New Technology Reports

# Band-Reconfigurable High-Efficiency Power Amplifier
## —900 MHz/1900 MHz Dual-Band PA Using MEMS Switches—

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*"Band-free radio frequency circuits" that can seamlessly operate among different wireless communication standards and spectra are being researched for future mobile services. As a part of this research, we have developed a prototype 900 MHz/1900 MHz dual-band power amplifier using MEMS switches.*

## 1. Introduction

Future mobile services will promote the conversion to broadband communications and a ubiquitous communications environment in which all kinds of devices and objects are interconnected and real space and virtual space interact. They are expected to facilitate the development of a "mobile ubiquitous" world, as shown in **Figure 1** [1]. In a ubiquitous world, all kinds of things ("ubiquitous devices" or simply "devices") will be interconnected as needed to form Ubiquitous Networks (UNs) that should arise frequently and simultaneously while changing continuously. Considering that various types of UNs should be able to coexist and intermingle, we can expect a system using radio waves (hereinafter referred to as "wireless system") to be the main means of connection in UNs.

In a mobile ubiquitous world, a Mobile Station (MS) will play the role of a gateway between the mobile network and UN. That is to say, connections between the MS and UN, and between the MS and mobile network will be achieved by radio waves. We can therefore envision a wireless system that possesses various sets of wireless transmission parameters (frequency band, bandwidth, modulation scheme, required signal-to-noise ratio, etc.) in accordance with device and user environments, and that can provide various means of connection simultaneously based on user demands or as controlled by the MS or network side.

