Development of an Electrically Small One-Sided Directional Antenna with Matching Circuit

Haruichi Kanaya[1], Ryusuke Nabeshima[1], Ramesh Pokharel[1], Keiji Yoshida[1],
Masato Tsujii[2], and Ryoichi Iino[2]

[1]Graduate School of Information Science and Electrical Engineering, Kyushu University,
744, Motooka, Fukuoka, 819-0395, JAPAN
[2]Manufacturing Center, Toppan Printing Co., Ltd., Sugito, Saitama, 345-8508, JAPAN

Abstract — **We designed an electrically small antenna (ESA) with coplanar waveguide (CPW) matching circuit. Matching circuit is realized by using interdigital gap and transmission line. Our ESA has one-sided directivity for IMS band application. By using and controlling the length of floating metal layer on the bottom side, we can realize the one-sided radiation on the thinner substrate than that of the standard patch antenna. We also made experiments on the ESA with CPW matching circuit using patterned circuit board.**

Index Terms — **Electrically small antenna, coplanar waveguide, matching circuit, one-sided directional antenna.**

I. INTRODUCTION

In micro- and millimeter- wave devices, integrating entire transceivers on a single chip is the vision for future wireless systems such as PDC, wireless LAN, RF-ID and MIMO systems. This has the benefit of cost and size reduction. However, antennas are considered to be the largest components of wireless systems, so that, it is necessary to miniaturize antennas.

Studies are also made of an electrically small antenna (ESA), i.e., the antenna whose dimension is much smaller than one-wavelength, towards further reduction of the antenna size [1]. It is widely known, however, that in order to realize the miniaturized antenna, we must simultaneously realize a broadband impedance matching circuit, which compensates the narrow bandwidth peculiar to the small antenna with low radiation resistance, and we must attain large impedance-matching ratios to connect with semiconductor amplifiers with high internal impedances. Also, the small antenna is sensitive to the conductor resistance because of its low radiation resistance, and the decrease of the radiation efficiency often makes serious problem.

Moreover, for size reduction, another problem occurs. Namely, omni directional antennas such as the slot antennas are remarkably deteriorated if metal blocks like a ground plane of MMIC, RFIC or body of a car approaches on the back of antenna because of the electro-magnetic interference. Patch antenna is one of the solutions to overcome these problems. However, radiation efficiency of a patch antenna decreases rapidly as the thickness of the substrate decreases; therefore, miniaturization of the patch antenna is usually carried out at the cost of the substrate thickness [2]. Miniaturized patch antenna at thicker substrate is not the vision for future 3-dimensional packaging techniques or layer structures of an antenna with semiconductor chip such as RF-ID tag and other next generation wireless communication systems.

In our previous works, we designed the slot dipole antenna whose length are one-wavelength and ESA with a bandpass filter using coplanar waveguide (CPW) transmission lines, which acts as an impedance matching circuit as well [3-6]. CPW are preferable for connecting MMIC and RFIC since no via holes are required for integration with devices [7, 8].

In this paper, we present the design method the one-sided directional ESA for IMS band (@2.4GHz) application, with attaching floating metal layer on the bottom side and controlling the length of the metal layer. We designed ESA with the aid of the commercial three-dimensional electro-magnetic field simulator (Ansoft; HFSS). We also made experiments on the one-sided directional ESA with CPW matching circuits by using patterned circuit board.

II. DESIGN OF THE ELECTRICALLY SMALL ANTENNA (ESA)

Fig. 1 shows the simulated layout of an electrically small antenna (ESA) with bottom floating conductor. The designed center frequency is 2.4GHz-band. The substrate has dielectric constant ε_r=4.25 and $\tan\delta$ = 0.015 (see the cross section in Fig.1). The thickness of the substrate and both copper metals are 0.8 mm and 18 μm, respectively. The antenna size is $0.15\lambda_0$ and $0.31\lambda_0$, respectively, where λ_0 is the wavelength in the vacuum at 2.4 GHz, which is especially smaller than that of the standard dipole slot antenna. Fig. 2 shows simulated radiation patterns of the ESA with a floating conductor. This floating conductor suppresses the radiation of the downward direction (*-Z* direction). Fig. 3 shows the length of the top mental (L_{front}) versus antenna properties. These data assume the loss-less impedance matching circuit. We chose the optimal L_{front} value from efficiency and the gain. Fig. 4 shows the Z_a ($=R_a+jX_a$) of the antenna, where R_a represents radiation resistance and metal loss, and X_a is the reactance of the antenna. The measuring point of Z_a is shown in Fig. 1. Because the quarter-wavelength parallel resonance appears at 2.5 GHz, the size of this antenna is electrically smaller than quarter wavelength when the antenna works at 2.4GHz. Z_a is $131.2+j260.4$ Ω at 2.4 GHz, which is far from 50Ω.

