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A RECONFIGURABLE ACTIVE ARRAY ANTENNA SYSTEM WITH THE FREQUENCY RECONFIGURABLE AMPLIFIERS BASED ON RF MEMS SWITCHES

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Abstract—In this paper, a frequency reconfigurable active array antenna (RAA) system, which can be reconfigurable at three different frequency bands, is proposed. The proposed RAA system is designed with a novel frequency reconfigurable front-end amplifiers (RFA) with the simple reconfigurable impedance matching circuits (RMC) with the MEMS switches. With the MEMS switch, the RFA is realized without any performance sacrifice especially linear characteristic. The proposed RAA antenna system is composed of the RMC, RFA with the RMC, 2×2 array of reconfigurable antenna elements (RAE), as well as a reconfiguration control board (RCB) for MEMS switch control, and the validity of the proposed RMC, RFA, as well as RAA system which is presented with the experimental results.

1. INTRODUCTION

Recent explosive growth in demand of high data rate transmission has led to the development of various highly functional wireless communication services. Moreover, modern wireless units or devices have to accommodate multiple wireless standards to support next

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generation communication standards. As a result, multi-standard, cognitive or reconfigurable radio systems have inspired a great deal of interests to many researchers in the academics and industries to realize compatibility between various standards or maximum efficiency of spectrum resource. Traditionally, reconfigurable devices have been studied in the areas of voltage controlled oscillator or tunable filter, and they are now widely expanded into various devices, including reconfigurable impedance matching circuits [1, 2], as well as frequency [3, 4], radiation pattern [5], polarization [6] tunable antenna, and RF front-end amplifiers [7]. To implement highly efficient and compact systems or devices, the reconfiguration method needs to be as simple as possible and easy to be realized. The previous tunable impedance networks in [1, 8] are based on π- or L-section matching network, and an impedance is transformed into another impedance with properly calculated electrical values of components consisting matching network. In this approach, accurate control of the component values is required for impedance transform. Moreover, the available impedance transformation range is restricted depending on the topology of the matching circuit [1, 2, 8, 9].

In this paper, a novel RMC is proposed based on L-section matching network with a shunt capacitor and a series transmission line, and a frequency reconfigurable RAA system is also presented with the RFA based on the proposed RMC topology. Moreover, the RMC, RFA, as well as RAA system proposed in this paper are realized with micro-electro-mechanical-system (MEMS) switches instead of varactor diodes in the conventional reconfigurable amplifiers [10] or reconfigurable system. Since a MEMS switch shows excellent isolation, insertion loss, as well as linear characteristics [11], the RFA can be realized with maximized performance. In this paper, the measured linearity of the RFA is compared with the same amplifiers except that the metal wire, a nearly ideal component in view of linear characteristic, is employed instead of the MEMS switches. The presented RAA system can be configured for three different frequency bands: Korean cellular communication system (850 MHz), WCDMA (1.9 GHz), as well as WiMAX (3.4 GHz) bands.

2. SYSTEM DESIGN

Figure 1 shows the block diagram of the designed RAA system. The proposed RAA system is composed of three 2×2 arrays of reconfigurable antenna elements (RAE) and four RFAs. The input signal to the RAA system is divided into four RFAs by a wideband power divider operating entire frequency bands, and the outputs of