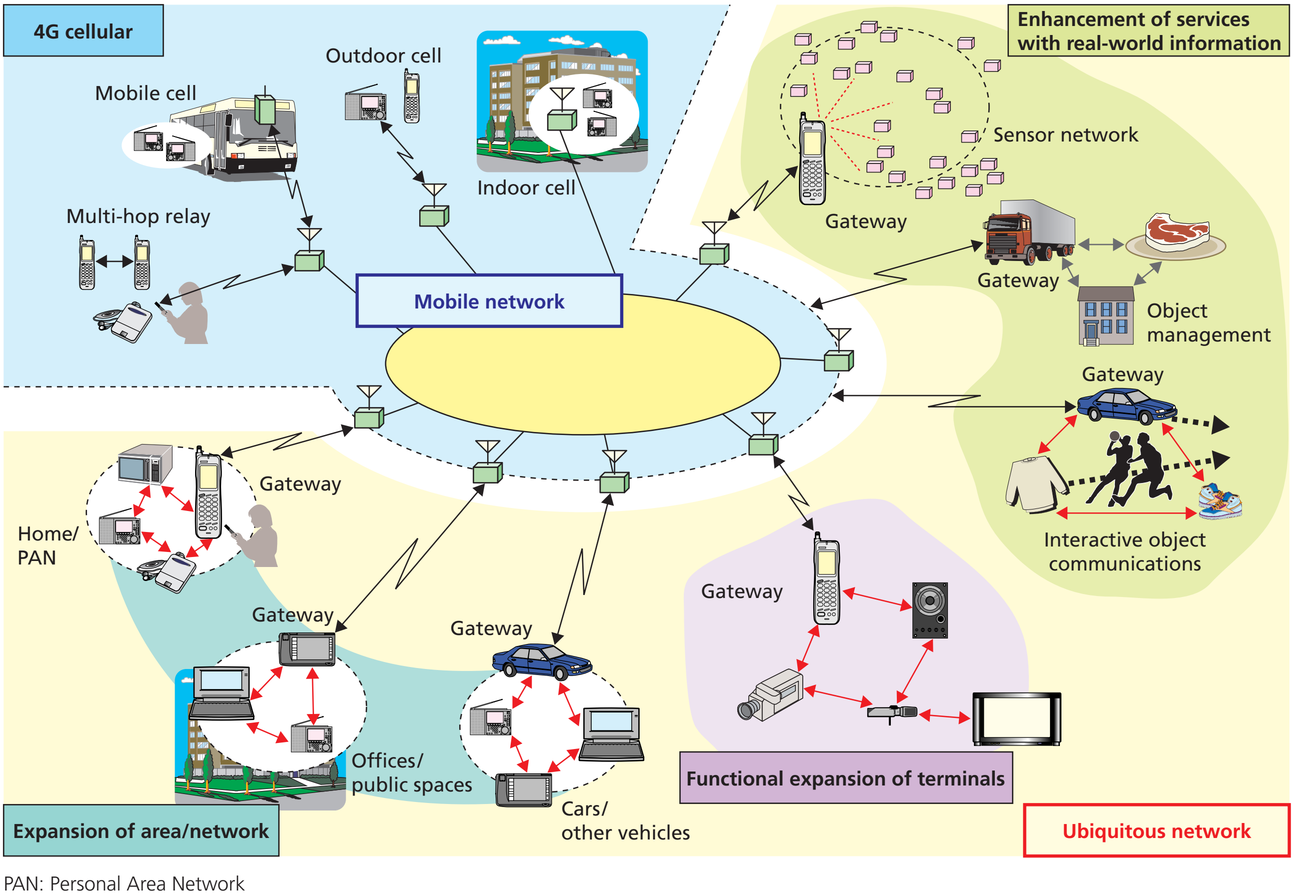



**Figure 1 Cooperation between mobile networks and ubiquitous networks**

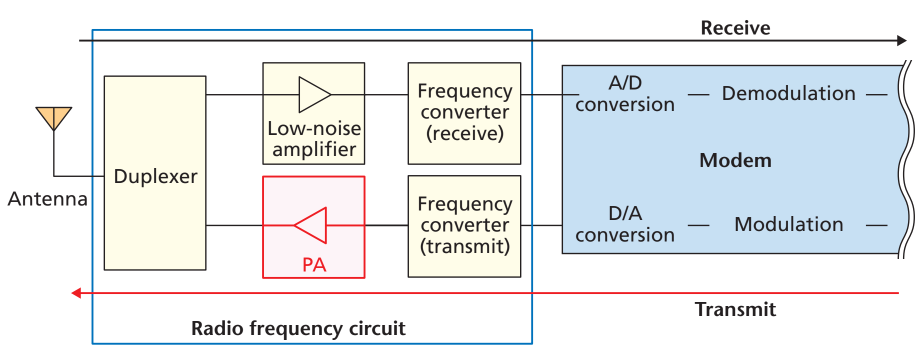



**Figure 2 Typical MS hardware configuration (section handling high-frequency signals)**

A Radio Frequency (RF) circuit is an essential element of an MS. **Figure 2** shows a typical hardware configuration of an MS from the antenna to the modem section. Here, the term "RF circuit" can be applied to individual circuits like the Power Amplifier (PA) and transmit-receive duplexer that handle high-frequency signals or to all of these circuits combined. In the past, we developed and implemented specialized RF circuits for specific wireless systems such as Freedom Of Mobile multimedia Access (FOMA). This is because it was necessary to make RF circuits as compact and power saving as possible in conjunction with their individual requirements that must satisfy a specific set of wireless transmission parameters determined by the specifications of the wireless system.

Future MSs will operate in a wireless environment in which a variety of wireless systems coexist and intermingle, and they will be expected to be available for all of those systems. In other words, the wireless transmission parameters of all the wireless systems in the environment will have to be satisfied, and MSs and therefore RF circuits will have to support all kinds of wireless environments.

The main wireless transmission parameter of wireless systems has been frequency band. We have been researching "band-free RF circuits" that can be used at all frequency bands, and have undertaken, in particular, the development of RF circuits that can be used at multiple frequency bands (multi-band RF circuits). It is difficult for a PA, a key device of an RF circuit, to operate at multiple frequency bands with adequate performance. It would therefore be of great benefit to develop technology that could solve this problem. We proposed a band-switchable Matching Network (MN) that would enable a PA to work well at multiple frequency bands [2].

This article outlines the configuration and features of a high-efficiency PA equipped with band-switchable MNs, and describes a prototype 900 MHz/1900 MHz dual-band PA using Micro-Electro Mechanical Systems (MEMS) switches based on the proposed configuration.

