DEVELOPMENT OF ELECTRICALLY SMALL PLANAR ANTENNAS WITH MATCHING CIRCUIT

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Abstract: We designed and fabricated an electrically small antenna (ESA) with coplanar waveguide (CPW) matching circuit. Matching circuit is realized by using interdigital gap and transmission line. We designed ESA with the aid of the commercial three-dimensional electro magnetic field simulator. We also made experiments on the ESA with CPW matching circuits using patterned circuit board.

1. INTRODUCTION

In micro- and millimeter- wave deices, integrating entire transceivers on a single chip is the vision for future wireless systems such as PDC, wireless LAN, RF-ID and MIMO systems [1]-[3]. 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 [4].

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 [5]. 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.

The interest for the coplanar waveguide (CPW) transmission lines has increased significantly in recent years. CPW transmission lines have lower radiation leakage and less dispersion than microstrip lines. Also, they are preferable for monolithic microwave integrated circuit (MMIC's) and RFIC (radio frequency integrated circuit) since no via holes are required for integration with devices [6, 7].

Slot antennas are suitable for CPW-fed configuration, and the conventional CPW-fed slot antenna is a one-wavelength center- fed type [8].

In our previous works, we designed the slot dipole antenna whose length is one-wavelength with a bandpass filter using CPW lines, which acts as an impedance matching circuit as well [9-11]. In order to reduce the total size of antenna, the slot loop antenna was also designed whose length is half wavelength in perimeter, and it was integrated to a low noise amplifier with the matching circuit for interconnecting them [12].

Also, we have designed a slot dipole antenna whose dimension is much smaller than one wavelength with aid of EM-simulator and carried out the experiments on the slot dipole antenna with 2-poles bandpass filter, whose total size is 4.1 mm x 3.7 mm, using high temperature superconductors YBCO thin film on the MgO substrate with relative permittivity of 9.6, in the 5.0 GHz band [13].

In this paper, we design the impedance matching circuit, which connects an ESA fabricated on the normal metal to a semiconductor amplifier. The proposed matching circuits have performances similar to those of the *n*-pole bandpass filter (BPF) [14]. By using the quarter wavelength transmission line and admittance (*J*) -inverter, we can reduce the total antenna size more than one-wavelength. In the beginning, theoretical performances of the ESA with the CPW impedance matching circuit are calculated by using the transmission line model as well as the commercial electro-magnetic (EM) field simulator (Ansoft; HFSS ver.10). In order to demonstrate the theory, we also carried out experiments on the ESA at 2.4 GHz, which has the size of 22.3 mm x 8.204 mm, with the pole number of n = 1 matching circuits using FR4 printed circuit board.

2. DESIGN THEORY OF THE ELECTRICALLY SMALL ANTENNA (ESA)

The conventional slot antenna is a one-wavelength center feed slot antenna as shown in Fig. 1. The designed center frequency is 2.4GHz-band. The substrate has dielectric constant ε_r=4.25 and $\tan\delta$ = 0.015. The thickness of the substrate and copper top metal is 0.8 mm and 18 μm, respectively. Three-dimensional EM simulator simulates the RF properties. Fig. 2 shows the return loss of the standard slot antenna. The input impedance is almost 50 Ω around 2.4 GHz, and –10 dB bandwidth is 165 MHz.

Fig. 3 shows the simulated radiation pattern of the standard slot antenna shown in Fig. 1. The peak gain and radiation efficiency are 3.192 dBi and

96.07 %, respectively, which is the characteristics of dipole antenna.