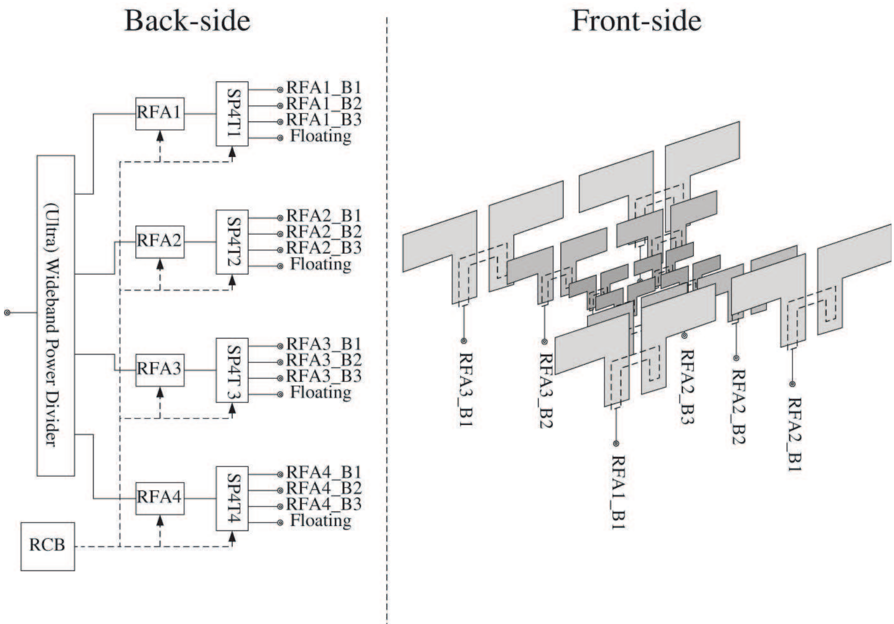


Figure 1. RAA system block diagram.

the each RFA are connected to the inputs of the corresponding RAE, which has a braodband dipole structure [12]. To reconfigure 2×2 array of RAEs, the distances between the array elements have to be changed according to the operating frequency bands. However, mechanical change for electrical reconfiguration is generally very slow, and it would be inefficient for multiple antennas. So, triple 2×2 arrays of RAEs are individually designed in this paper, and the signal connection from the output of RFA to the inputs of RAEs is controlled by using single-pole-4-throw (SP4T) swithes. The control signals for RFAs as well as SP4T switches are generated by the RCB, and the RCB is operated with the control program on user computer. The RFA, SP4T, as well as RAE are separately designed and fabricated, and they are assembled after verification of each component.

2.1. RFA Design

Conventional reconfigurable amplifiers are commonly implemented with varactor diode as a variable capacitor to change electrical value of the capacitor in the impedance matching circuits [10]. However, varactor diodes show poor linearity, causing degradation of linearity performance, which is the most critical parameter for modern non-constant envelop communication schemes for high rate data transmission such as orthogonal frequency division multiplexing (OFDM). Recently, MEMS capacitors have been utilized to realize reconfigurable amplifiers due to their very low insertion loss, high isolation, as well as linearity [7, 13]. In the conventional variable capacitance based RMC [7, 10, 13], the capacitance of the varactor, however, has to be controlled with very fine and accurate with complicated control circuit for a given impedance point. Moreover, available impedance range is restricted depending on the topology of the RMC. As a result, the RMC would be very complicated for many different frequency bands. In this paper, a very simple RMC topology based on the variable capacitance of a shunt capacitor and variable electrical length of a series transmission line is employed [14], and the RFA and RAA system are designed with the proposed RMC. Fig. 2 shows the block diagram of the designed RFA with the proposed input and output RMCs. To provide accurate impedance transformation with the L-section matching network, not only the capacitance of the shunt capacitors but also the electrical length of the series transmission lines are need to be controlled to arbitrary desired values. To realize this configuration, MEMS switches are employed to control signal path as shown Fig. 2, and, as a result, the input and output shunt capacitance and electrical length are controlled independently. For example, if the switch 1 is closed and switch 2 and 3 are open, the input shunt capacitance and electrical length are C_1 and $\theta_2 + \theta_3 + \theta_4$, respectively. In the same manner, if the switch 1 and 3 are open,

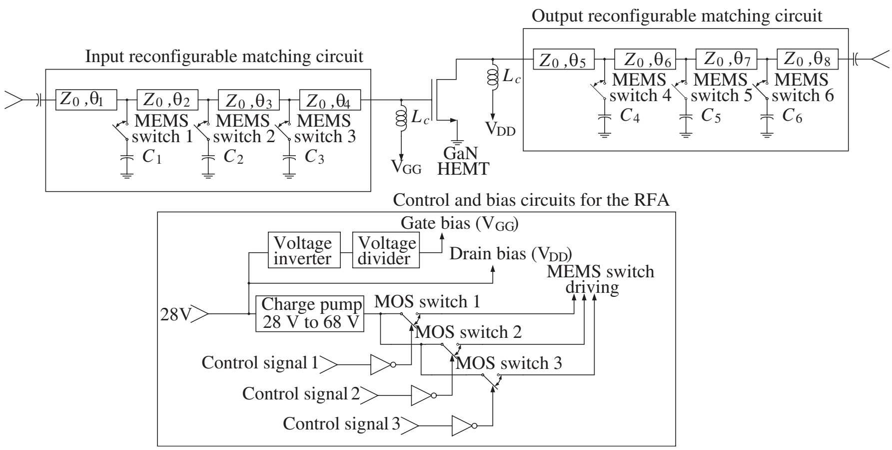


Figure 2. RFA block diagram.