## 2. Achieving a Multi-Band PA

### 2.1 PA

As shown in Fig. 2, the role of the PA is to amplify a high-frequency signal from the frequency converter up to the power level required by the wireless system, and the amplified signal is fed to the antenna via the duplexer. The power consumed by the PA is more than that of consumed by the other RF circuits in most cases. As a result, the amount of required current for the PA is large as the amount of generated heat if the efficiency of the PA is low. Thus, the PA should be operated at high efficiency while satisfying the requirements specified by the wireless system for wireless transmission parameters like output power to achieve long battery operation and the compact MS.

**Figure 3** shows the basic configuration of a PA. The input MN is a circuit that matches transistor input impedance $Z_{in}$ with signal-source impedance $Z_0$. Similarly, the output MN is a circuit that matches transistor output impedance $Z_{out}$ with load impedance $Z_0$. Each of these MNs is designed under the following guidelines taking into account the requirements that must be satisfied and the performance that must be optimized by the PA.

- Maximize output power
- Minimize distortion
- Maximize Power Added Efficiency (PAE)

Here, PAE is a measure of efficiency given by the following expression where $P_{in}$ is RF input power of the PA, $P_{out}$ is RF output power of the PA, and $P_{dc}$ is the Direct Current (DC) power supplied to the PA.

$$\mathrm{PAE} = \frac{P_{out} - P_{in}}{P_{dc}}$$

In the above, PAE depends on the performance of the transistor adopted and the matching conditions for termination. An appropriate MN design is therefore important for configuring a high-efficiency PA that exploits the transistor's maximum performance.

### 2.2 Multi-Band PA

The transistor's $Z_{in}$ and $Z_{out}$ change according to frequency. Thus, even if the MNs are designed to maximize PAE with desired output power at a certain frequency, it will not be possible to maximize PAE at another frequency, and in many cases, it will not even be possible to obtain desired output power. This frequency dependence has made it difficult to develop a multi-band high-efficiency PA.

Various ways of achieving a multi-band amplifier have been studied. **Figure 4** shows typical methods for configuring a multi-band amplifier based on these studies. First, Fig. 4 (a)

