OVERVIEW: The dissemination of mobile phones is proceeding at a rapid pace throughout the world. This trend has been driven by smaller size and lighter weight, and by the much lower price that has become possible because of technological innovation in components—especially semiconductors. Achieving smaller size, lighter weight, lower price, and longer talk-time are unchangeable propositions, and even now technological innovation proceeds step by step. At present the progress being made in bringing higher functionality to mobile phones is leading to an increase in components including semiconductors. This in turn tends to cause an increase in power consumption. Also, to increase convenience of use, dual-band types and dual-mode types are being implemented, decreasing the space available for those components. This further increases requirements that semiconductors become smaller, thinner, and operate with lower power consumption. Hitachi, Ltd. has responded to these needs by developing and producing a variety of high-frequency semiconductor devices for mobile phones. These include power amplifiers with high efficiency and low power consumption, GaAs microwave monolithic ICs (MMIC) that can be densely integrated and bipolar complementary metal-oxide semiconductor (Bi-CMOS) analog signal processing ICs for dual-band operation.

INTRODUCTION

REQUIREMENTS for mobile phones, which enable anyone to communicate anytime at anyplace, include small size, light weight, and long talk-time. Smaller size and lighter weight can be implemented by integrating semiconductors more densely and using smaller packages. Long talk-time has been made possible by the higher efficiency and performance of semiconductors, which results in longer battery life. In this paper we will discuss mobile phone systems

![Fig. 1—Principal High-Frequency Semiconductors for Mobile Phones. Three dual-band circuits were developed and are now being produced. The compactly designed dual-band high-frequency power amplifier module features a small package and high efficiency in each band. The dual-band receiver section is a composite GaAs MMIC consisting of a low-noise amplifier, mixer circuits, and local oscillator amplifier with on-chip input and output matching circuits in a small surface-mount package. The dual-band high-frequency analog signal processing IC incorporates most of the required high-frequency receiver and transmitter analog functions implemented on-chip in a small package.](image)

(a) Si-MOSFET dual-band high-frequency power amplifier module
(b) Bi-CMOS dual-band high-frequency analog signal processing IC
(c) GaAs MMIC low-noise amplifier, mixer circuit, and local-oscillator amplifier

MOSFET: metal-oxide semiconductor field-effect transistor
trends and requirements. We will also describe the high efficiency, high performance, and high-integration technology of high frequency semiconductor devices developed by Hitachi together with the outlook for the future.

**SYSTEM TRENDS AND REQUIREMENTS**

Mobile phones are undergoing a generation change from the analog types that were called the first generation to the second generation digital types that have become predominant. The principal second generation communications systems are shown in Table 1.

Conversations cannot be carried out between mobile phones using different communications systems. Thus, for convenience, manufacturers are making dual mode types - code division multiple access (CDMA) and Advanced Mobile Phone Service (AMPS), etc.; and dual band types - Global System for Mobile Communications (GSM) and Digital Cellular System 1800 (DCS-1800), etc.

The communications area of mobile phones is confined to within a limited area on land, but systems such as Iridium using low earth-orbit communications satellites circling the earth will provide seamless worldwide communications so that conversations will be possible at anyplace with a single mobile phone.

If one uses a dual-mode mobile phone, one can change the mode of operation to utilize satellite service when in an area beyond the reach of terrestrial signals. These services feature the use of low earth orbit circling satellites: thus the distance to the earth is small, the propagation delay time of the radio waves is short, and the delay of the other party’s voice is small enough not to be noticeable. The next generation mobile phone, which will be the third generation, will provide multimedia services. Moreover the International Telecommunication Union (ITU) aims to introduce in the year 2001 the IMT-2000 digital communications system that will make worldwide roaming possible. Dual-mode mobile phones are under consideration to promote coordination with current systems, and even triple mode types are also a possibility. Trends of the various generations are shown in Fig. 2.

Considering these trends, requirements for high frequency semiconductors include even smaller packages occupying less volume inside mobile phones for dual-band systems, higher integration to realize space saving, higher efficiency for longer battery life, more precise modulation characteristics to improve

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**Table 1. Principal Communication Systems for Digital Mobile Phones**

*PDC is used in Japan, GSM has its hub in Europe but extends to a total of more than 100 countries, and N-CDMA is used in Asia including Japan, and in the US. W-CDMA has been proposed by Japan as a candidate for IMT-2000.*

<table>
<thead>
<tr>
<th>Communication system</th>
<th>Frequency band</th>
<th>Channel spacing</th>
<th>Transmitting power</th>
<th>Frequency between carriers</th>
<th>User data rate</th>
<th>Signal transfer rate</th>
<th>Access method</th>
<th>Voice channels per carrier</th>
<th>Modulation method</th>
<th>Voice coding method</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDC</td>
<td>800 MHz/1.5 GHz</td>
<td>25 kHz (alternate allocation)</td>
<td>0.8 – 3 W</td>
<td>130 MHz (800 MHz)</td>
<td>9.6 – 28.8 kbit/s</td>
<td>42 kbit/s</td>
<td>TDMA/FDD</td>
<td>3 (6)</td>
<td>4-phase shift QPSK</td>
<td></td>
</tr>
<tr>
<td>GSM</td>
<td>900 MHz</td>
<td>200 kHz</td>
<td>0.8 – 20 W</td>
<td>45 MHz</td>
<td>14.4 kbit/s</td>
<td>270.833 kbit/s</td>
<td>TDMA/FDD</td>
<td>8 (16)</td>
<td>GMSK</td>
<td></td>
</tr>
<tr>
<td>N-CDMA (IS95)</td>
<td>800 MHz</td>
<td>1.25 MHz</td>
<td>0.2 – 6.3 W</td>
<td>48 MHz (1.5 GHz)</td>
<td>9.6 – 64 kbit/s</td>
<td>1.2288 Mchip/s spreading</td>
<td>CDMA/FDD</td>
<td>55</td>
<td>OQPS/QPSK</td>
<td></td>
</tr>
<tr>
<td>W-CDMA (IMT-2000)</td>
<td>2 GHz</td>
<td>5 MHz</td>
<td>0.01 – 2 W</td>
<td>900 MHz</td>
<td>16 k – 2 Mbit/s</td>
<td>(For example: 4.096 Mchip/s)$^1$ spreading</td>
<td>CDMA/FDD, TDD</td>
<td>(256)$^2$</td>
<td>BPSK/QPSK</td>
<td></td>
</tr>
</tbody>
</table>

