Technology Reports

Power Amplifier for Broadband Applications Beyond the Third- Generation —Multi-band, High-efficiency Power Amplifier Using MEMS Switches for Mobile Terminals—

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Research is currently underway on a high-performance power amplifier able to accommodate a wide range of frequency bands. This article describes the design and development of a multi-band, high-efficiency power amplifier using a band-switchable matching network that is capable of operation over a wide range of frequencies up to 5 GHz, and the prototype of a quad-band power amplifier for the 0.9-, 1.5-, 2- and 5-GHz bands.

1. Introduction

Mobile communications services in the future will be expected to accelerate a ubiquitous environment where everything is interconnected and real and virtual spaces are linked, thus helping to develop a world of ubiquitous mobile communications. The Mobile Station (MS) providing this type of service will be required to function as gateways connecting mobile networks and ubiquitous networks [1]. MSs and mobile networks will be connected by radio waves.

Radio frequency (RF) circuits are an essential element in the MS that uses radio waves. Here, an RF circuit is the circuit placed between the antenna and the modulator-demodulator section, for example, the individual circuits handling high-frequency signals such as a Power Amplifier (PA), or the entirety of all such circuits.

The PA is a key device in an RF circuits, taking the weak high-frequency signals from the frequency converter, amplifying these signals to the level of power necessary for the radio system, and supplying these signals to the antenna via a duplexer. Since the power consumption of the PA is often greater than that of other RF circuits, large currents are required, with considerable levels of heat dissipation and required current flow. Particularly when reducing MS power consumption, high-efficiency PA operation is an important characteristic to be optimized under the system conditions to be satisfied (such as output power). However, improving the bandwidth and implementing multi-band operation in a single PA while maintaining high-efficiency characteristics have proven difficult. The authors have proposed a method of configuring a multi-band PA in which PA frequency characteristics are switched using switches within a Matching Network (MN), and reported high output power of 1W or greater and high-efficiency operation (60% or greater) in the 0.9- and 1.9-GHz bands [2]. This article describes the addition of a simple adjustment point to achieve a reduction in MN size while permitting band-switching across a wide frequency range, expansion of the PA's operating frequency band to the 5-GHz band, and the design, trial manufacture, and evaluation of a multi-band PA able to accommodate a frequency band of 0.9 to 5 GHz wider than that previously proposed [2].

2. Multi-band PA Implementation

2.1 PA Design

Figure 1 shows the basic configuration of the PA. Here, the input MN is a circuit in which transistor input impedance Z_{in} is matched to signal source impedance Z_0. The output MN is a circuit in which transistor output impedance Z_{out} is matched to load impedance Z_0. In general, each MN is designed in accordance with the following guidelines and in consideration of the conditions the PA is required to satisfy, and the desired optimized performance.

- Maximization of output power
- Power leakage to adjacent channels within standards
- Maximization of Power Added Efficiency (PAE)

PAE is a measure of PA efficiency obtained with the equation below. Here, PA input power is assumed as P_{in}, output power as P_{out}, and the DC power supplied to the PA as P_{dc}.

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

The efficiency of the PA varies depending on the unique performance of the transistor used and the associated matching conditions. Moreover, as the frequency of the signals handled becomes higher, transistor gain is diminished, and since circuit loss also tends to increase, it is essential to configure a low-loss MN. Deterioration in PAE due to loss in the output MN is particularly severe. **Figure 2** shows an example of the relationship between output MN loss and PAE. PA gain is computed as 5 dB. When the MN is loss-free, the PAE obtained is 60%, though this deteriorates to 42% with MN loss of 1dB. A low-