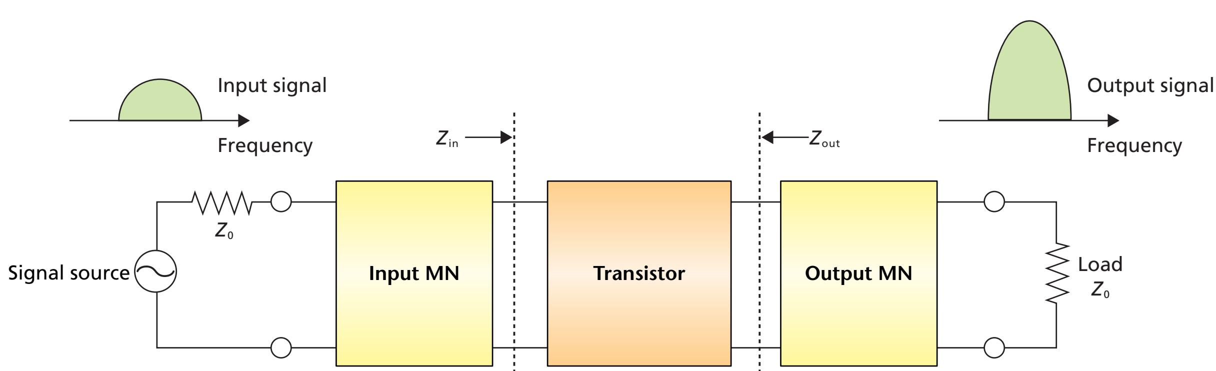



Figure 3 PA basic configuration

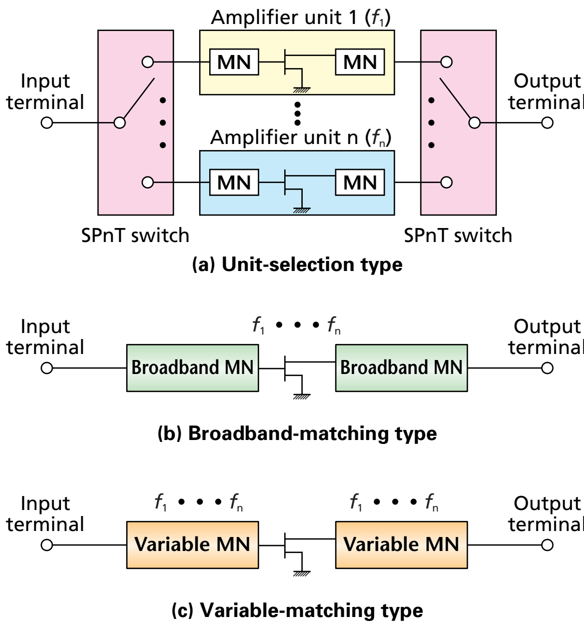



**Figure 4 Typical multi-band PA configurations**

shows a "unit-selection type" [3] of multi-band amplifier that is equipped with a set of amplifier units each corresponding to a different frequency band. A particular amplifier unit is selected by means of a Single-Pole-n-Throw (SPnT) switch that connects the input and output terminals of that unit. This type of configuration achieves a high-efficiency multi-band PA by preparing each amplifier unit as a high-efficiency PA designed especially for a particular frequency band. The design of each unit is the same as that of a single-band PA and is therefore considered simple to achieve. However, circuit scale increases in proportion to the number of frequency bands needed. It often happens that low insertion loss and sufficient isolation cannot be obtained in an SPnT switch at microwave frequencies and higher. Even for a set of high-efficiency PA units, the loss especially on the output side makes it difficult to achieve high-efficiency operation for a multi-band PA on the whole. Next, Fig. 4 (b) shows a "broadband-matching type" [4] of multi-band amplifier. In this case, the MNs are configured so that the amplifier has flat frequency response among all of the required frequency bands ($f_1$, $f_2$, ..., $f_n$). However, a high-output, high-efficiency PA design is difficult when the upper and lower limits of the required frequency bands are farther apart. Finally, the "variable-matching type" [5] of multi-band amplifier shown in Fig. 4 (c) consists of a single amplification device such as a Field Effect Transistor (FET) and variable MNs whose circuit constants can be changed. This type can be designed for various frequency bands as in the unit-selection type, which means that a high-power, high-efficiency PA design can be easily achieved even if the required number of bands increases. That is to say, the variable-matching type can eliminate redundant sections in the circuit and can achieve a smaller configuration than the unit-selection type. It does, however, require a low-loss variable device to provide a means of changing circuit constants. Variable devices such as the varactor diode currently used for microwave circuits suffer from high loss and cause distortion. **Table 1** compares the above configuration methods in terms of ease of design, circuit scale, and efficiency.

**Table 1 Comparison of multi-band PA configurations**

| Configuration | Ease of design | Circuit scale | Efficiency |
|---|---|---|---|
| Unit-selection type | ○ | △ | ○ (Low-loss switch required) |
| Broadband-matching type | △ | ◎ | △ |
| Variable-matching type | ○ | ◎ | ○ (Low-loss variable device required) |

## 3. Band-Switchable PA

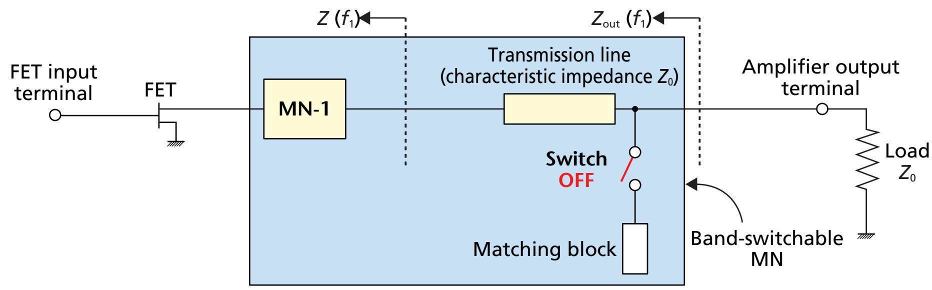
### 3.1 Configuration of Band-Switchable PA

From above, we focus on the variable-matching type of multi-band PA as a configuration that shows promise for achieving a future band-free PA, and propose a band-switchable MN and a PA using that MN (band-switchable PA) [2]. The following describes the operation principle and characteristics of the proposed configuration.

