Multi-band | PA | Variable MN

Technology Reports

A PA for Mobile Terminals Supporting 9 Bands from 700 MHz to 2.5 GHz

Commercially available mobile terminals currently use separate single-band PAs for multi-band operation, which will cause increases in mobile terminal size and cost when more frequency bands are used near future. In solving these issues, NTT DOCOMO has developed a novel multi-band PA. It can support 9 bands, while providing the same gain, output power, and other characteristics as single-band PAs. Miniaturization and integration of the PA can be achieved by applying semiconductor switches to proposed variable input and output MNs that can be optimally designed for each band. The amplifier promises support for almost all mobile phone services such as LTE, W-CDMA and GSM both domestically and overseas, without an increase in mobile terminal size.

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1. Introduction

Whereas voice calls were the main application for mobile phones when they first entered service, as they become more popular, other non-call functions such as electronic money, digital cameras, and audiovisual playback have also been introduced. In spite of increased mobile phone functionality, consumers still want small and light terminals, and as a result, circuitry and components for implementing a range of functions are mounted in the confined space within mobile terminals [1].

In mobile terminals, Radio Frequency (RF) circuits[*1] are critical components. Currently, the FOMA service deployed by NTT DOCOMO uses three frequency bands; 800 MHz, 1.7 GHz and 2 GHz. Mobile terminals that support these bands require three separate RF circuits. In addition, another RF circuits are also required to support GSM [2]. This means there are size and cost impracticalities due to the separate RF circuits required for each band or systems for existing or emerging next-generation LTE[*2]. For this reason, we have been studying a single RF unit that can support a range of bands and systems (hereinafter referred to as “multi-band RF unit”).

A Power Amplifier (PA)[*3] is a key component of the multi-band RF unit design for mobile terminal. The PA converts the power supplied by a mobile terminal battery to RF signal power. However, because of the limited amount of power available from the battery, the PA must not only amplify the RF signal to the level required in each band, but also operate with high efficiency. The performance of the PA depends on the characteristics of the

*1 **RF circuit**: Individual circuits such as the PA (see *3) that handle RF signals, transmission/reception branching filters, or these as a whole. Transmission/reception branching filters are devices that separate and multiplex signals in different frequency bands.

*2 **LTE**: Extended standard for the 3G mobile communication system studied by 3GPP. It is equivalent to Super3G as proposed by NTT DOCOMO.

transistors (amplification devices) and Matching Networks (MNs)[*4]. It is especially important to include a low-loss "multi-band MN" configuration to optimize power efficiency for each band. Accordingly, a multi-band PA prototype with multi-band MNs was fabricated and evaluated [3][4].

This article describes the configuration of the band-switchable MN that is proposed for the multi-band MN and evaluates the band-switchable PA prototype with band-switchable MNs adopting semiconductor switches through 9 band operation. The results indicate that the specified target values for a mobile terminal PA have been achieved, thus confirming the suitability of the proposed multi-band MN configuration.

2. Multi-band PA

2.1 PA Configuration

The basic configuration of the PA is shown in **Figure 1**. The PA comprises transistors, input MNs, and output MNs. Here, the input and output MNs convert (match) the transistor input impedance Z_{in} and output impedance Z_{out} to the external circuit impedance Z_0 in individual bands, respectively. Importantly, the output MN is designed to achieve high Power Added Efficiency (PAE) while meeting requirements such as gain[*5], output power and adjacent channel leakage power[*6] based upon PA specifications. Here, PAE is an index used to evaluate the power efficiency and can be calculated using equation 1, where input power of the RF signal is P_{in}, output power of the RF signal is P_{out}, and the Direct-current (DC) power supplied from the battery or other power source is P_{DC}.

$$PAE = \frac{P_{out} - P_{in}}{P_{DC}} \tag{1}$$

2.2 Configuration of Multi-band PAs

Recent advances in semiconductor technologies have resulted in the commercialization of transistors that can amplify high frequency signals; however, conventional MN configurations and characteristics have been restricted to specific operation bands. In other words, an MN designed for a certain band does not mach in other bands. This is because the Z_{in} and Z_{out} for the transistors as shown in Fig. 1 varies depending on frequency, as do the characteristics of the MN. Accordingly, commercially available terminals are equipped with separate PAs in parallel to support each band [2]. However, with increases in emerging bands and bands for international roaming, the parallel PA configuration is not practical, because the size increases in proportion to the number of supported bands. To solve this issue, multi-band MNs have been considered. Multi-band MNs can share parts of the PA such as transistors and other necessary elements, which enables the construction of compact circuits. The proposed "band-switchable MN" can change the frequency response by controlling a small number of internal switches, thus optimizing the MN for each band [5].