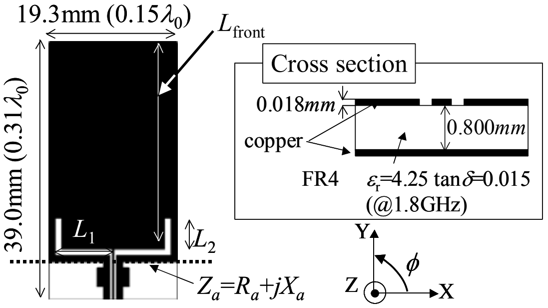

Fig. 1. Layout of the electrically small one-sided directional antenna with floating metal plane.

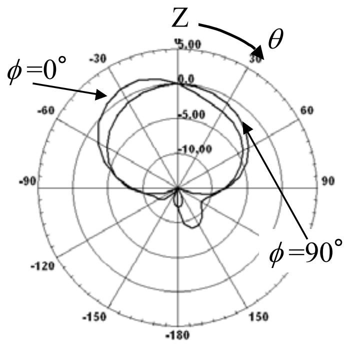

Fig. 2. Simulated radiation pattern of the one-sided directional ESA.

III. DESIGN OF THE IMPEDANCE MATCHING CIRCUIT BETWEEN ESA AND SEMICONDUCTOR AMPLIFIER

In order to connect between ESA and RF front-end, impedance matching must be attained between the antenna and amplifiers. The present matching circuit is based on the bandpass filter (BPF) composed of the transmission line and *J*-inverters [9]. Fig. 5(a) shows the n=1 BPF, where, Y_0 is the admittance of the load and B_1 is the susceptance in the parallel resonator with a susceptance slope parameter b_1. The design parameters of the n=1 BPF are

$$J_{01}=\sqrt{w}\sqrt{\frac{Y_0 b_1}{g_0 g_1}},\quad J_{12}=\sqrt{w}\sqrt{\frac{b_1 Y_0}{g_1 g_2}} \qquad (1)$$

where, w is the relative bandwidth and g_i is the filter parameter.

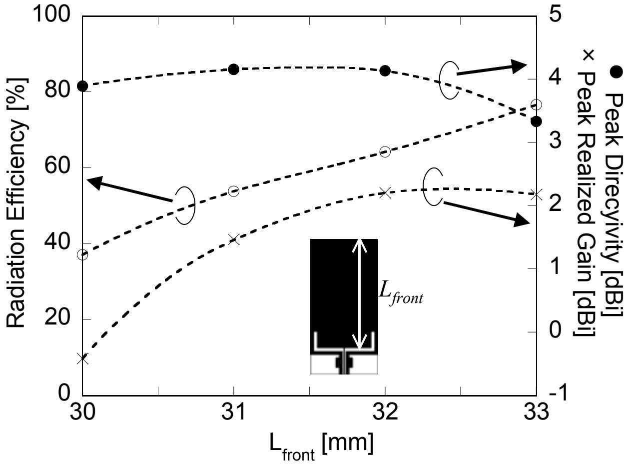

Fig. 3. The length of L_{front} versus antenna properties.

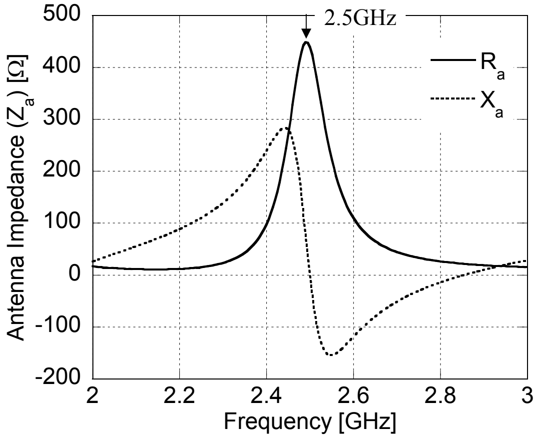

Fig. 4. Input impedance (Z_a) of the ESA without matching circuit.