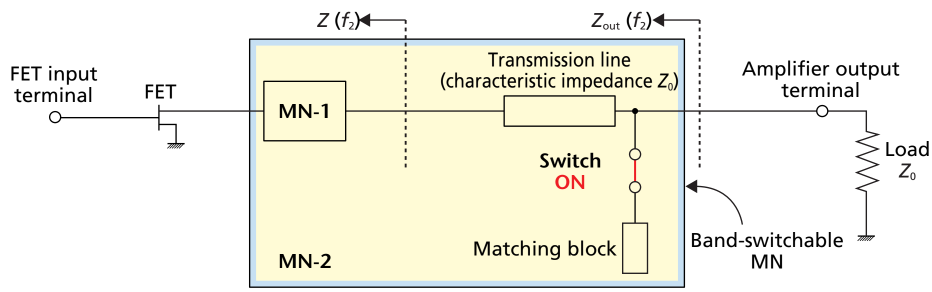
### 3.2 Operation Principle of Band-Switchable MN

A band-switchable MN can be designed for various frequency bands to provide multi-band operation. The basic operation of a band-switchable MN when used as an output MN in the case of dual-band switching is described in the following. The same operation principle applies when using a band-switchable MN as an input MN.

**Figure 5** shows the configuration and operation principle of this band-switchable MN. The band-switchable MN consists of MN-1, a transmission line with equivalent characteristic impedance $Z_0$, a switch, and a matching block, as shown in Fig. 5 (a). MN-2 consists of the same elements, as shown in Fig. 5 (b). In these figures, $Z(f)$ and $Z_{out}(f)$ are output impedances at MN-1 and the amplifier output terminal, respectively, at frequency band $f$. Here, MN-1 is an MN for a signal of frequency band $f_1$, and it is



(a) Matching at frequency $f_1$



(b) Matching at frequency $f_2$

**Figure 5 Configuration and operation principle of band-switchable MN**

designed so that $Z(f_1)$ matches impedance $Z_0$. The characteristic impedance of the transmission line connected to MN-1 is $Z_0$. If the matching block will be completely separated by setting the switch to OFF state, as shown in Fig. 5 (a), output impedance $Z_{out}(f_1)$ at the amplifier output terminal will maintain the impedance $Z_0$, which matches load impedance $Z_0$. At this time, the band-switchable MN operates as an MN for a signal of frequency band $f_1$. However as pointed out earlier, the input/output impedance of the FET generally changes with frequency. As a result, output impedance $Z(f_2)$ of MN-1 for a signal of frequency band $f_2$ will not match $Z_0$ as long as $f_2$ is fairly apart from $f_1$. For this reason, the proposed band-switchable MN sets the switch to ON state to connect the matching block to the transmission line as shown in Fig. 5 (b). If the electrical length of the transmission line and the reactance of the matching block are appropriately set, $Z_{out}(f_2)$ can be made to match target load impedance $Z_0$ for any $Z(f_2)$. In short, the band-switchable MN can be designed so that $Z_{out}(f)$ matches load impedance $Z_0$ even for a signal of frequency band $f_2$. The band-switchable MN shown in Fig. 5 can be extended in the same way to a multi-band configuration.

