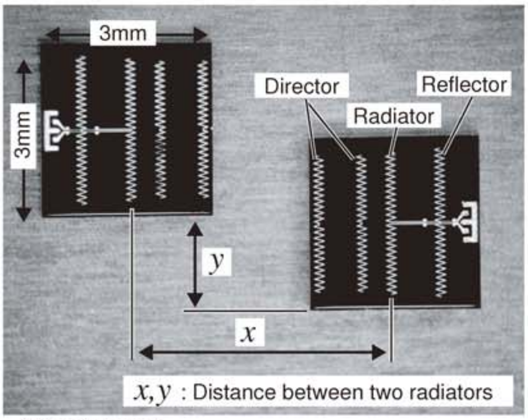

Fig. 2. Chip micrograph.

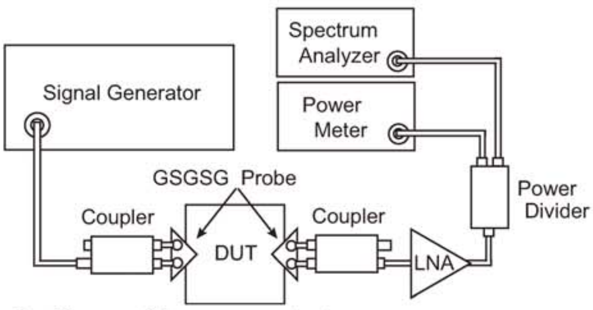

Fig. 3. Diagram of the measurement setup.

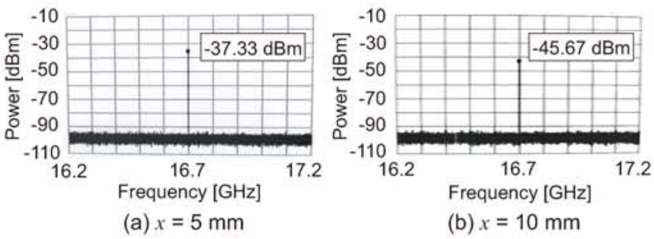

Fig. 4. Received spectrum at the spectrum analyzer at (a) x = 5 mm, (b) x = 10 mm.

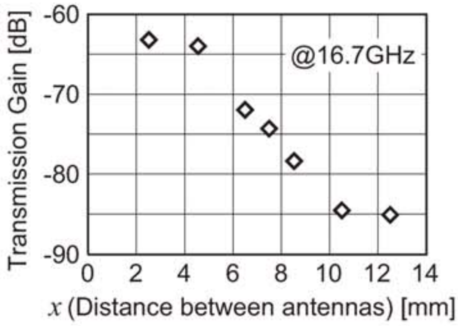

Fig. 5. Antenna transmission gains at 16.7 GHz.

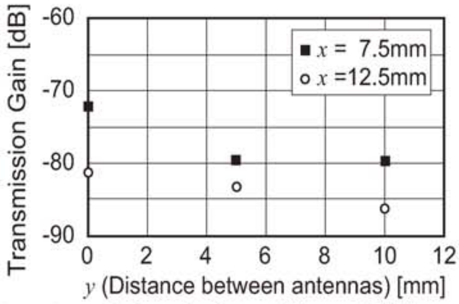

Fig. 6. Antenna transmission gains for x = 7.5 mm and 12.5 mm at 16.7 GHz.

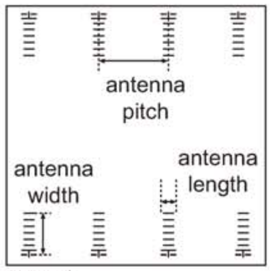

Fig. 7. Antenna arrangement.

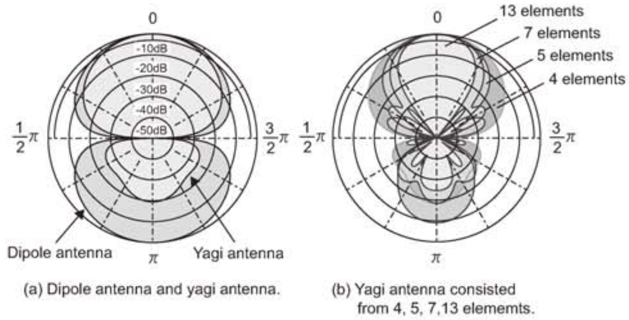

Fig. 8. Simulated directional characteristics of (a)dipole antenna and yagi antenna, (b) yagi antenna consisting of 4, 5, 7 or 13 elements.

TABLE I

Scaling scenario for on-chip directional antenna.

hp	90 nm	45 nm	25 nm	14 nm
local clock [MHz]	5,204	15,079	33,403	73,122
throughput (= local clock) [MHz]	**5,204**	**15,079**	**33,403**	**73,122**
the number of antenna elements	4	5	7	13
carrier frequency f_c [MHz]	13,010	37,698	83,508	182,780
band width (= 0.3× f_c) [MHz]	3,903	11,309	25,052	54,834
wavelength [mm]	11.5	3.98	1.80	0.821
antenna length [mm^2]	5.76	1.99	0.898	0.410
SNR [dB]	6.6	6.6	6.6	6.6
antenna pitch [mm] (*)	**18.0**	**12.5**	**9.75**	**8.28**

(*) at 20 mm of antenna distance.