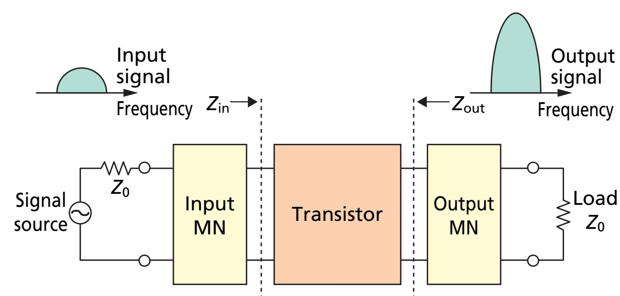

Figure 1 Basic PA configuration

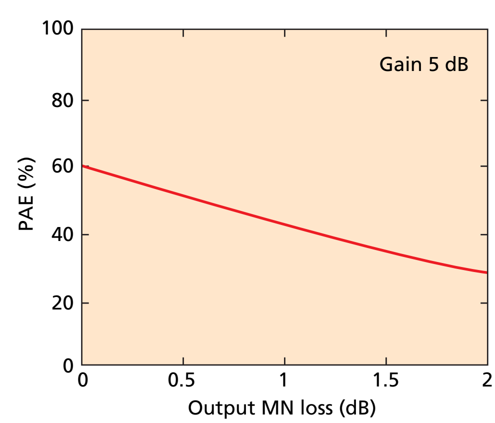

Figure 2 PAE versus output MN loss (example)

loss MN providing the optimum matching conditions for the transistor is therefore necessary to extract the maximum performance from the transistor and provide a PA of high efficiency.

2.2 Implementation of a Multi-band PA

Since transistor Z_{in} and Z_{out} vary with frequency, as do the MN characteristics, when the MN is designed to maximize PAE at the desired output power for a particular frequency band, the same operation may not be obtained at other frequencies, and in many cases the desired output power will not be obtained. The establishment of a multi-band PA therefore requires a configuration to provide the optimum matching conditions for the amplification device in each frequency band. A number of methods are being considered for this purpose [2].

As shown in **Figure 3**, one method of implementing a multi-band PA employs the configuration of a discrete amplification device such as a Field Effect Transistor (FET)[*1] and a variable MN for which the circuit constant can be changed.

In general, the amplification device has wide-band amplification characteristics, and when a MN suited to the desired frequency band is used, the frequency range over which the PA can operate with high efficiency is considerable. The authors have proposed a band-switchable MN that incorporates switches so that the frequency characteristics of the MN may be switched in response to the frequency band [3].

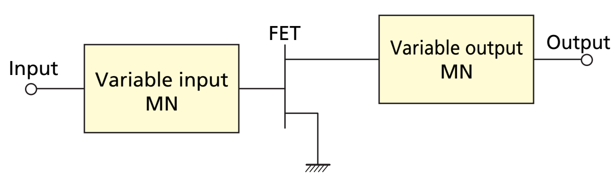

Figure 3 Configuration of a multi-band PA using variable MN

3. A Band-switchable PA

The principles and characteristics of a multi-band PA using a band-switchable MN (band-switchable PA) are described below.

3.1 Operation Principles of Band-switchable MN

Figure 4 shows the configuration of the band-switchable MN. For the sake of simplified explanation, an example is given in which the basic operation of the output MN accommodates only two bands. Operation is the same for the input MN. The band-switchable MN is comprised of the first MN, a transmission line having characteristic impedance Z_0 equal to load impedance Z_0, a switch, and a matching block[*2]. As shown in Fig. 4(b), the second MN is comprised of all the above components. $Z_1(f)$ and $Z_2(f)$ are the output impedance of the first and second MN, respectively, and $Z_{out}(f)$ is the output impedance at frequency f at the amplifier output port. The first MN may be of any configuration and is designed so that $Z_1(f_1)$ matches imped-