**Figure 6** shows the circuit diagram of a multi-band band-switchable PA using band-switchable MNs extended to n bands (n: a natural number equal to 3 or greater). This PA can amplify each signal of the desired frequency band. When amplifying a signal of frequency band $f_i$, for example, switch (i–1) is set to ON state and all other switches are set to OFF state (with the exception of i=1, in which case all switches are set to OFF state). The number of required switches for an n-band PA is (n–1) on the input side and (n–1) on the output side for a total of 2(n–1) switches. If using switches having ideal characteristics (meaning that signals are transmitted without loss in the ON state and that the path is completely cut off in the OFF state), the characteristics of the band-switchable PA at each frequency band should be nearly the same as a single-band PA using the same amplification device. If appropriate MNs for the target frequency bands are being used, the amplification device can be used for high-efficiency amplification at various frequency bands because it generally has wide-band amplification characteristics. In other words, we can expect a band-switchable PA to be capable of high-efficiency operation over a wide range of frequencies.

### 3.3 Effects of Switch Characteristics

Controlling the state (ON or OFF) of the switches in the above band-switchable MN changes the band for amplifying signals of the band-switchable PA. The characteristics of a real switch, however, are not ideal, and its insertion loss and isolation characteristics will affect the amount of loss caused by the band-switchable configuration. In particular, for the multi-band band-switchable MN of Fig. 6, the number of OFF-state switches increases for a larger number of operating frequency bands. We estimated the amount of additional loss caused in a multi-band band-switchable configuration for switch isolation charac-

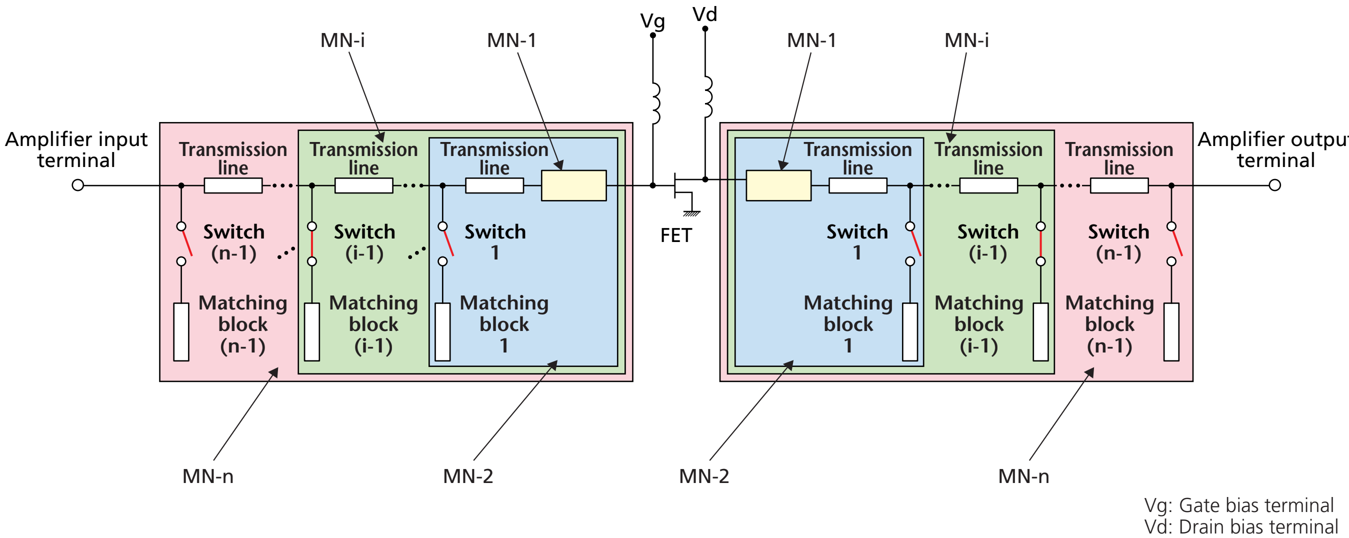



**Figure 6  Multi-band band-switchable PA**

teristics [6]. For example, for 10 bands and isolation characteristics of about 30 dB, the amount of loss caused by OFF-state switches in the band-switchable MNs was sufficiently small at under 0.1 dB.