2.3 Band-switchable MNs

The basic configuration of the band-switchable MN is shown in **Figure 2**. Fig. 2 shows the configuration of an output MN for N bands (bands b_1 to b_N, in this article, $N \geqq 3$; where N is an integer). If used as an input MN, the output MN is configured symmetrically with the transistor. Band-switchable MNs consist of the 1st MN for band b_1, a transmission line with a characteristic impedance of Z_0 matched with external circuit impedance of Z_0, and $(N-1)$ switches and $(N-1)$ matching blocks[*7].

The n-th MN is the MN for band b_n, and consists of the $(n-1)$-th MN, as

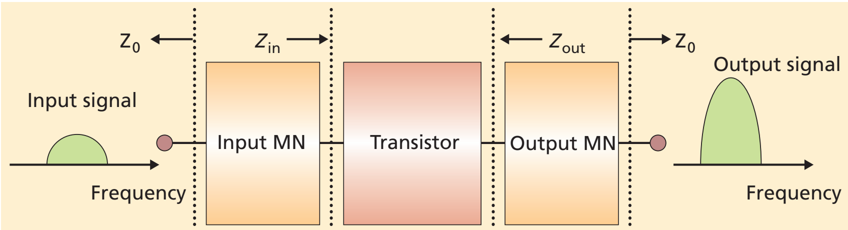

Figure 1 Basic configuration of PA

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*3 **PA**: Electronic circuitry to amplify a signal to the output power required for communications.

*4 **MN**: Prevents power loss due to reflection within the transmission path to maintain signal quality.

*5 **Gain**: The ratio of input power to output power (of an amplifier).

*6 **Adjacent channel leakage power**: The power that leaks to frequency bands adjacent to the transmission frequency band due to nonlinear distortion in the amplifier.

*7 **Matching block**: A single component or multi-component circuit used for matching. Part of the MN.

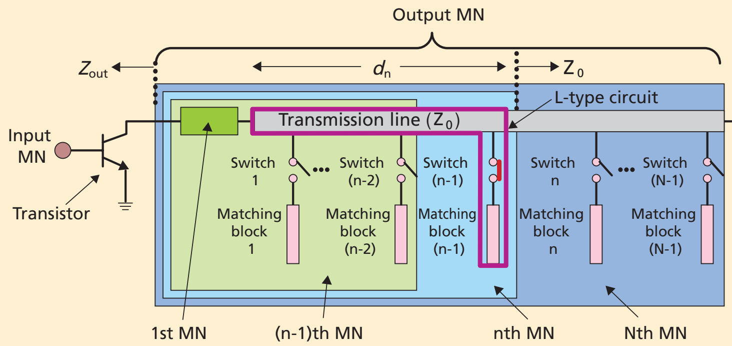

Figure 2 Basic configuration of band-switchable MN

well as (n−1)-th switch and (n−1)-th matching block connected to the transmission line. Here, n is configured to be ($2 \leqq n \leqq N$). Controlling these switches reconfigures the circuit and changes the characteristics of the MN. Additionally, since the number of available bands depends on combinations of switches and matching blocks, this design provides the flexibility to increase and decrease the numbers of bands.