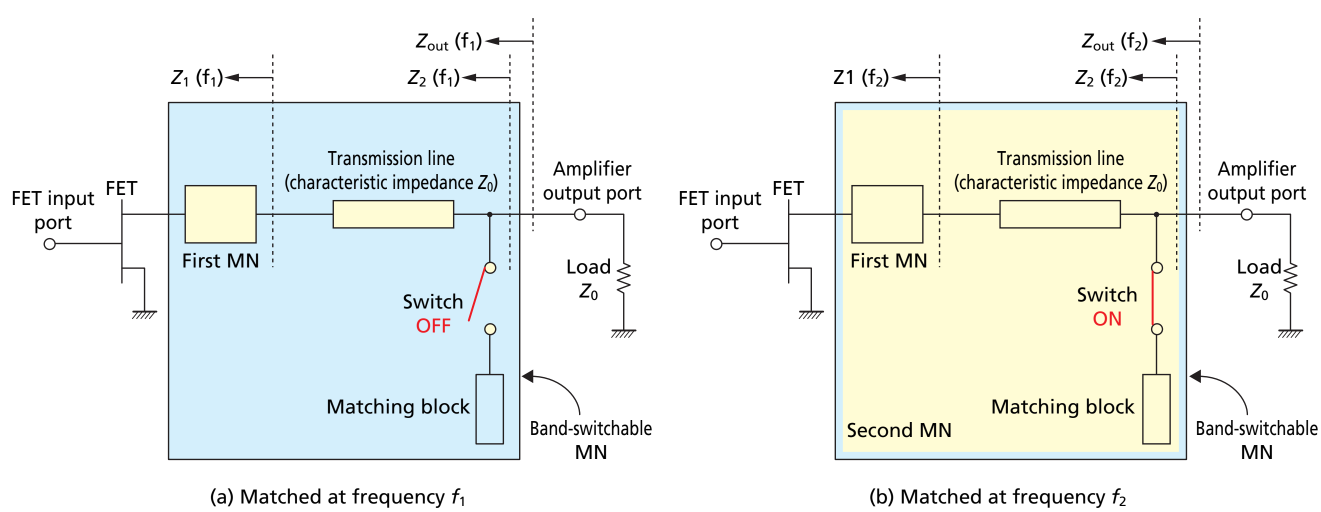

Figure 4 Configuration of a band-switchable MN

*1 FET: A transistor in which the conduction between the drain and source electrodes is due entirely to the flow of majority carriers through a conduction channel controlled by an electric field arising from a voltage applied between gate and source electrodes.

*2 Matching block: Part of a matching network. A device or circuit comprised of multiple elements, used for matching.

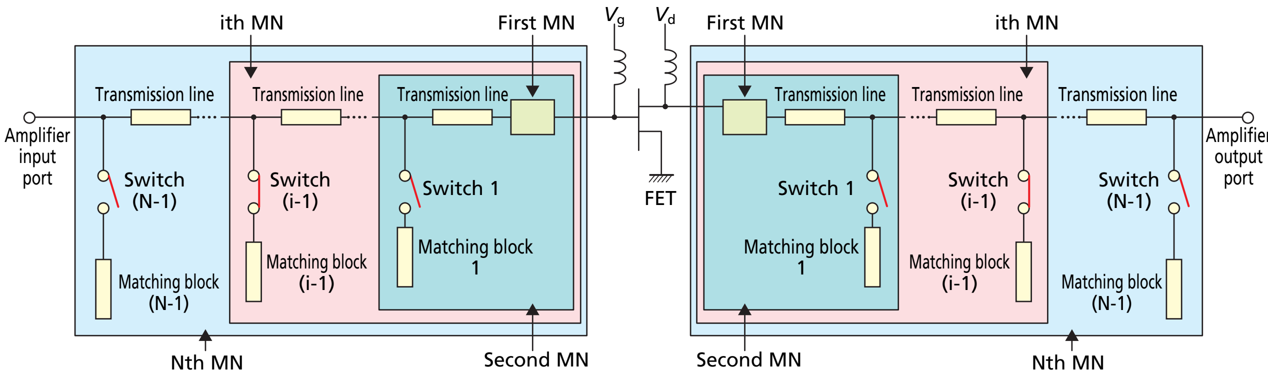

Figure 5 Multi-band band-switchable PA

ance Z_0 in the MN for the frequency f_1 signal. If the matching block is completely isolated with the switch OFF as shown in Fig. 4(a), the characteristic impedance of the transmission line connected to the first MN is Z_0, and $Z_{out}(f_1)$ matches load impedance Z_0. The band-switchable MN therefore operates as a MN for the signal of frequency f_1; however, since FET input/output impedance generally varies in response to frequency, output impedance $Z_1(f_2)$ of the first MN for the signal of frequency f_2 rarely matches Z_0 unless the frequencies f_1 and f_2 become too close. In the proposed band-switchable MN, a matching block is connected to the transmission line with the switch ON as shown in Fig. 4(b). Here, it is possible to match $Z_2(f_2)(= Z_{out}(f_2))$ to desired load impedance Z_0 for any $Z_1(f_2)$ by selecting an appropriate electrical length[*3] for the transmission line, and an appropriate reactance[*4] value for the matching block. Thus, the band-switchable MN can also operate as a MN for any signal of frequency f_2.