while switch 2 is closed, input shunt capacitance and electrical length are C_2 and $\theta_3 + \theta_4$, respectively. With this configuration, only one switch control is necessary for frequency reconfiguration. With this approach, one RFA with input and output RMCs for triple reconfigurable frequency bands can be realized with six switches and three control signals. The proposed RMC with shunt capacitors and series transmission lines has a low-pass topology, and its gain of the RFA is similar to the transfer function of a low pass filter. As a result, the RFA with the proposed RMCs may reveal higher gain at lower frequency than the desired operating frequency band. To mitigate high gain at lower frequency might cause some problem, band pass or high pass filter can be employed.

The proposed RFA is implemented using commercial gallium nitride (GaN) high-electron-mobility-transistors (HEMT) showing excellent high frequency operation and power efficiency [15]. The MEMS switches are employed to realize RFA, RMC, as well as SP4T circuits. The employed MEMS switches need 68 V for turn on and off, and the charge pump circuit is designed to generate 68 V from system voltage of 28 V. The 68 V generated by the charge pump circuit is applied through the metal-oxide-semiconductor (MOS) switch to MEMS switch with respect of the control signal generated by the RCB. The drain-source voltage of the GaN HEMT is 28 V, and the negative voltage for gate bias is generated by using a voltage inverter and divider. The SP4T board for RAE reconfiguration also has its own control circuit like that of the RFA shown in Fig. 2.

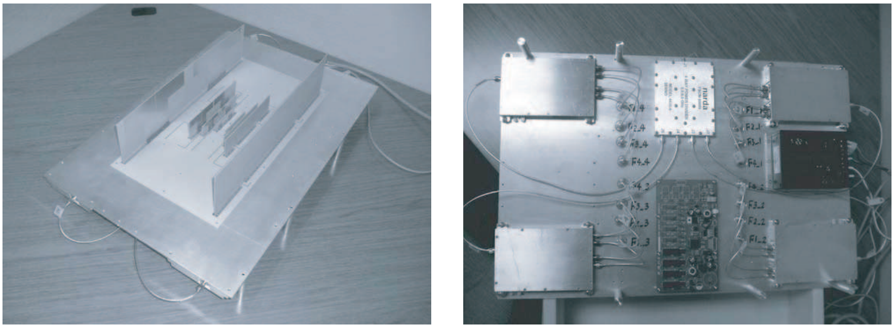
2.2. RAE and Array Design

The RAA system presented in this paper has 2×2 array configuration to achieve high directivity. To achieve proper radiation pattern with suppressed side lobes, the electrical distance between array elements has to be adjusted as a function of operating frequency. Three RAEs with broadband dipole structure [12] for triple frequency bands and their 2×2 arrays are designed separately to minimize coupling between antenna elements and to optimize their performance, and the SP4T switch is employed to reconfigure the signal path from RFA output to RAE input. The RAE with broadband dipole structure shown in Fig. 1 is consisted of the printed dipole arm and integrated balun. This topology is advantageous to optimize the antenna performance, because the input impedance and radiation pattern are mainly functions of balun and dipole arm, respectively, and they can be optimized separately [12]. The distances between RAEs of 2×2 array are 200 mm by 200 mm, 80 mm by 80 mm, and 60 mm by 50 mm for x- and y-directions for 850 MHz, 1.9 GHz, and 3.4 GHz, respectively.

These distances are close to the half wave length at their own operating frequency bands, and the distances are slightly optimized to minimize the coupling between RAEs for different frequency bands.

3. EXPERIMENTAL RESULTS

The proposed RFA, SP4T, as well as RAE used in the RAA system are fabricated on high performance substrate with dielectric constant of 3.5 and dielectric thickness 0.75 mm. The fabricated RAA system is shown in Fig. 3. The RAA system is mounted on a metal plate ($600 \times 400\,\mathrm{mm}^2$). The triple 2×2 arrays of RAEs are placed on the front side, and the RFAs, RCB, broadband power divider, and power supply unit are placed on the back side of the plate as shown in Fig. 3.



(a) Front-side (b) Back-side

Figure 3. Photograph of the fabricated RAA system.

