Reconfigurable RF Circuits for Future Multi-Mode Multi-Band Mobile Terminals

Hiroshi Okazaki [1], Takayuki Furuta [2], Kunihiro Kawai [3], Yuta Takagi [4], Atsushi Fukuda [5], Shoichi Narahashi [6]

Research Laboratories, NTT DOCOMO, INC.
3-6, Hikarino-oka, Yokosuka, KANAGAWA 239-8536 JAPAN

[1] okazakih@nttdocomo.co.jp
[2] furutat@nttdocomo.co.jp
[3] kawaikun@nttdocomo.co.jp
[4] takagiyu@nttdocomo.co.jp
[5] fukudaat@nttdocomo.co.jp
[6] narahashi@nttdocomo.co.jp

***Abstract*—Reconfigurable radio frequency (RF) circuits will be a predominant solution for future global and compact mobile terminals, which supports 2G, 3G, and LTE cellular systems in various frequency bands. A single-path configuration and use of single-band devices with distributed reconfigurable matching networks have the potential to achieve the optimum RF front-end for future multi-band mobile terminals. Considering the difficulties in configuring a practical tunable band-pass filter as a top filter or duplexer, collaboration between the filter and low-noise amplifier (LNA) is a candidate to achieve the performance level required for the RF front-end. In addition, a power amplifier (PA) is also one of the key components in the RF front-end because its power consumption affects operating time of the terminal. This paper overviews the recent progress in our research on the reconfigurable LNA and PA. These RF circuits will contribute to the multi-mode band-free operation in future mobile terminals.**

I. Introduction

Having always-on access to other users and the Internet is becoming the standard modern lifestyle where mobile terminals play an important role. To be able to connect from anywhere, mobile terminals must have multi-mode and multi-band operation capabilities. Because the main specification for wireless systems is the frequency band, future mobile terminals will be expected to function in all the required frequency bands. Some reports indicate that the number of equipped frequency bands required for a global mobile terminal is 3-5 for the third generation (3G) cellular system and it will be increased to 7-9 in the Long Term Evolution (LTE) era. In other words, like a “band-free” mobile terminal will be expected. One of the key components is the band-free radio frequency (RF) front-end, which mainly consists of a power amplifier (PA), RF filter as a part of duplexer, and low noise amplifier (LNA). It would be of great benefit to develop technology that could make RF circuits band-free or at least available in various frequency bands. Mobile terminals are also required to be compact in terms of usability. Thus, development of compact multi-band radio frequency (RF) circuits is urgent [1], [2].

A tunable or reconfigurable technique is a solution for multi-band PAs and LNAs, and it seems to be the only solution for filters used in multi-band terminals. This paper introduces a reconfigurable LNA, concurrent multi-band amplifier, and reconfigurable multi-band PA as reconfigurable RF circuits.

II. Conventional Multi-Band RF Front-End

Figure 1 shows an example of RF front-end configuration for a multi-band mobile terminal based on a conventional scheme, which is selecting the most suitable circuit among several built-in circuits for each frequency band. The front-end consists of an RFIC, PAs, LNAs, filters, duplexers, and antenna switches. RFIC generally includes most of RF functions except PA and LNA, and may have transceivers for wireless LAN (“Wi-Fi” in the figure), Bluetooth (“BT”) and a receiver for GPS. The RF front-end in the figure can process 5 different frequency bands, and also have a diversity or 2-stream multiple-input and multiple-output (MIMO) receiving capability at 3 out of the 5 bands by using an additional receiver (“Sub RX”). However, this type of configuration will reach impasse for future mobile terminals, which should be required to handle more frequency bands and spatial streams for MIMO. For example, 9 bands and 4 streams require 36 receivers. The terminal will be bulky and high price.

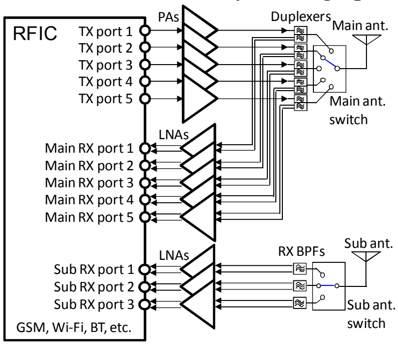

Fig. 1. An example of conventional RF front-end configuration of multi-band terminal for frequency-division duplexing systems

III. Single-Pass Configuration for Multi-Band RF Front-End

As shown in Fig. 2, a single-path configuration with multi-band circuits for each receiver and transmitter has the potential to achieve the optimum RF front-end for future multi-band mobile terminals. There are two ways of achieving such a multi-band circuit: broadband matching, and using variable or reconfigurable devices. However, broadband circuits seem to be inferior to a single-band circuit in terms of performance and they do not suit future band-free mobile terminals. This is because the mobile terminal faces constant requirement revisions focusing on minimizing the size and power consumption.