The band-switchable MN shown in Fig. 4 can be expanded to handle three or more bands with the same configuration. **Figure 5** shows the configuration of a PA expanded to N bands (with N denoting an integer of 3 or greater). Here, the signals of frequencies $f_1 - f_N$ may be amplified, and for example, when frequency f_i ($2 \leqq i \leqq N$)is amplified, the switch (i-1) is set ON and other switches are set OFF. If the number of bands is N, 2 (N-1) switches are required: (N-1) for input and (N-1) for output.

In actual switches, an insertion loss occurs when the switch is ON. In this configuration, however, only one switch (or none of the switches) is set ON for each MN during operation in each frequency band so as to minimize circuit deterioration due to switch insertion loss, even if the number of bands is increased. Furthermore, all switches are connected in parallel to the signal path by the MN design, thus reducing the effects of insertion loss [4]. The band-switchable PA operates in multiple frequency bands and the characteristics in each frequency band can be expected to be similar to those of a single-band PA using the same amplification device.

3.2 Application of MEMS Switches

In order to expand the applicable frequency range of the band-switchable PA to the frequency band capable of being amplified by the amplification device, a switch with both low insertion loss and high isolation characteristics is required across the band. It is also important to take non-linear distortion effects of the switch into account, particularly when used with the PA output MN. The Micro-Electro Mechanical Systems (MEMS) switches manufactured with micro-machining technology can satisfy these requirements. A MEMS switch is a mechanical relay, and including its actuator (drive mechanism), is implemented in a size of only a few mm square or less. Many research institutes such as universities or enterprises are working toward the practical use of the MEMS switches. Given the low power consumption of MEMS switches, the authors have focused on electrostatically actuated[*5] MEMS switches [5] and verified that the high-frequency characteristics (including power handling capability) are problem-free, and have thus employed such switches in a band-switchable PA. The measured charac-

*3 Electrical length: The length of an equivalent lossless reference air line introducing the same total phase shift as the two-port when each is terminated in a reflectionless termination.

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

*5 Electrostatically actuated: Driven by electrostatic force.

Table 1 Major characteristics of MEMS switch

Switch type	Electrostatically actuated SPST switch
Control voltage	DC15–19V[6]
Series resistance	0.4–0.45Ω[6]
Off-state capacitance	10fF

fF : femto Farad
SPST : Single-Pole, Single-Throw

teristics of the MEMS switches for insertion loss (0.6 dB or less) and isolation (30 dB or greater) are quite satisfactory up to 5 GHz. **Table 1** shows the electrical characteristics of these switches.

The operating characteristics of a 0.9-GHz and 1.9-GHz dual-band, band-switchable PA were verified by simulation in consideration of the high-frequency characteristics of MEMS switches in actual use. **Figures 6** and **7** show output power versus input power for each frequency band (mode), and the results of simulating the PAE characteristics (in 0.9-GHz mode, with measured frequency of 0.875 GHz) and (in 1.9-GHz mode, with measured frequency of 1.875 GHz), respectively. Here, the results of simulating the input/output characteristics of a single-band PA for each frequency band and with the same circuit topology[*6] are also shown for cases when the switches are not used. The band-switchable MN was designed so that the 0.9-GHz band is selected with the switch ON, and the 1.9-GHz band selected with the switch OFF.

Furthermore, the design served to reduce, as much as possible, the loss occurring in the MN due to insertion loss when the switch is ON. As a result, output power of 30 dBm or greater, and maximum PAE of 60% or greater was obtained for the band-switchable PA for each band. These characteristics are similar to those of the single-band PA, and given these characteristics, it was apparent that highly efficient multi-band PA operation could be achieved by switching.