Fig. 5(b) shows the equivalent circuit model for the smallest matching circuit, corresponding to BPF with n=1 [6]. In this figure, Z_a ($=1/Y_a$) denotes the input impedance of ESA and Z_L ($=1/Y_L$) represents the input impedance of LNA or the output impedance of PA. Z_{01} ($=1/Y_{01}$) and θ_i are characteristic impedance and electrical length of the transmission line. In Fig. 5(b), Y' is the admittance for looking the antenna from *A-A*', and Y'_{in} is the admittance for looking amplifier from *A-A*' and given by,

$$Y' = G' + jB' = Y_{01}\frac{Y_a + jY_{01}\tan\theta_{01}}{Y_{01} + jY_a\tan\theta_{01}} \quad , \qquad (2)$$

$$Y_{in}' = G_{in}' + jB_{in}' = \frac{\dfrac{1}{Z_L + 1/j\omega C_m} + jY_{01}\tan(-\theta_{02})}{Y_{01} + j\dfrac{1}{Z_L + 1/j\omega C_m}\tan(-\theta_{02})} \quad . \qquad (3)$$

Finally, the comparison of the Fig. 5(a) and 5(b), the proposed design value θ_{01}, Z_{01}, θ_{02}, C_m are led in the numerical value as follows:

$$\mathrm{Im}B'\big|_{\omega=\omega_0} = \mathrm{Im}B_{in}'\big|_{\omega=\omega_0} = 0 \quad (\theta_{01}, \theta_{02} \le \pi/2) \quad , \tag{4}$$

$$\frac{b'}{G'} = \frac{g_0 g_1}{w}, \quad \frac{b'}{G_{in}'} = \frac{g_1 g_2}{w} \quad , \tag{5}$$

$$b' = \frac{\omega_0}{2} \frac{\partial B'(Z_{01}, \theta_{01})}{\partial \omega}\bigg|_{\omega=\omega_0} \quad . \tag{6}$$

Fig. 6 shows the final layout of one-sided directional ESA with CPW matching circuit. In order to realize θ_{02} and C_m, we adopted the interdigital gap and CPW transmission line, where Z_L is assumed to be Z_0=50 Ω by the experiment to be convenient. Fig. 7 shows the input impedance (Z_{in}), which is the impedance for looking the antenna from *B-B*' in Fig. 5(b). Fig. 8 shows the simulated radiation pattern of the ESA. We can realize that Z_{in} is almost 50Ω around 2.4 GHz, and also one-sided directivity.

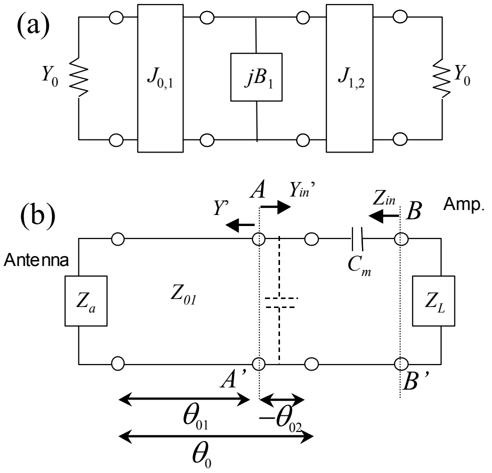

Fig. 5. Circuit model of the *n*=1 bandpass filter (a) and *n*=1 impedance matching circuit (b).