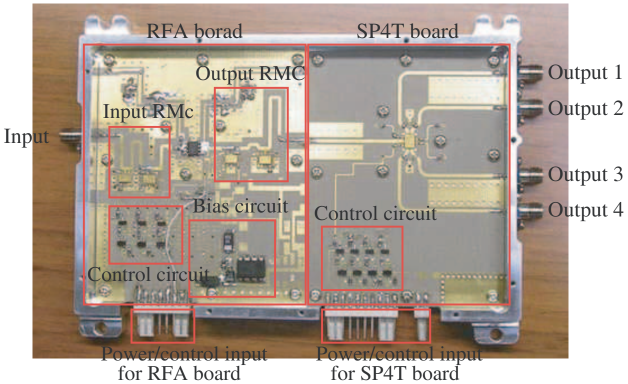
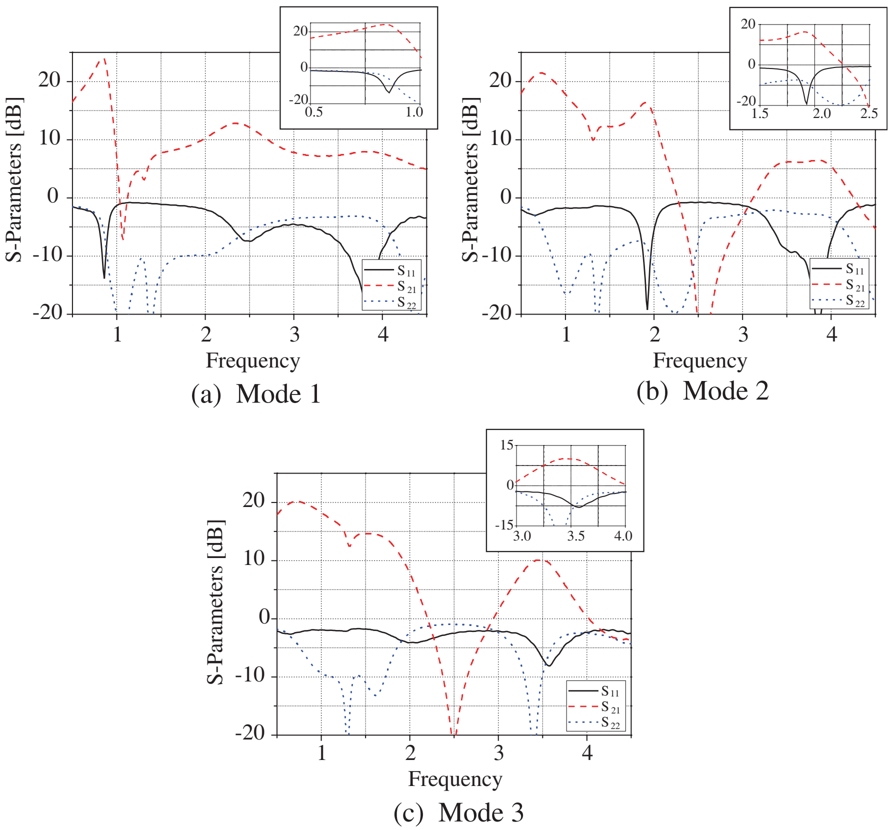


Figure 4. Photograph of the fabricated RFA/SP4T board.

Figure 4 shows the RFA and SP4T boards mounted on the conductor box. The sizes of the RFA and SP4T, which includes control, bias, and input and output RMCs, are $73 \times 87\,\mathrm{mm}^2$ and $67 \times 87\,\mathrm{mm}^2$, respectively. The operating current of RFA is about 50 mA with 28 V supply voltage. Fig. 5 shows the measured input and output return losses and gain characteristics of the fabricated RFA. As shown in the figure, the input and output impedance matching are appropriately reconfigured with proper reconfiguration control at 850 MHz, 1.9 GHz, and 3.4 GHz. The gain characteristics also show the optimum value with about -10 dB input and output return losses. However, as previously mentioned, the measured gain of the fabricated RFA shows low pass characteristics. For example, the measured gain at 850 MHz, the lowest frequency band of three reconfiguration frequency bands, of the RFA operating for 1.9 GHz or 3.4 GHz for frequency band as shown



(a) Mode 1

(b) Mode 2

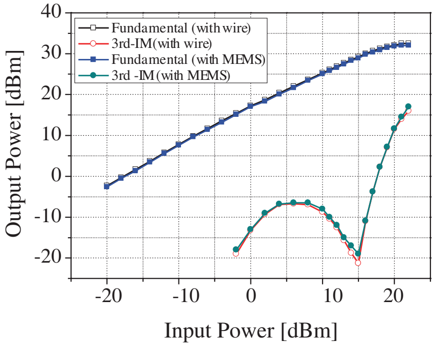
(c) Mode 3

Figure 5. Measured S-parameters of the fabricated RF.