3.3 Expansion of the Frequency Band

As described in Chapter 2, the band-switchable PA can be expanded to multi-band operation, although with the multi-band matching in which the upper and lower limits of the operating frequency band are separated, the input and output impedance of the amplification device becomes distributed over a wide

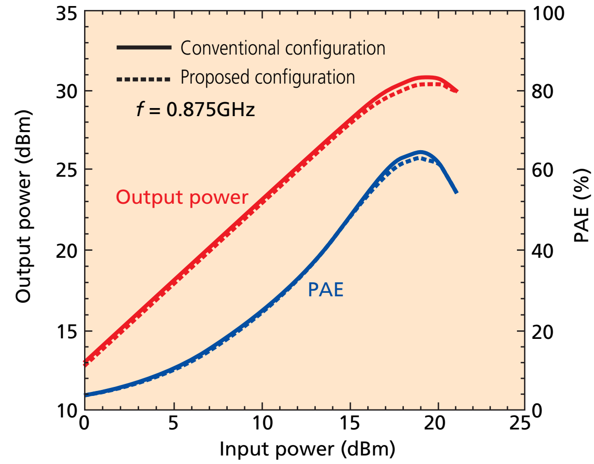

Figure 6 Input/output characteristics in 0.9 GHz mode

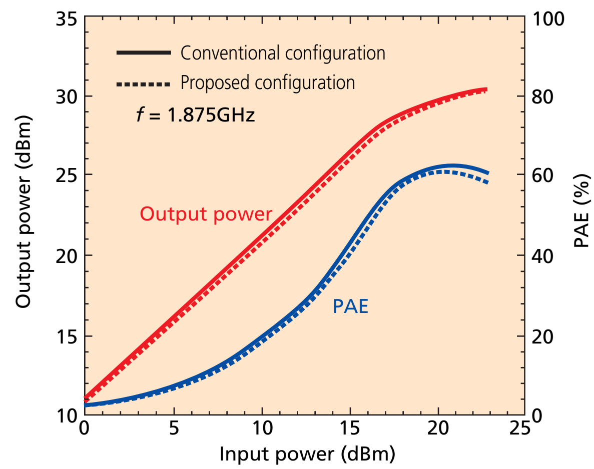

Figure 7 Input/output characteristics in 1.9 GHz mode

range. In this case, depending on the impedance, the length of transmission lines used for all the frequencies may need to be increased in order to achieve matching, resulting in a larger circuit size. To reduce the length of the transmission lines, a new matching block (matching block 0) is added between the first MN and the FET as shown in Fig. 5 [7]. **Figure 8** shows the configuration of the proposed input MN. Here, the first MN is comprised of a transmission line and a matching block, as are the second and later MNs. Furthermore, d_N in the figure is the required length of the transmission line from the FET to the Nth MN. Conversely, since the matching block connected to the transmission line via the switch is basically intended for use with only a single frequency band, its size may be reduced

*6 Topology: The positional relationship and network configuration of equipment. In this article, a circuit configuration.

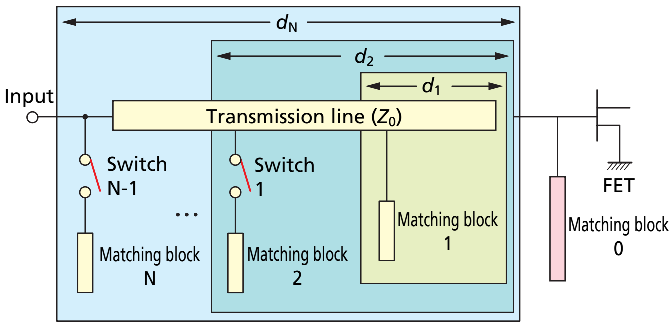

Figure 8 Configuration of proposed input MN

Table 2 Comparison of reduced transmission line length (design example)

Frequency band (GHz)	0.9	1.5	2	3	4	5
Conventional configuration d_N (mm)	16.8	46.8	30.6	16.6	12.8	10.8
Proposed configuration d_N (mm)	13.8	6.9	3.9	18.8	8.8	3.6

when using lumped elements[*7].