The basic operation of band-switchable MNs and their design are explained below. To amplify the band b_1 signal, all switches are set to "off-state." To amplify the band b_n signal, (n−1)-th switch is set to "on-state" while other switches are set to "off-state." The transmission line length d_n and reactance[*8] value of the (n−1)-th matching block in Fig. 2 are designed to match for band b_n. As is shown in Fig. 2, an L-type circuit that comprises a transmission line and a matching block connected via a switch enables matching of any impedance to Z_0. This enables matching for band b_n. Here, the transmission line connecting the n-th MN and the load has a characteristic impedance of Z_0, and if the matching blocks connected via switches in the off state can be completely isolated from the circuit, then matching for band b_n can be maintained all the way to the load. Accordingly, the band-switchable MN as a whole operates as an MN for the band b_n. If n is equal to or greater than 3, the MN can be designed with one or several matching blocks connected via up to the (n-2) switches in the on state. Because all switches are connected in parallel to the transmission line, a low loss MN design can be achieved even though switches are inserted [6]. Additionally, independent design for multiple bands is possible. Furthermore, since the MN can provide transistors with the same matching conditions as conventional MNs in each band, this promises almost the same characteristics as single-band PAs that use the same transistors [6].

2.4 Previous Work

As well as investigating operation up to the 5 GHz band being considered for future mobile communication applications, the authors have been focusing attention on the characteristics of Micro Electro Mechanical Systems (MEMS) switches[*9] [7], and have been considering potential designs that aim for highly-efficient multi-band PA configurations using MEMS switches in band-switchable MNs [8]. However, the incorporation of MEMS switches in mobile terminals still poses issues in ensuring reliability, reducing the operating voltage and so forth. On the other hand, semiconductor switches[*10] have a proven track record as antenna switches. If limited to bands below 3 GHz, there are no practical problems with their electrical characteristics, and are expected to have good compatibility with multi-band PAs. Accordingly, using semiconductor switches instead of MEMS switches for applications below the 3 GHz band is currently more practical. For this reason the authors decided to consider semiconductor switches for the band-switchable MNs that have been under investigation for PAs designed to support the much larger total of 9 bands.

3. Design and Prototype

3.1 Design Requirements

A multi-band PA (**Photo 1**) has been designed and fabricated. Perfor-

*8 **Reactance**: The imaginary part of impedance in an AC circuit. Expressed in units of Ω.

*9 **MEMS switch**: A mechanical relay-type switch that is configured using MEMS technology.

*10 **Semiconductor switch**: Generic term for electronic switches that consist of transistors or diodes. Compared to mechanical switches, these have fast on/off response speeds, and no contacts that wear, giving advantages such as long life.

mance target values for the prototype are shown in **Table 1**. This supports a total of 9 bands from 700 MHz to 2.5 GHz that might be used in both domestic and overseas mobile communications systems including LTE, W-CDMA and GSM. A Heterojunction Bipolar Transistor (HBT)*11 was selected, because of its high-speed capabilities, its requirement for a single power supply only, and its high efficiency and low distortion characteristics. This design also has a gain of 30 dB or more, and in consideration of GSM, an output power of 33 to 35 dBm, with a target PAE of over 40%. Mobile terminal voltage restrictions mean this operates at 3.5 V.

Gallium Arsenide (GaAs)-Field Effect Transistor (FET)*12 switches are used for the semiconductor switches. There are several reasons for selecting GaAs-FET switches. In the operational frequency range (below 2.5 GHz), they satisfactorily balance low insertion loss*13 with high isolation*14 characteristics, their power handling capabilities support the target PA output (35 dBm or more), they have good compatibility with other components for integration in the PA, and they hold promise for future miniaturization.

The objectives of this prototype are to confirm the operation of the 9 band PA, obtain its basic characteristics, and to test the suitability of GaAs-FET switches for band-switchable MNs. Other characteristics required in a PA, such as in-band and out-band distortion, were not taken into account in this design.