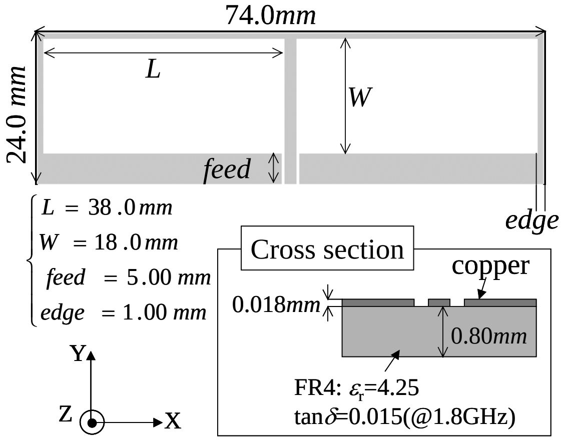

Fig.1. Layout of the standard slot dipole antenna.

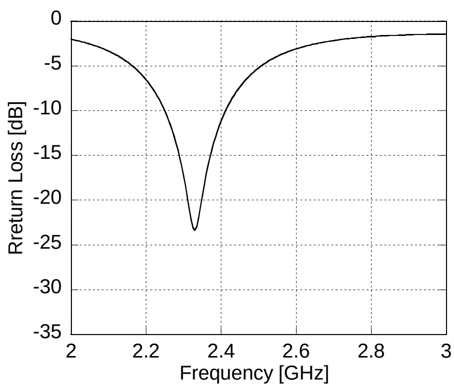

Fig. 2. Return loss of the standard slot dipole antenna.

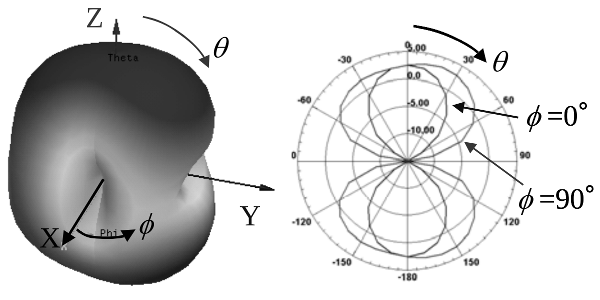

Fig. 3. Simulated radiation pattern of the standard slot dipole antenna.

Fig. 4 shows the simulated layout of an electrically small antenna (ESA). The physical properties of the substrate are the same as those of standard antenna. The antenna size is $0.18\lambda_0$ and $0.067\lambda_0$, respectively, where λ_0 is the wavelength in the vacuum at 2.45 GHz, which is especially smaller than that of the standard dipole slot antenna. Figs. 5(a) and 5(b) show the Z_a ($Z_a=R_a+jX_a$) and return loss of the antenna, where R_a represents radiation resistance and metal loss, and X_a is the reactance of the antenna. Because the quarter-wavelength parallel resonance appears at 2.74 GHz, the size of this antenna is electrically smaller than quarter wavelength when the antenna works at 2.4GHz. Z_a is 42.5+j385 Ω at 2.4 GHz, which is far from 50Ω, so that, return loss is almost 0 dB. It is shown that most RF signals reflect for the impedance miss-match.

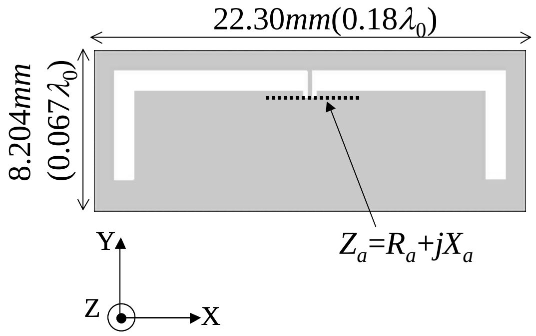

Fig. 4. Layout of the ESA.