The MN shown in Fig. 8 was used in the design of a six-band (0.9, 1.5, 2, 3, 4, and 5 GHz) PA for band-free operation. Even with this PA, matching block 0 was added to reduce the length of the transmission line. **Table 2** shows the comparison of reduced transmission line length. While the transmission line length was 46.8 mm without matching block 0, adding matching block 0 reduced this length by more than half to 18.8 mm. **Figure 9** shows the results of simulating gain for the designed PA. In each frequency band, gain equal or greater than that without matching block 0 was obtained, and the reduction in transmission line length increased 3-dB bandwidth.

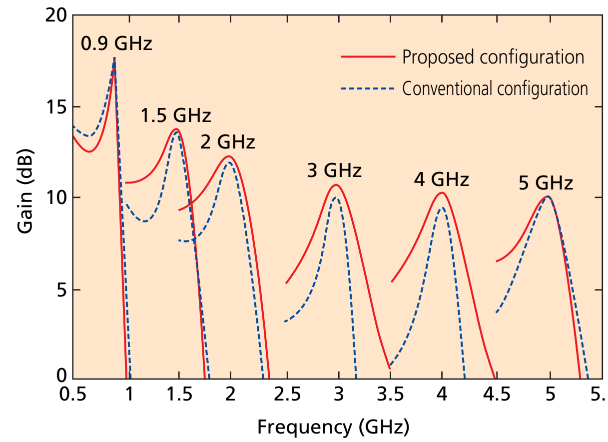

Figure 9 Frequency characteristics of a six-band PA

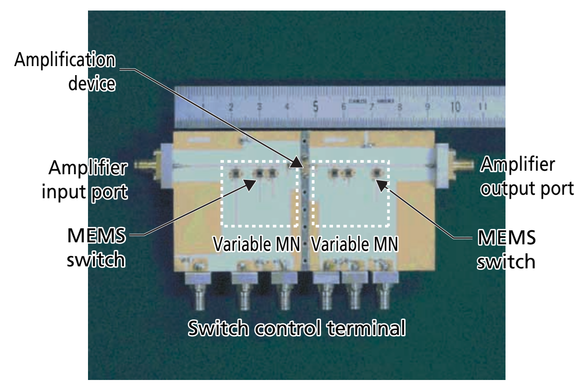

Photo 1 0.9, 1.5, 2 and 5-GHz quad-band PA

Table 3 Operating modes and switch settings

Mode	0.9 GHz	1.5 GHz	2 GHz	5 GHz
SW_1	OFF	OFF	ON	OFF
SW_2	OFF	ON	OFF	OFF
SW_3	ON	OFF	OFF	OFF

4. Quad-band PA Design and Prototype

4.1 Quad-band (0.9, 1.5, 2 and 5 GHz) PA Prototype

Photo 1 shows the prototype of a quad-band (0.9, 1.5, 2 and 5 GHz) PA to verify operation of the 0.9 to 5-GHz multi-band PA described above. The first MN was designed for the 5-GHz frequency band, the second for the 2-GHz frequency band, the third for the 1.5-GHz frequency band, and the fourth for the 0.9-GHz frequency band. A total of six switches were employed—three in the input MN and three in the output MN. **Table 3** shows the switch settings in each mode.

A commercially available GaAs MESFET[*8] of 1W class output power was employed as the amplification device. The quad-band MN was manufactured on an alumina substrate having relative dielectric constant[*9] of 9.6.

4.2 Evaluation of the Quad-band PA

Figures 10, **11**, **12** and **13** show measured output power versus input power, and PAE characteristics in the 0.9-GHz mode (with measured frequency of 0.9 GHz), the 1.5-GHz mode (with measured frequency of 1.45 GHz), the 2-GHz mode (with measured frequency of 1.85 GHz), and the 5-GHz mode

*7 Lumped element: A discrete inductor, capacitor, or resistor, etc.
*8 GaAs MESFET: A FET using MEtal and a Semiconductor of Gallium ArSenide compound.
*9 Relative dielectric constant: The relative of the capacitance of a given configuration of electrodes with the material as a dielectric to the capacitance of the same electrode configuration with a vacuum.