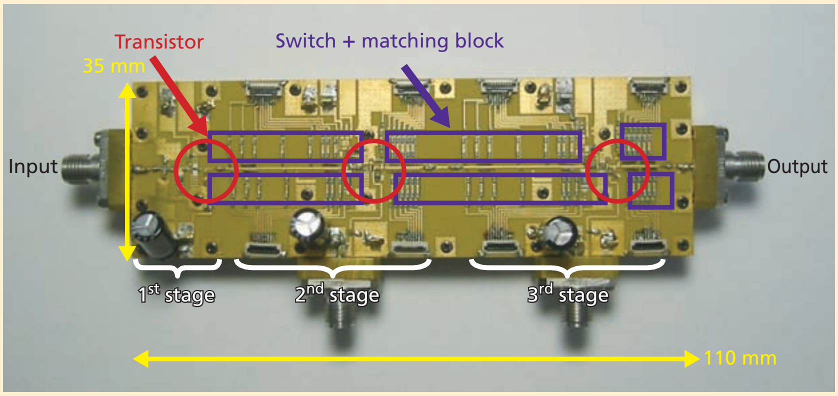

Photo 1 3-stage band-switchable PA with support for 9-bands

To achieve a gain of over 30 dB for each of the 9 bands, a 3-stage amplifier was configured for the prototype PA (**Figure 3**). Here, the third stage handles the maximum power, being supplied with large DC current, which has a significant impact on the PAE. Therefore, for the PA to operate efficiently, the third stage MN should be low loss and provide matching conditions optimized for each band to the transistors. However, while the first and second stages have only to provide the third stage with sufficient gain and power, their matching conditions are not as critical as those of the third stage. Accordingly, this can be used together with a broadband MN that has flat gain characteristics over a range of target bands. This prototype used a broadband MN for the first stage, and band-switchable MNs for the second and third stages, and each component value is configured so that the design of the second stage provides sufficient gain, while the third stage provides the target output power. For easy evaluation of the individual stages, the input and output impedance were each set to 50 Ω.

Table 1 Performance target values

Band (GHz)	0.7, 0.8, 0.9, 1.5, 1.7, 1.8, 1.9, 2.3, 2.5
Gain (dB)	≧ 30
Output power (dBm)	33-35
PAE (%)	≧ 40
Voltage (V)	3.5

3.2 Performance of GaAs-FET Switches

The basic characteristics of the GaAs-FET switches used in the prototype are shown in **Figure 4** and **5**. Fig. 4 shows insertion loss and isolation at different frequencies. As frequency rises, insertion loss and isolation characteristics degrade, which means that the limitations of GaAs-FET switches become a problem at high frequencies. The prototype PA achieved an insertion

*11 **HBT**: Transistor manufactured by bonding semiconductors with different structures. Component that controls current flowing into the collector depending on the flow of base current.

*12 **FET**: Component that controls current flowing into the drain depending on the voltage applied to the gate electrode.

*13 **Insertion loss**: Loss that occurs when a component is inserted into a circuit, and for switches, indicates the loss of signal when the switch is in the ON state.

*14 **Isolation**: Indicates the degree of signal separation, and for switches, indicates signal leakage when the switch is in the OFF state.

loss of below 0.6 dB, and isolation of over 12 dB up to the highest frequency band that is to be supported (2.5 GHz band). Fig. 5 shows the power handling characteristics for GaAs-FET switches, and illustrates the changes in insertion loss and isolation for input power with 2.5 GHz Continuous Wave (CW)[*15] input. Insertion loss and isolation for input power of below 35 dBm showed nearly constant values. In this input power range, insertion loss and isolation are not very dependent on input power, and it was confirmed that these can function well. Good power handling capabilities were also confirmed for input power of below 35 dBm in other frequencies.

As shown in Photo 1, the prototype band-switchable 3-stage PA that supports 9 bands incorporates 3 HBTs and multiple GaAs-FET switches on the printed circuit board.