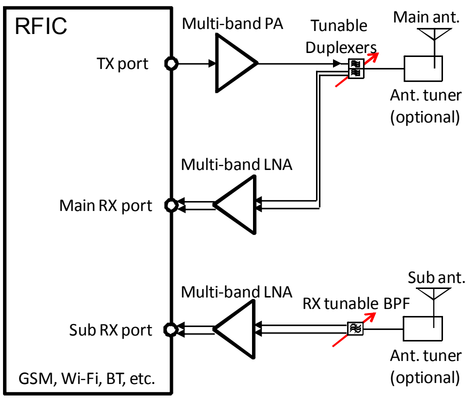

Fig. 2. A single-pass RF front-end configuration of multi-band terminal for frequency-division duplexing systems

IV. Reconfigurable LNA

It is a considerable challenge to attain a tunable band-pass filter with low-loss and a wide-tuning frequency range [3]. Considering a tunable filter as a part of duplexer, one of the serious problems for receivers is to generate gain and phase modulation caused by strong out-of-band signals. The LNA will be required to enhance its frequency selectivity in order to prevent the performance degradation from undesired out-of-band signals in a multi-band receiver that yields non-optimum RF filter performance.

To investigate the collaboration between the filter and LNA described above, the frequency response adjustment of the LNA will be a solution. Figure 3 shows a circuit diagram of the proposed reconfigurable amplifier [4]. The amplifier consists of a GaAs FET, input and output matching networks (MNs) with switches, and biasing networks with a high-impedance transmission line. The amplifier is designed based on a single-stub tuning scheme so that the circuit topology is simple. Each MN has transmission lines, shorted or open stubs, and four DC-contact cantilever type MEMS switches. All the chips and chip capacitors for biasing circuits are mounted on a 19 x 13 mm^2 printed-circuit board (PCB), as shown in Fig. 4.

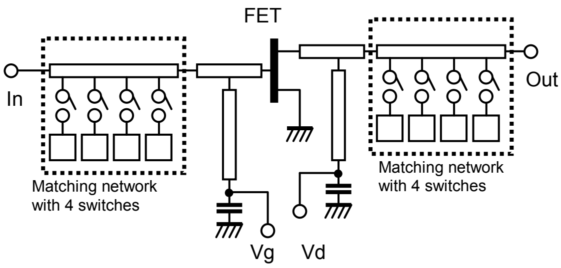

Fig. 3. Circuit diagram of reconfigurable amplifier

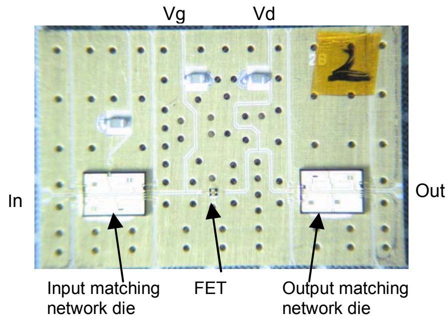

Fig. 4. Photograph of reconfigurable amplifier

Small signal frequency responses of the amplifier in two switch states (0 and 1) at a class A bias condition are shown in Fig. 5. S21 and S11 mean the gain and input reflection coefficient, respectively. At 2.0 GHz, the linear gain in states 0 and 1 are 9.3 dB and 5.8 dB, respectively. The input power of the 1-dB compression point of gain (IP_{1dB}) at the frequency of 2.0 GHz is 0.7 dBm, and 3.7 dBm, in states 0 and 1, respectively. At 3.1 GHz, the linear gain and IP_{1dB} in states 0 and 1 are 10.5 dB and 11.4 dB, and 1.8 dBm and -1.5 dBm, respectively.