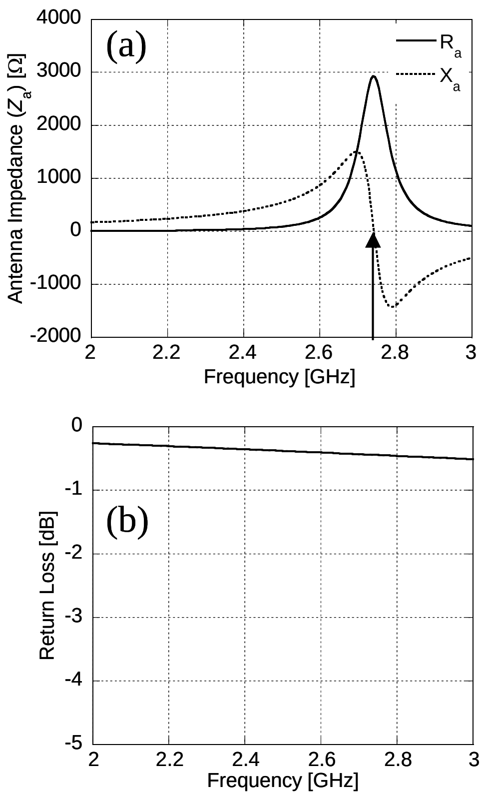

Fig. 5. Input impedance (a) and return loss (b) of the ESA without matching circuit.

3. DESIGN THEORY OF 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. Fig. 6(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

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

$$J_{12} = \sqrt{w}\sqrt{\frac{b_1 Y_0}{g_1 g_2}} \quad (2)$$

$$B_1 = b_1\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right) \quad (3)$$

where, w is the relative bandwidth and g_i is the filter parameter. Fig. 6(b) shows the equivalent circuit model of the Fig. 6(a) at the center frequency. In the figure, G'_S and G'_L, and Q_{ei} are the equivalent conductance and external quality factor, respectively.

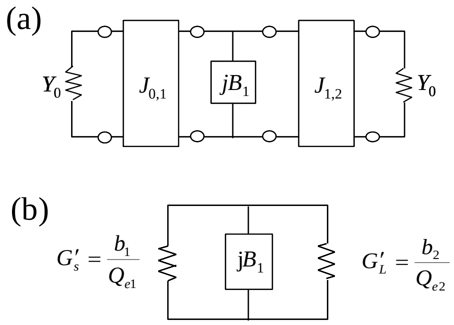

Fig. 6. Circuit model of the n=1 bandpass filter (a) and equivalent circuit model at center frequency (b).

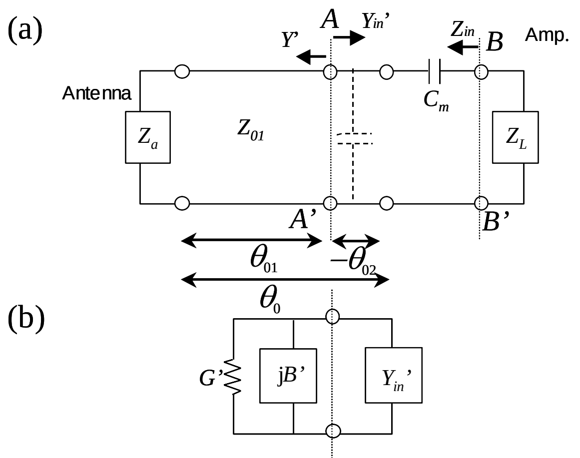

Fig. 7. Circuit model of the n=1 impedance matching circuit (a) and equivalent circuit model at center frequency (b).

Fig. 7(a) shows the equivalent circuit model for the smallest matching circuit, corresponding to BPF with n=1. 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 transition line. Fig. 7(b) shows the equivalent circuit model of the Fig. 7(a) at the center frequency. In Fig. 7 (a), 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,

$$Y' = G' + jB' = Y_{01}\frac{Y_a + jY_{01}\tan\theta_{01}}{Y_{01} + jY_a\tan\theta_{01}} \quad (4)$$

$$Y_{in}' = G_{in}' + jB_{in}' = \frac{\dfrac{1}{Z_L + 1/j\omega C_m} + jY_{01}\tan(-\theta_{02})}{Y_{01} + j\dfrac{1}{Z_L + 1/j\omega C_m}\tan(-\theta_{02})} \quad . \quad (5)$$