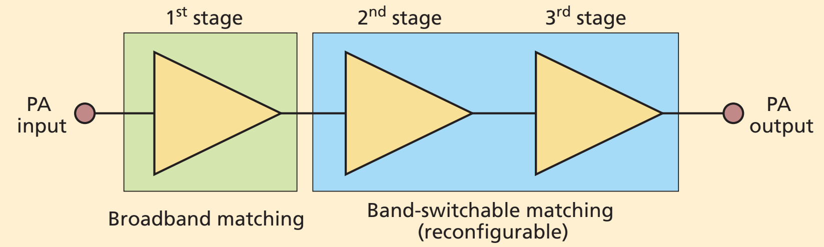

Figure 3 Configuration of 3-stage band-switchable PA with support for 9-bands

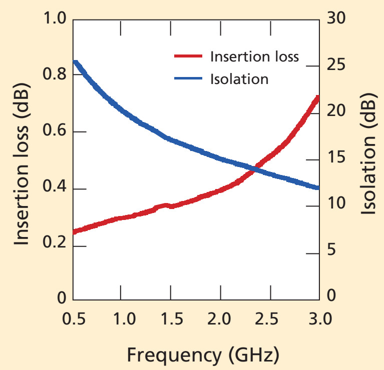

Figure 4 Frequency characteristics of GaAs-FET switches

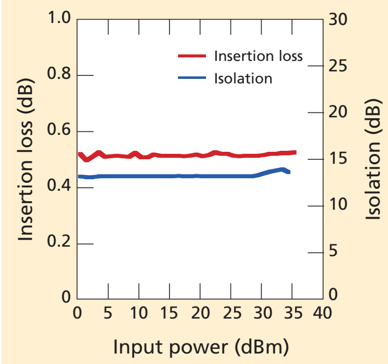

Figure 5 Power handling capability of GaAs-FET switches

4. Measurement Results

Measured frequency responses of the gain for the prototype PA are shown in **Figure 6**. Fig. 6 (A) to (H) correspond to the on/off status for switches for each band. Fig. 6 shows that the prototype multi-band PA achieved over 30 dB gain in all bands. Thus, by changing the on/off status of switches, the characteristics of the band-switchable MN can be adjusted for each band, and it has been confirmed that the target signal gain for each band can be achieved. The reason for the higher gain in lower rather than higher bands is that the gain for the transistors in each stage is higher in lower bands.

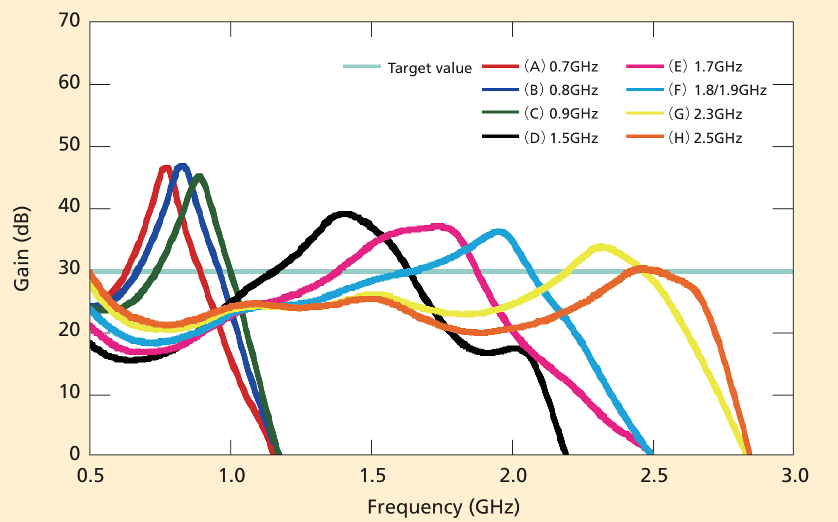

Figure 6 Gain for 3-stage band-switchable PA with support for 9-bands

*15 **CW**: A non-modulated high-frequency signal (sine wave).

Saturated output power[*16] and maximum PAE at several frequencies with CW input are shown in **Figure 7**. Fig. 7(a) shows the measured results for low band modes of 0.7/0.8/0.9 GHz, Fig. 7(b) for middle band modes of 1.5/1.7/1.8/1.9 GHz and Fig. 7(c) for high band modes of 2.3/2.5 GHz. Gain, saturated output power, and maximum PAE for each band are shown in **Table 2**. These measured results show that the design objectives are achievable, and confirm the feasibility of high power output, high efficiency multi-band PAs even with GaAs-FET semiconductor switches.