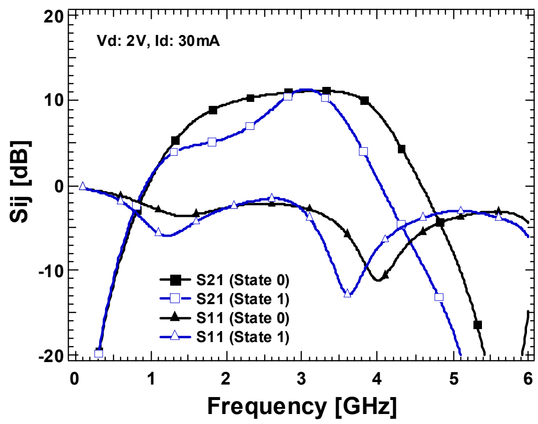

Fig. 5. Frequency response of the reconfigurable amplifier

Figure 6 shows the results of the gain suppression measurement at 3.1 GHz with out-of-band signals of 2 GHz. From the results above, the input power of 3.1 GHz for each state is set to -20.3 dBm, which lies in a linear region. In Fig. 6, “gain difference” and “gain diff. at 3.1-GHz,” correspond to the difference in gain at 3.1 GHz between with and without the 2.0-GHz signal input power indicated on the horizontal axis, respectively. The gain of the 2.0-GHz signal without the 3.1-GHz input is also shown for comparison. The gain suppression is observed at a higher level of 2.0-GHz input power, and is mitigated in state 1 even though state 1 exhibits a lower IP_{1dB} at 3.1 GHz than that for state 0. Thus, the proposed reconfigurable amplifier is effective in the gain suppression problem caused by out-of-band signals. The reason considered for this is that the gain degradation at 2 GHz occurs at a lower input level in state 0 because of the high 2.0-GHz gain.

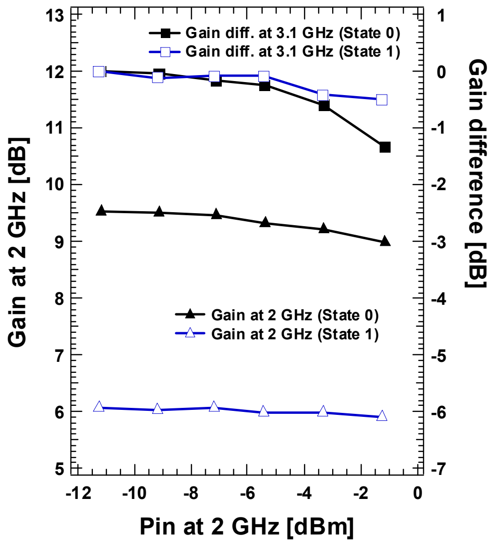

Fig. 6. Results of the gain suppression measurement

V. CONCURRENT MULTI-BAND AMPLIFIER

One candidate to obtain a wide operating band for future cellular systems is spectrum aggregation or carrier aggregation technology [5], which employs several bands aggregately and concurrently. One technical issue is configuring RF components with concurrent operation in multiple bands without increasing the circuit size significantly.

The proposed MN configuration for the concurrent multi-band amplifier is shown in Fig. 7. Detailed descriptions of the MN are shown in [6].

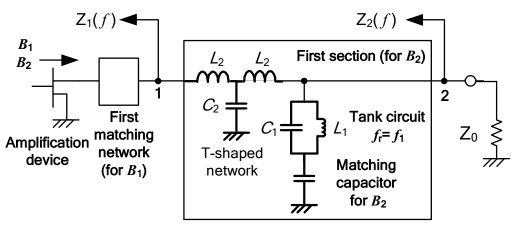

Fig. 7. Matching network configuration of concurrent multi-band amplifier

The 0.8-GHz/3.3-GHz single stage concurrent dual-band amplifier with the proposed MN is designed and fabricated. The size of the PCB is 50 x 60 mm^2. A GaAs MESFET is employed. The lumped components for multi-band matching networks are deployed on both sides of the transistor. A photograph of the fabricated concurrent dual-band amplifier is shown in Fig. 8. Figure 9 shows the measured small-signal frequency response. As shown in Fig. 9, the dual-band amplifier achieves a gain exceeding 13 dB and 9 dB in the 0.8-GHz and 3.3-GHz operating bands, respectively.

The results confirm that the proposed MN can be successfully operated in dual bands in a wide frequency range, such as 0.8-GHz and 3.3-GHz. Future research topic is to examine the feasibility of increasing the operating bands more than two bands and employing a multi-stage amplifier with an adequate gain.