Finally, the comparison of the Fig. 6(b) and 7(b), the proposed design value θ_{01}, Z_{01}, θ_{02}, C_m are led in the numerical value as follows:

$$B'\big|_{\omega=\omega_0} = 0 \quad (\theta_{01} \le \pi/2) \quad (6)$$

$$\frac{b'}{G'} = Q_{e1}\left(= \frac{g_0 g_1}{w}\right) \quad (7)$$

$$B_{in}'\big|_{\omega=\omega_0} = 0 \quad (\theta_{02} \le \pi/2) \quad (8)$$

$$\frac{b'}{G_{in}'} = Q_{e2}\left(= \frac{g_1 g_2}{w}\right) \quad (9)$$

$$b' = \frac{\omega_0}{2}\frac{\partial B'(Z_{01},\theta_{01})}{\partial\omega}\bigg|_{\omega=\omega_0} \quad . \quad (10)$$

Fig. 8 shows the simulated layout of the ESA with CPW transmission line which has Z_{01} and θ_{01} (See A-A' in Fig. 7 (a)). Fig. 9 shows the frequency dependence of the Y'. We can see the parallel resonance around 2.4 GHz.

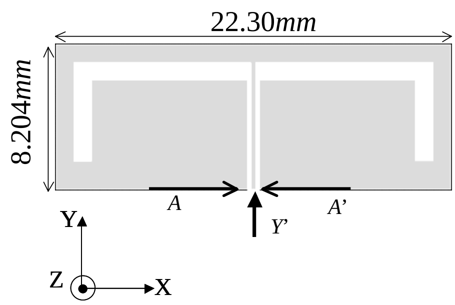

Fig. 8. Layout of the electrically small antenna with CPW transmission line.

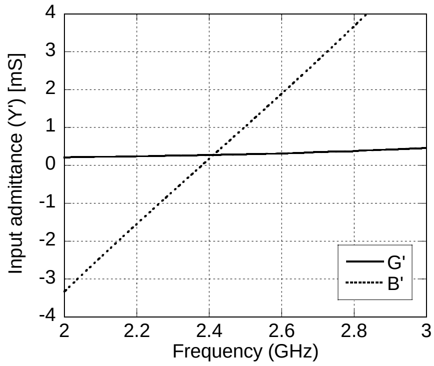

Fig. 9. Input admittance (Y') of the ESA with CPW transmission line.

Fig. 10 shows the layout of 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. 11 shows the input impedance (Z_{in}), which is the impedance for looking the antenna from *B-B'* in Fig. 7 and Fig. 10. Fig. 12 shows the return loss and Smith chart of the ESA with CPW matching circuit. Z_{in} is almost 50Ω around 2.4 GHz, so that, return loss is –32.58 dB at 2.4 GHz. Fig. 13 shows the simulated radiation pattern of the ESA with CPW matching circuit.

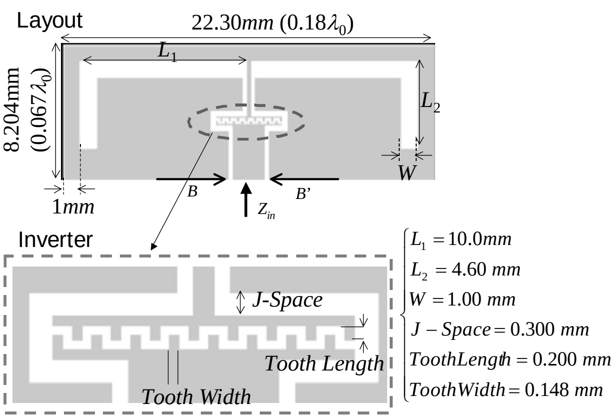

Fig. 10. Layout of the ESA with CPW matching circuit.