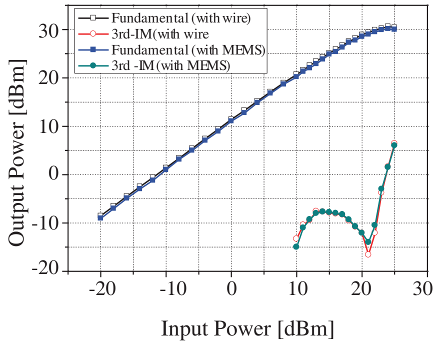
in Fig. 5(b) or 5(c) is quite high, even though the RFA is not operating for 850 MHz. If this high gain may cause any problem, additional filters need to be used to suppress this gain level at lower frequency. Another interesting measured result is that there is a transmission-zero point at slightly higher frequency than the operating frequency of the fabricated RFA, and this phenomenon is clear for 850 MHz and 1.9 GHz operations as shown in Figs. 5(a) and 5(b). The size of the MEMS switch employed in this paper is $3.25 \times 4.5\,\mathrm{mm}^2$. The MEMS switch and the signal routing path for the shunt capacitor connection produce signal delay, and the length of this line is about 5 mm. This delay line can be modeled as a high impedance transmission line or inductor. This inductive component forms a series LC resonator with the shunt capacitor of the RMC, and the realized RMC can be modeled as a series LC resonator shunted from a series transmission line. Thus, a transmission-zero is occurred at the resonant frequency of the series LC resonator, and the proposed RMC reveals a elliptic type low pass characteristic as shown in Fig. 5. The maximum gains with proper reconfiguration are 23 dB, 12 dB, and 10 dB at 850 MHz, 1.9 GHz, and 3.4 GHz, respectively. The measured input and output return losses for 850 MHz and 1.9 GHz shows excellent results of −15 dB to −20 dB. However, the input return loss for 3.4 GHz operation is degraded to −8 dB.

The fundamental and 3-rd order inter-modulation tones of the output signal with respect of the various input signal levels are measured to characterize the linearity performance of the fabricated RFA. Moreover, the measured linear characteristics are compared with that of the amplifiers, which are the same with the fabricated RFA except that the metal wires are employed instead of the MEMS switch. Since the linearity of a wire is nearly perfect, the amplifiers with wire connection can be a good reference to analyze the effect of the MEMS switches. As shown in Fig. 6, the measured linearities of the fabricated RFA as well as the amplifiers with the metal wire show exactly the same characteristics including gain compression as well as 3-rd order inter-modulation distortion for all three reconfiguration frequency bands. These measured results mean that the linearity degradation due to the MEMS switches employed to realize the RFA is negligible, and the RFA can be realized without any performance sacrifice with the MEMS switch for the modern communication schemes, such as a OFDM system generally requiring high linear characteristic.

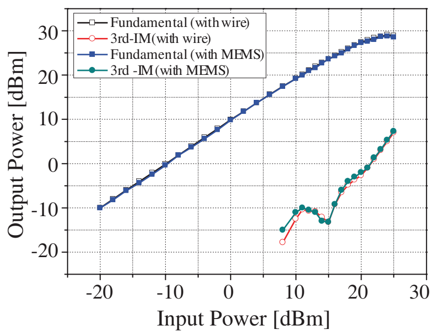
The four sets of RFA-SP4T boards are fabricated with the RFAs and SP4T boards described above. The delay difference in the four signal paths causes radiation pattern degradation, so each RFA-SP4T board is carefully fabricated to minimize the amplitude and phase