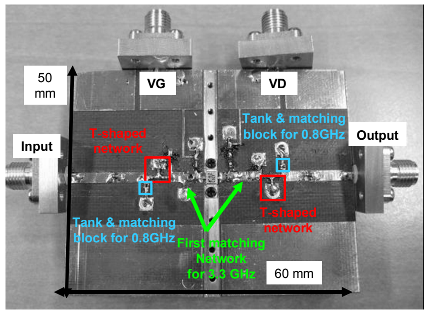

Fig. 8. Photograph of the concurrent dual-band amplifier

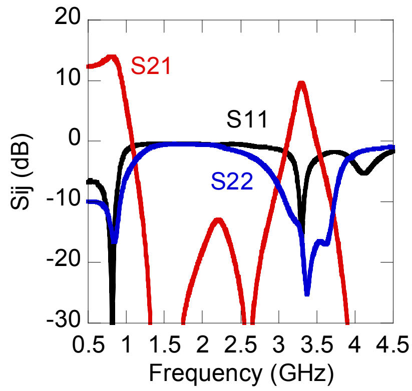

Fig. 9. Frequency response of the dual-band amplifier

VI. RECONFIGURABLE MULTI-BAND PA

The multi-band PA is a key component in mobile terminals. Reconfigurable PAs with band-switchable matching networks (MNs) have been investigated to provide 9-band operation from 0.7 GHz to 2.5 GHz, which covers almost all the uplink frequencies of cellular service worldwide [7]-[8]. A band-switchable MN can change its matching conditions by changing the state of its switches. One PA is integrated on a 35 x 110 mm^2 PCB [7] and the other is integrated on a 25 x 25 mm^2 multi-layer low temperature co-fired ceramic substrate [8]. However, there still remains the possibility for additional downsizing of the reconfigurable PA because the size is 3 or 4 mm square for current commercially available single band

PAs, and 5 or 6 mm square for a 2-in-1 style multi-band PA, which integrates a 0.8-0.9 GHz PA and a 1.8-1.9 GHz PA into a single package, for example.

One possible solution to minimize the size of the PA is to divide the nine bands into two groups, for example, three low bands and six high bands, and have two PAs covering each group. The high-band PA confines the covered frequency bands to 6 bands, i.e., 1.5, 1.7, 1.8, 1.9, 2.3, and 2.5 GHz. The prototype of the high-band PA [9] has a reconfigurable MN configuration similar to that for the 9-band PAs [7]-[8]. The PA prototype comprises 3 stages, as shown in Fig. 10. The input MN of the first stage (MN1) and the MN between the first and second stage (MN2) are designed to have broadband matching characteristics without switches. The band-switchable MNs are used in the MN between the second and third stage (MN3) and the output MN of the third stage (MN 4). Fig. 11 is a photograph of the high-band PA prototype on a 4-layered PCB. The size of the prototype PA is 6.2 x 8.05 mm^2. GaAs hetero-bipolar transistors (HBTs) are adopted. Three transistors at each stage are integrated into one chip, which downsizes the PA remarkably. The PA also employs InGaAs pseudomorphic high electron mobility transistor (pHEMT) switches in band-switchable MNs. In total, 12 switches are used in the PA, and they are integrated into 5 dies, as shown in Fig. 11. The MNs also use surface mount type chip capacitors. The bias feed lines of the switches are assigned to the intermediate layers of the PCB. The collector biases are fed through chip inductors. These points also aid in compacting the PA.

Figure 12 shows the frequency responses for 5 operation modes, i.e., the 1.5-GHz mode, 1.7-GHz mode, 1.8/1.9-GHz mode, 2.3-GHz mode, and 2.5-GHz mode. The gain exceeds 25.5 dB at the targeted frequency range in each operation mode. The input and output reflection characteristics are approximately -10 dB and -6 dB in all frequency bands.

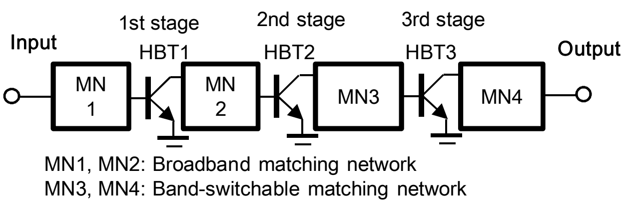

Fig. 10. Block diagram of the high-band PA

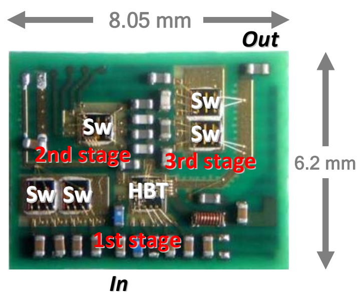

Fig. 11. Photograph of the high-band PA

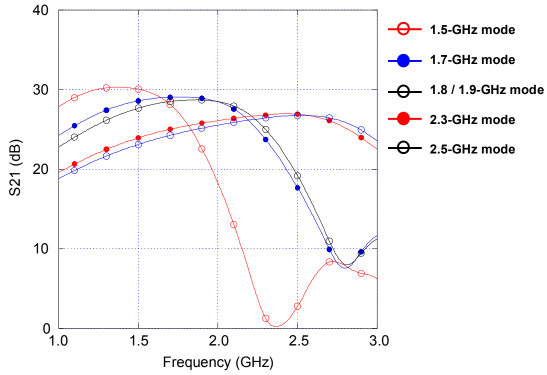

Fig. 12. Frequency response of the high-band PA

VII. Conclusion

This paper introduced recent results on our reconfigurable LNA, concurrent multi-band amplifier, and reconfigurable PA. There are still some issues to be solved to achieve reconfigurable RF front-end for future mobile terminals, such as detailed analysis on collaboration between filters and LNA, efficiency improvements of PA, and high-performance concurrent PA.

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