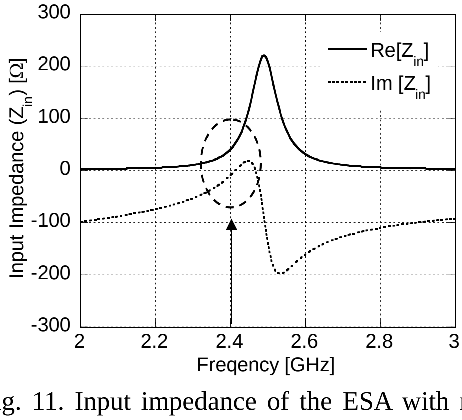

Fig. 11. Input impedance of the ESA with matching circuit.

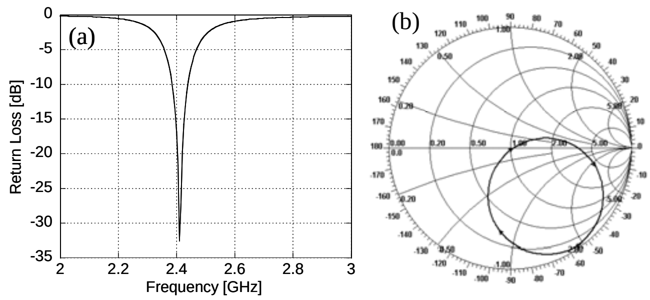

Fig. 12. Return loss (a) and Smith chart (b) of the ESA with CPW matching circuit.

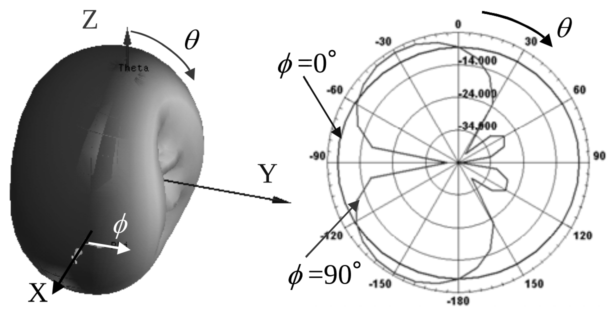

Fig. 13. Simulated radiation pattern of the ESA.

4. EXPERIMENTAL

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. 14 shows the photographs of the antenna fabrication system. In the figure, the close up of the high-frequency milling cutter is also shown.

Fig. 15 shows the photographs of the ESA with CPW matching circuit. In the figure, an interdigital gap is also shown. RF signal is input through MMCX connecter, which has characteristic impedance = 50 Ω. Fig. 16 shows the photographs of the RF measuring system. We measured the *S*-parameters by using a GP-IB controlled vector network analyzer (HP; HP8722C).

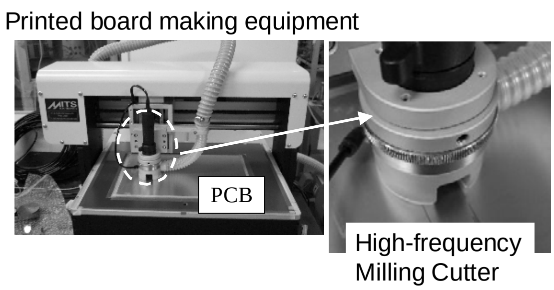

Fig. 14. Photographs of the antenna fabrication system.

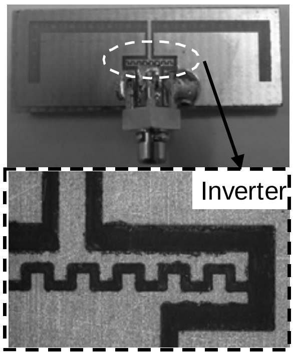

Fig. 15. Photograph of the ESA.