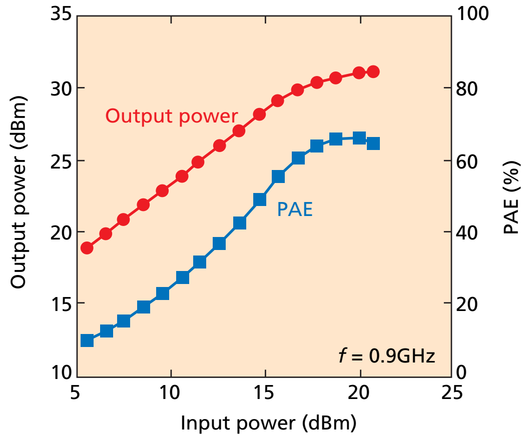

Figure 10 Input/output characteristics in 0.9 GHz mode

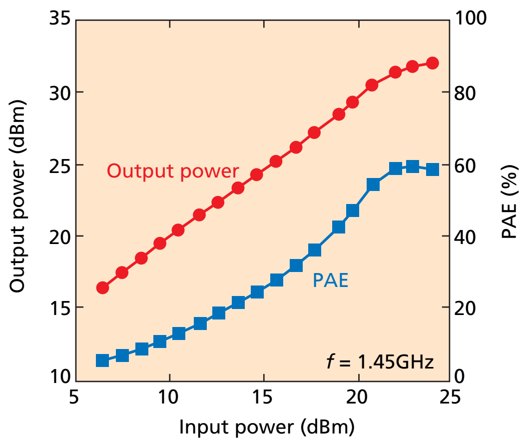

Figure 11 Input/output characteristics in 1.5 GHz mode

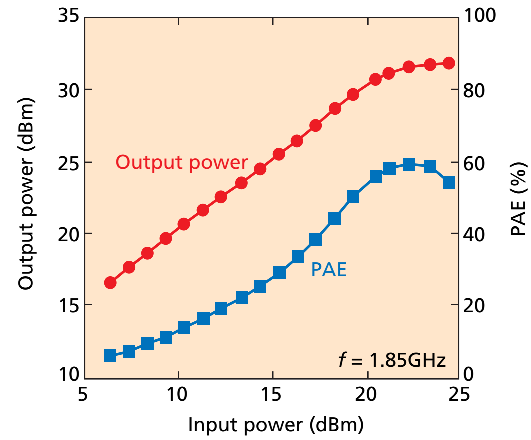

Figure 12 Input/output characteristics in 2 GHz mode

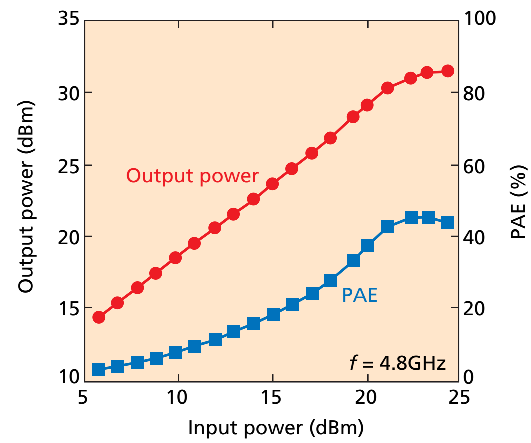

Figure 13 Input/output characteristics in 5 GHz mode

(with measured frequency of 4.8 GHz), respectively. The PA was operated in Class AB[*10] for all modes. The maximum PAE values were 64, 58, 58, and 45% in the respective modes. Furthermore, saturated output power was 30.5, 31.0, 31.0, and 30.8 dBm, respectively. These results show that output power and efficiency of the quad-band PA were equal to those of a single-band PA.

5. Conclusion

RF circuits able to support a variety of radio environments will be required in the world of ubiquitous mobile communications. This article has described the configuration and characteristics of a band-switchable PA that can operate with high efficiency in multiple bands over a wide range of frequency bands, as part of the research conducted on this topic. The prototype quad-band (0.9, 1.5, 2 and 5 GHz) band-switchable PA demonstrated switching operation of its characteristics over a wide range of frequency bands, high output, and high-efficiency operation in each frequency band.

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*10 Class AB: An operating class of an active device at amplification. Indicates operation midway between Classes A and B. Class A describes a linear, less-distorted relationship between input and output; Class B describes an efficient operation superior to that of Class A.

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