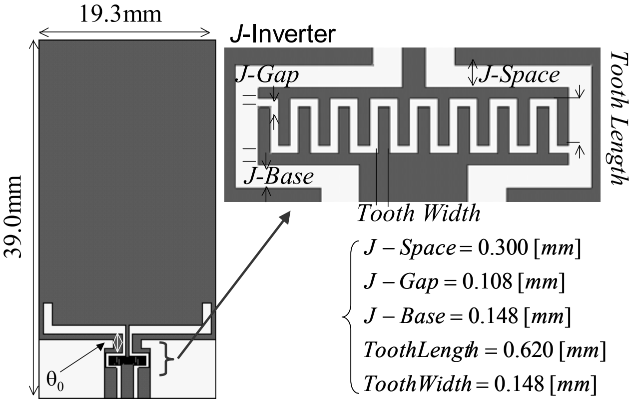

Fig. 6. Layout of the one-sided directional ESA with CPW matching circuit.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

An ESA is fabricated on FR4 substrate by using the print board making equipment (MITS; FP-21T model 40), which has 100 μm-diameter milling cutter. Fig. 9 shows the photograph of the ESA with CPW matching circuit. In the figure, the micrograph of an interdigital gap is also shown. RF signal is input through MMCX connecter, which has characteristic impedance = 50 Ω. We measured the *S*-parameters by using a GP-IB controlled vector network analyzer (HP; HP8722C).

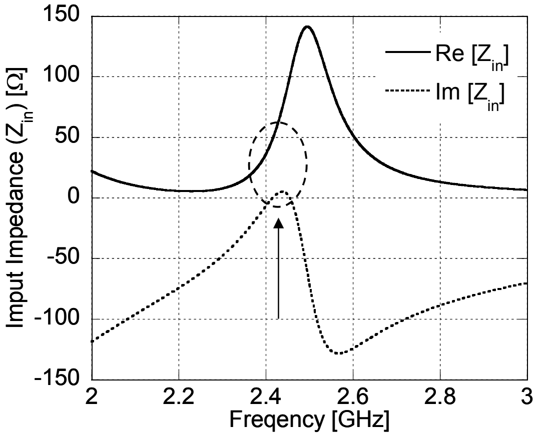

Fig. 7. Input impedance of of the ESA with matching circuit.

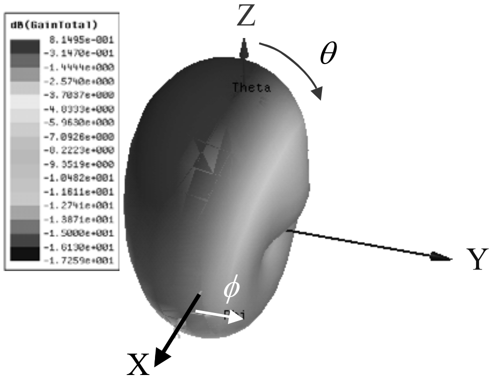

Fig. 8. Input impedance of of the ESA with matching circuit.

Fig. 10 shows the experimental results of the return loss of the ESA with CPW matching circuit. The observed experimental results are caused by an error in edge part of the interdigital gap (see Fig. 9), an error of the dielectric constant of the FR4 substrate and residual loss of the connection between connector and antenna. However the center frequency and –10 dB bandwidth are corresponding well. The communication distances are measured by using the RF-ID system at 2.4GHz band. Fig. 11 shows the comparison of the communication distance of the patch antenna with the ESA. Although the communication distance of our one-sided directional ESA (39 x 19 x 0.8 mm^3) is almost the same as the 45 x 45 x 1.6 mm^3 patch antenna, the volume of the antenna can be reduced to about 81%. Also, we can realize the bandwidth design.

V. CONCLUSIONS

In this paper, a planar slot dipole antenna with an impedance matching circuit and bandpass filter for IMS band application have been designed and tested. We succeeded in realizing the circuit, which matches the small radiation resistance of ESA to the amplifier. Also, we can realize the thinner one-sided directional ESA, which has 0.8 mm thickness. The antenna size is about 81% as small as the patch antenna. Our ESA is very advantageous for mounting 3-dimensional packages or layer structures in miniaturized RF devices.

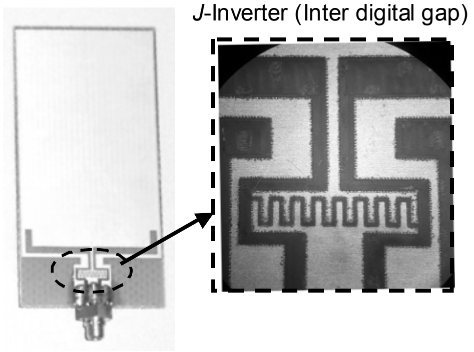

Fig. 9. Photograph of the one-sided directional ESA with CPW matching circuit.