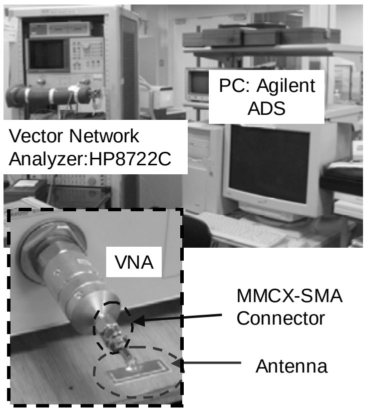

Fig. 16. Photographs of the RF measuring system.

5. RESULTS AND DISCUSSIONS

Fig. 17 shows the experimental results of the return loss of the ESA with CPW matching circuit. In the figure, broken line shows the return loss of the EM simulated result. It seems that the bandwidth slightly decreases, and the center frequency shifts 37 MHz to lower side. Also, the return loss at the center frequency is –18 dB. The observed experimental results are caused by an error in edge part of the interdigital gap (see Fig. 15), an error of the dielectric constant of the FR4 substrate and residual loss of the connection between connector and antenna. Fig. 18 shows the comparison between experimental results and simulated results taking account of the permittivity error. In EM simulation, we made the ε_r from 4.25 to 4.05, so that, the experiment results and the simulation values are corresponding well.

Fig. 19 shows the comparison of the standard slot antenna with the ESA. The antenna size can be reduced to about 90 % and bandwidth design becomes possible.

6. CONCLUSIONS

In this paper, slot dipole antenna with a bandpass filter have been designed and tested. We succeeded in realizing the circuit which matches the small radiation resistance of ESA to the amplifier. As a result, we designed a small-size (22.30 mm x 8.204 mm) slot antenna. Moreover, ESA with CPW matching circuit was fabricated and measured the RF properties, thereby we demonstrated frequency characteristics as expected.

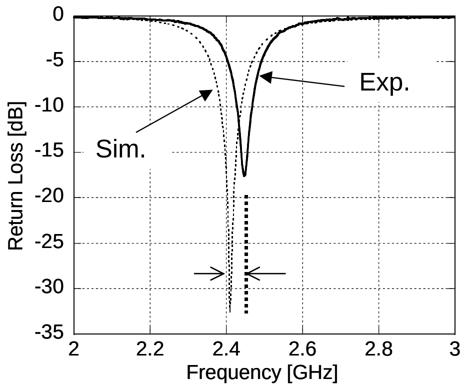

Fig. 17. Experimental result of the ESA.

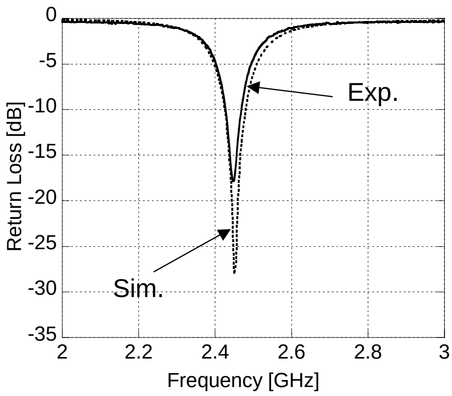

Fig. 18. Experimental results and simulated results by taking account of permittivity error.

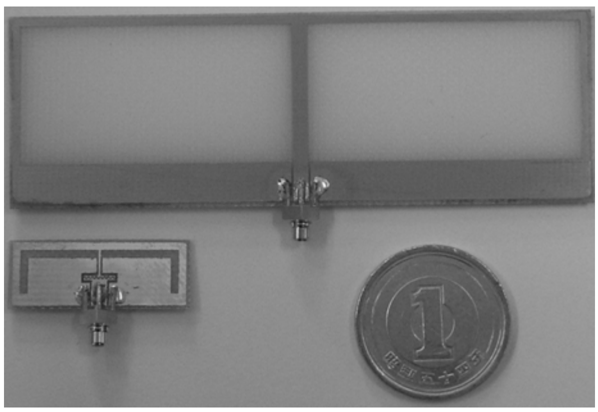

Fig. 19. Comparison of the standard slot antenna with the ESA.

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