Because a switch in the ON state operates as part of an MN, the insertion loss in that state causes the loss of that MN. It is therefore desirable that the insertion loss of an ON-state switch be small. For the configuration of Fig. 6, switches are connected in parallel to the signal path, which makes it easier to reduce power loss due to switch insertion loss compared to switches connected in series with the signal path. Furthermore, as shown in Section 3.2, only switch (i–1) will be in the ON state when amplifying a signal of frequency $f_i$ (for i≥2), which means that the effect of switch insertion loss on the loss of a band-switchable MN is independent of the number of operating frequency bands.

### 3.4 Features of Proposed Configuration

As explained in Section 3.3, the PA based on the proposed configuration can change its operating frequency band with high efficiency by a simple method of controlling the ON/OFF state of switches. And as an additional benefit, the parallel connection of switches to the signal path in this configuration can minimize the effects of switch insertion loss. The simplicity of the circuit configuration and its high-efficiency operation makes it relatively easy to expand to a multi-band configuration in terms of both performance and circuit scale. Finally, an increase in the number of operating frequency bands should affect output power and PAE by only a little.

### 3.5 Applying MEMS Switches to the Proposed Configuration

To maximize the potential of the proposed PA configuration, switches that can exhibit both low loss and high isolation across a wide band are required. One such switch now being researched and developed is the MEMS switch that uses micromachining technology [7]. This switch can be achieved at a size less than several millimeters square including the actuator of a mechanical relay-type switch. Prior to this study, however, there had been no reports of applying MEMS switches to a high-efficiency PA of the 1 W-class or higher even for a unit-selection type of PA. Therefore we first verified that MEMS switches of the electrostatic-drive type that consume little power [8] would not present any problems in terms of high-frequency characteristics including power handling capability, and then decided to apply them to the proposed PA configuration.

## 4. Design and Prototype of a Dual-Band PA

### 4.1 Prototype 900 MHz/1900 MHz Dual-Band PA

To verify the feasibility of the proposed band-switchable PA, a 900 MHz/1900 MHz dual-band PA were designed and prototyped as shown in **Photo 1**. These 1900-MHz and 900-MHz bands correspond to $f_1$ and $f_2$, respectively, in Fig. 5. Here, MN-1 was configured with a transmission line and an open-stub, and an FET having output power of the 1 W-class (30 dBm) was used as the amplification device. The MEMS switch used here featured an insertion loss of 0.4 dB or less and an isolation of 30 dB or greater.