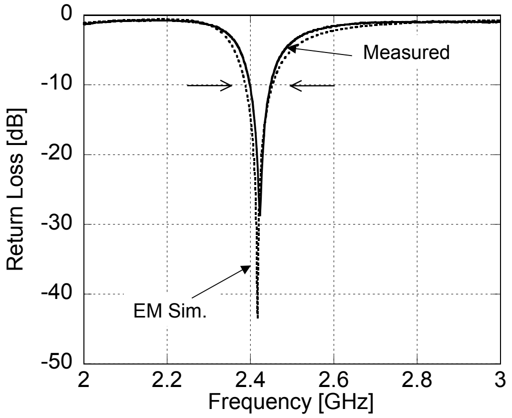

Fig. 10. Experimental results of the one-sided directional ESA with CPW matching circuit.

ACKNOWLEDGEMENT

This work was partly supported by a Grant-in-Aid for Scientific Research (C) from the Japan Society for the Promotion of Science (JSPS).

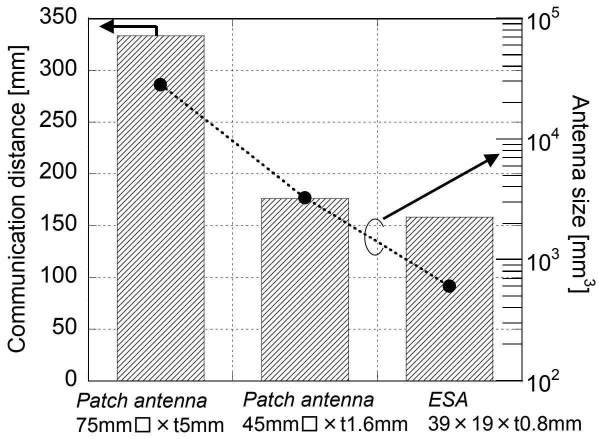

Fig. 11. Measured communication distance and antenna size of the patch antenna and ESA.

REFERENCES

[1] R. Azadegan and K. Sarabandi, “A novel approach for miniaturization of slot antennas,” *IEEE Trans. Antennas Propagat.*, vol. 51, no. 3, pp. 421-429, March 2003.

[2] J. S. Kula, D. Psychoudakis, W. J. Liao, C. C. Chen, J. L. Volakis, and J. W. Holloran, “Patch-antenna miniaturization using recently available ceramic substrate,” IEEE Antennas and Propagation Magazine, vol. 48, no. 6, pp. 13-19, December, 2006.

[3] K. Yoshida, T. Takahashi, H. Kanaya, T. Uchiyama, and Z. Wang, “Superconducting slot antenna with broadband impedance matching circuit,” IEEE Trans. Appl. Supercond., vol. 11, pp. 103-106, March 2001.

[4] H. Kanaya, Y. Koga, J. Fujiyama, G. Urakawa and K. Yoshida, “Design and performance of high Tc superconducting coplanar waveguide matching circuit for RF-CMOS LNA,” IEICE Trans. Electron., vol. E86-C, no. 1, pp. 37-41, January 2003.

[5] H. Kanaya, Y. Koga, G. Urakawa, and K. Yoshida, “Design of HTS coplanar waveguide matching circuit for low noise CMOS-HTS receiver,” IEEE Trans. on Appl. Supercond., vol. 13, no. 2, pp. 1031-1034, June 2003.

[6] S. Oda, S. Sakaguchi, H. Kanaya, R.K. Pokharel, and K. Yoshida, ”Electrically small superconducting antennas with bandpass filters”, IEEE Trans. on Appl. Supercond., vol. 17, 2007 (in press).

[7] B.K. Kormanyos, W. Harokopus, L. Katehi, and G. Rebeiz, “CPW-fed active slot antennas”, *IEEE Trans. Microwave Theory & Thech.*, vol. 42, pp.541-545, April, 1994.

[8] S. S. Garcia, and J. J. Laurin, “ Study of a CPW inductively coupled slot antenna”, *IEEE Trans. Antennas Propagat.*, vol. 47, no. 1, pp. 58-64, January 1999.

[9] G. L. Matthaei, L. Young and E. M. T. Jones, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures*, Norwood, MA: Artech House. 1980.