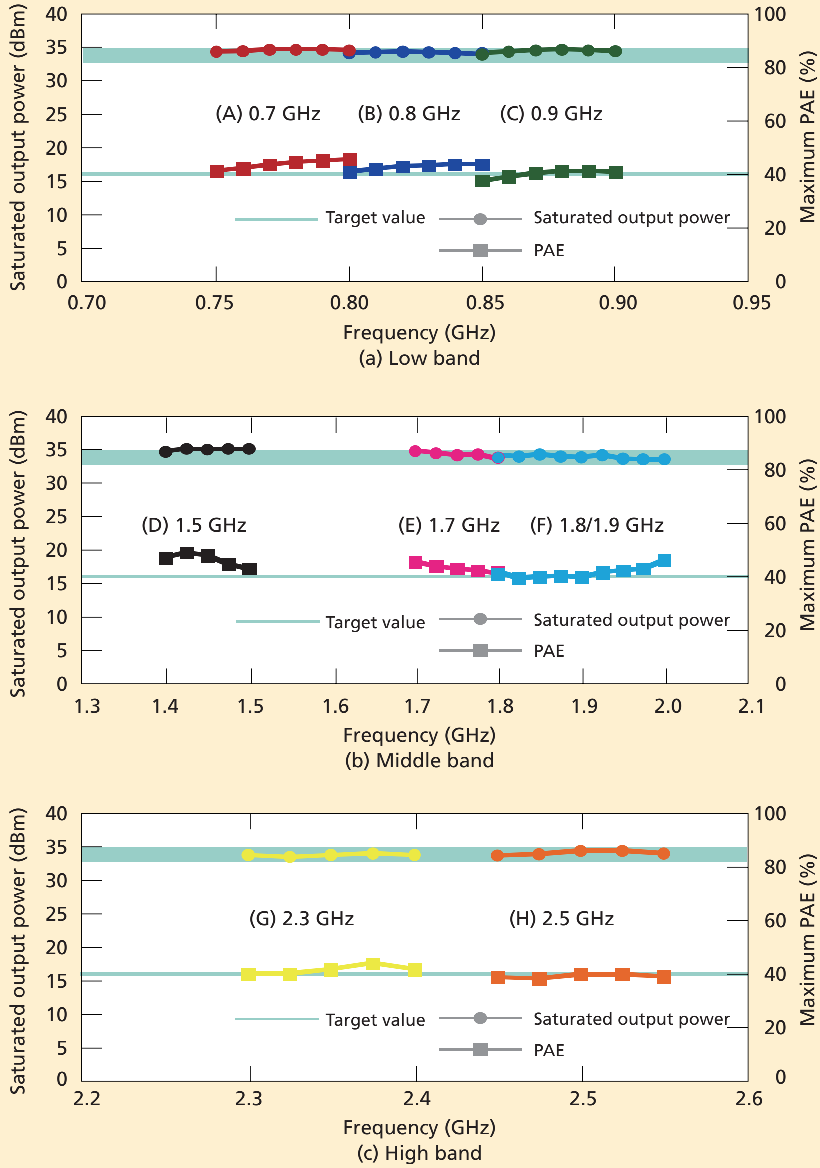

Figure 7 Saturated output power and maximum PAE

5. Conclusion

We have developed a technology that enables a single PA to support 9 bands, while attaining the same characteristics as the single-band PAs currently in use. This prototype multi-band PA has a reconfigurable MN, and controlling the PA frequency characteristics with GaAs-FET switches provides the desired characteristics for each band. As a result, we have achieved a gain of more than 30 dB and a maximum power output of more than 34 dBm over all 9 bands, and this experimental verification shows feasibility for device integration. This promises performance compatible with nearly all domestic and international mobile phone services such as LTE, W-CDMA, and GSM without increasing the PA size of mobile terminals. In the future, we plan to confront technical issues such as miniaturization and improved efficiency.

Table 2 Characteristics of 3-stage band-switchable PA with support for 9-bands

Band (GHz)	0.7	0.8	0.9	1.5	1.7	1.8	1.9	2.3	2.5
Gain (dB)	> 30	> 30	> 30	> 30	> 30	> 30	> 30	> 30	> 30
Output power (dBm)	34	34	34	35	34	34	34	34	34
PAE (%)	42	43	40	47	43	40	40	41	40

*16 **Saturated output power**: As input power increases in an amplifier, an output power at a point where it cannot increase any further.

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