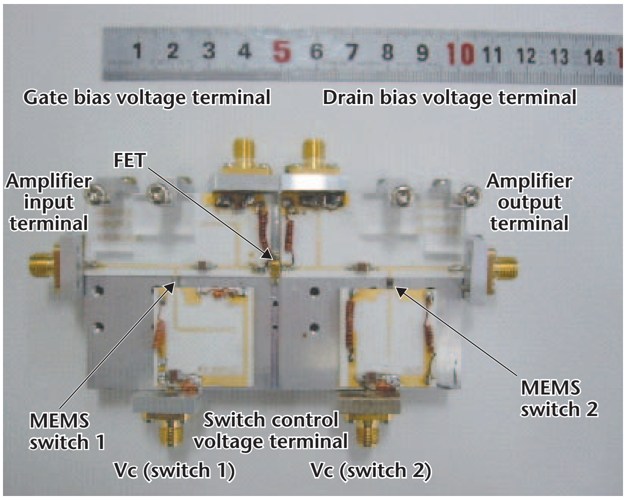



Photo 1 Prototype 900 MHz/1900 MHz dual-band PA

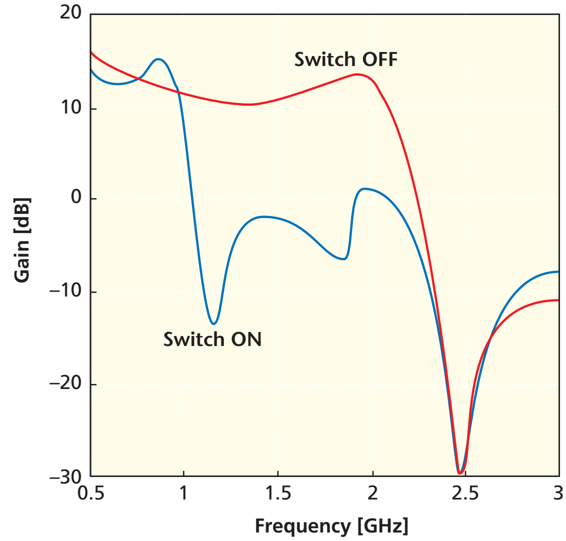
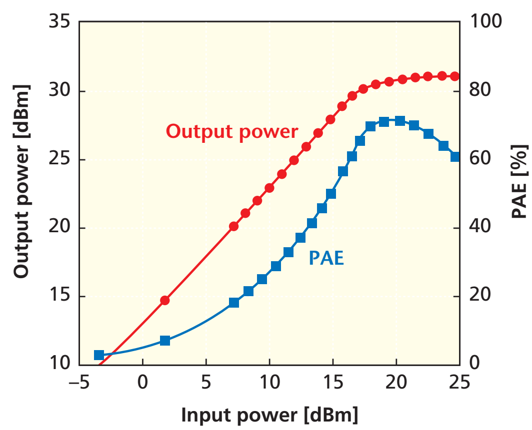



Figure 7 Gain vs. frequency for ON and OFF switch states

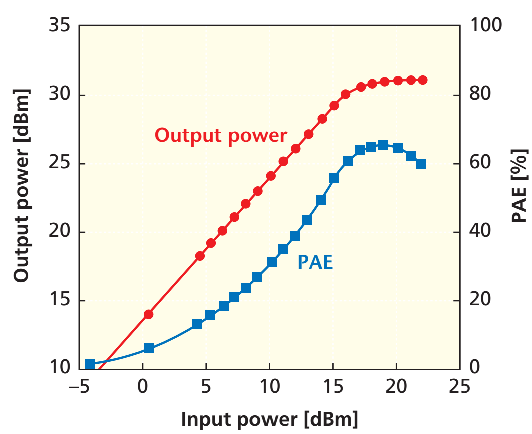
### 4.2 Evaluation of Dual-Band PA

**Figure 7** shows measured frequency responses of gain for ON and OFF switch states in the prototype dual-band PA. Desirable gain is obtained in the 900-MHz band for the ON state and in the 1900-MHz band for the OFF state. This means that controlling the state of the switch successively changes the frequency response of the PA.

**Figure 8** shows input/output characteristics of the PA in each of these frequency bands. A maximum PAE of 67% and output power of 30.4 dBm was obtained at a frequency of 875 MHz, while a maximum PAE of 63% and output power of 31.5 dBm was obtained at a frequency of 1875 MHz. In other words, output power greater than 1 W and a maximum PAE greater than 60% was obtained for both frequency bands. The results showed that high-output and high-efficiency operation equivalent to that of a single-band PA could be achieved by this prototype dual-band PA.




(a) Measurement frequency: 875 MHz




(b) Measurement frequency: 1875 MHz

Figure 8 Input/output characteristics

## 5. Conclusion

The mobile ubiquitous world will require band-free RF circuits that can support the use of a variety of frequency bands. As part of the research for band-free RF circuits, the configuration and characteristics of a newly proposed band-switchable PA as a multi-band high-efficiency PA was described. A prototype dual-band PA, despite its simple configuration, could achieve high-output and high-efficiency operation in each band by changing its characteristics through simple switch control. We plan to continue our studies on transforming high-efficiency PAs into multi-band and high-frequency devices toward the attainment of band-free PAs while investigating various issues in relation to MEMS switches, which are devices still under development.

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## Abbreviations

DC: Direct Current
FET: Field Effect Transistor
FOMA: Freedom Of Mobile multimedia Access
MEMS: Micro-Electro Mechanical Systems
MN: Matching Network
MS: Mobile Station
PA: Power Amplifier
PAE: Power Added Efficiency
PAN: Personal Area Network
RF: Radio Frequency
SPnT: Single-Pole-n-Throw
UN: Ubiquitous Network