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 electromagnetic field simulator. We also made experiments on the ESA with CPW matching circuits using patterned circuit board.

1. 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 [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 \( \varepsilon_r=4.25 \) and \( \tan\delta = 0.015 \). The thickness of the substrate and copper top metal is 0.8 mm and 18 \( \mu \)m, 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 \( \Omega \) 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. 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 $\lambda_0$ 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 2.4 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.

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

\[ J_{\delta 1} = \sqrt{w} \left( \frac{Y_{0} J_{10}}{g_{10}} \right) \]  
\[ J_{\delta 2} = \sqrt{w} \left( \frac{b_1 Y_0}{g_{12}} \right) \]  
\[ B_1 = b_1 \left( \frac{\omega}{\omega_0} - \frac{\omega_0}{\omega} \right) \]

where, $w$ is the relative bandwidth and $g_2$ 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 $Q_e$ are the equivalent conductance and external quality factor, respectively.

\[ G'_S = b_1 \left( \frac{1}{\omega_0} \right) \]  
\[ G'_L = b_2 \left( \frac{1}{Q_e} \right) \]

Finally, the comparison of the Fig. 6(b) and 7(b), the proposed design value $\theta_0$, $Z_0$, $\theta_0$, $C_m$ are led in the numerical value as follows:

\[ B' \big|_{\omega_0} = 0 \quad (\theta_0 \leq \pi/2) \]  
\[ \frac{b'}{G'} = Q_{\alpha} \left( 1 - \frac{g_{01}}{w} \right) \]  
\[ B'' \big|_{\omega_0} = 0 \quad (\theta_0 \leq \pi/2) \]  
\[ \frac{b''}{G''} = Q_{\beta} \left( 1 - \frac{g_{21}}{w} \right) \]  
\[ b' = \frac{g_{01} \beta'}{2} \left( \frac{Z_{01} \theta_0}{\tan^{-1}(\theta_0)} \right) \]

Fig. 8 shows the simulated layout of the ESA with CPW transmission line which has $Z_{01}$ and $\theta_0$ (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. 10 shows the layout of ESA with CPW matching circuit. In order to realize $\theta_0$, $\phi_0$, and $C_m$, we adopted the interdigital gap and CPW transmission line, where $Z_L$ is assumed to be $Z_0=50 \, \Omega$ 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 50 $\Omega$ around 2.4 GHz, so that, return loss is $-32.58 \, \text{dB}$ at 2.4 GHz. Fig. 13 shows the simulated radiation pattern of the ESA with CPW matching circuit.

4. EXPERIMENTAL

An ESA is fabricated on FR4 substrate by using the print board making equipment (MITS; FP-21T model 40), which has 100 $\mu$m-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 connector, which has characteristic impedance = 50 $\Omega$. Fig. 16 shows the photographs of the RF measuring system. We measured the S-parameters by using a G-P-IB controlled vector network analyzer (HP; HP8722C).
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 \( \varepsilon_r \) 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.

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REFERENCES