(a) Mode 1



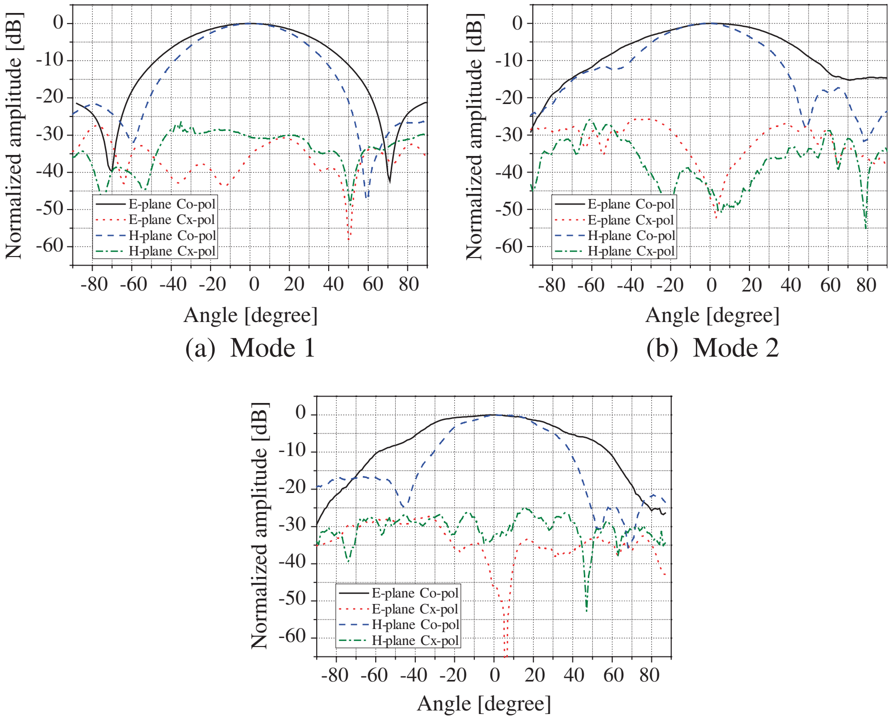
(b) Mode 2



(c) Mode 3

Figure 6. Measured linear characteristics of the fabricated RFA with MEMS and wire.

transfer characteristics. Note that additional amplitude or phase control circuit is not employed in this work. The measured radiation patterns with proper reconfiguration control are shown in Fig. 7. During the measurement, the fabricated RAA system is automatically reconfigured by the control program on the user computer with the RCB on the RAA system. The maximum values of the measured radiation patterns displayed on Fig. 7 are normalized to 0 dBi. As shown in the figure, the radiation patterns for 850 MHz and 3.4 GHz show excellent results with symmetrical shape and about -30 dB lower cross polarization level at bore-sight direction. However, the radiation pattern for 1.9 GHz shows asymmetrical characteristics, which is resulting from gain and phase mismatches of the transfer functions of four signal paths, and further optimization would be necessary. The maximum gains of the fabricated RAA system, which do not include the gain of the RFA stage, are 12.5 dBi, 12.0 dBi,



(a) Mode 1

(b) Mode 2

(c) Mode 3

Figure 7. Measured radiation patters of the fabricated RAA system.

and 11.5 dBi for 850 MHz, 1.9 GHz, and 3.4 GHz, respectively. The measured radiation efficiencies are 85%, 69%, and 58% for each of frequency band. The 3 dB beamwidths of the measured radiation patterns are 56°, 60°, and 63° on the E-plane and 44°, 41°, and 42° on the H-plane for the three reconfiguration frequency bands. With the proper reconfiguration control, the RAA system rarely radiates the signal power at other frequency bands, since the RAEs radiate only at their own operating frequency and the input impedance of the RAE and the output impedance of the RFA are matched together only at one frequency. With the presented experimental results the concept of the proposed RAA system with the RFA and RMC is verified.

4. CONCLUSION

In this paper, a reconfigurable active array antenna (RAA) system, which can be reconfigured for three distinct frequency bands, is proposed. To realize the RAA system, reconfigurable matching circuit (RMC) and front-end amplifiers (RFA) are designed and implemented with the MEMS switches. The reconfiguration control method and the topology of the proposed RMC are quite simple, because only one switch control for a given desired frequency band is required to adjust two variables, the electrical length and the capacitance, simultaneously. Moreover, by employing the MEMS switches, the performance of the fabricated can be maximized in view of linear characteristics, one of the most important performance parameter of non-constant envelop communication scheme of nowadays like OFDM system. The proposed RAA system is composed of three 2×2 arrays of RAE having broadband dipole structure, a RCB for RFA and SP4T reconfiguration, and four RFA-SP4T boards. The RAA system is realized for Korean cellular communication system band (850 MHz), WCDMA band (1.9 GHz), as well as WiMAX band (3.4 GHz), and the proposed RAA system with the RFA and RMC is verified with the experimental results. The proposed reconfiguration concept as well as RMC with MEMS swithces are advantageous for the RFA and RAA design, and they can be also applied to other reconfigurable system designs.

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