*PDC: personal digital cellular telecommunication system
IS-95: Interim Standard 95
TDMA: time division multiple access
QPSK: quadrature phase shift keying
PSI-CELP: pitch synchronous innovation code-excited linear prediction
EVRC: enhanced variable bit rate coder

*1: 1.024 M/4.096 M/192 M/16.384 M are available; maximum user data rate at 4.096 M is 2 Mbit/s
*2: 4.096 spreading @ 16 kbit/s channel
communications quality, and better linearity for lower distortion amplification. We will describe the technologies and products developed by Hitachi to fulfill these needs.

TOWARD HIGH EFFICIENCY AND HIGH PERFORMANCE
Si-MOSFET Dual Band (GSM/DCS-1800) High-Frequency Power Amplifier
The aim of a dual-band terminal is to improve the convenience of the user. To obtain acceptance by the largest number of users it is necessary to approach as close as possible to the size and price of a single-band terminal. Thus it is imperative that the high frequency components feature lower cost and smaller size.

The transmitter can easily be configured using two single-band power amplifiers suitable for two-band use, but this is not the best solution from the size and price standpoint. If a single amplifier is used to amplify two bands, then the size of the power amplifier alone can be made small. But since the 2nd harmonic of the GSM band is close to the DCS-1800 band, specially designed components will be required for harmonic filtering, and the overall cost will become expensive. Hitachi developed the PF08103A small-size low-cost dual-band high-frequency power amplifier module, which uses shared amplifiers for the first and second stages, but 2 separate final stages with operating efficiency optimized for each band. Below it is called “RF module.” A block diagram of the 3-stage dual-band RF module is shown in Fig 3. The matching circuits at the input and between the first and second stages are matched for 2 frequencies, while the input and output of the final stages are matched for their

![Fig. 2—Mobile Phone Trends and Forecast. At present second-generation digital phones have become predominant. The International Telecommunications Union (ITU) is promoting the introduction of IMT-2000 communications system mobile phones that can be used anyplace on the Earth.](image)

![Fig. 3—Block Diagram of Dual-Band RF Module. Compactly configured with 1 input, 2 outputs, and internal circuits; and designed for high efficiency in both bands. Controllability is enhanced with 1 control signal and 2 band-switching digital signals.](image)
With an aim to making the assembly area even smaller, we developed the HA22032 Composite MMIC with LNA + MIX + Lo and matching circuits on chip. Active devices for the amplifier are high-performance MOSFETs fabricated with a fine-pattern process. MOSFETs are easily controlled, have excellent thermal stability, and are suitable for mass production because they are based on a silicon process.

Characteristics of the Dual-Band RF Module

This amplifier is suitable for 2 bands: Extended GSM (E-GSM) and DCS-1800. Output power at the high-frequency terminal and efficiency dependence on the control voltage are shown in Fig. 4, while principal characteristics are shown in Table 2. Efficiency values of 50% in the GSM band and 40% in the DCS-1800 band are achieved. Noise characteristics in the receiving band are -138 dBm/Hz for E-GSM at f = 915 MHz and -139 dBm/Hz for GSM at f = 935 MHz. Moreover, when operating in the GSM band, 2nd harmonic leakage to the DCS-1800 port is held down below -20 dBm, decreasing the burden on the external filter characteristics. A leadless multilayer ceramic package is used enabling small size to be realized.

<table>
<thead>
<tr>
<th>Item</th>
<th>Characteristics</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power output</td>
<td>E-GSM: 35.78 dBm (standard)</td>
<td>( V_{dd} = 4.8 \text{ V} )</td>
</tr>
<tr>
<td></td>
<td>DCS-1800: 33.0 dBm (standard)</td>
<td>( V_{apc} = 3.0 \text{ V} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( P_{in} = 4.5 \text{ dBm} )</td>
</tr>
<tr>
<td>Efficiency</td>
<td>E-GSM: 48% (standard)</td>
<td>( P_o = 34.5 \text{ dBm} )</td>
</tr>
<tr>
<td></td>
<td>DCS-1800: 40% (standard)</td>
<td>( P_o = 31.5 \text{ dBm} )</td>
</tr>
<tr>
<td>Package</td>
<td>Surface-mounting type, 11 ( \times ) 13.75 ( \times ) 1.8 (mm)</td>
<td></td>
</tr>
</tbody>
</table>

ACHIEVING HIGHER INTEGRATION

GaAs Microwave Monolithic ICs

Response to the rapid increase in demand for mobile phones is causing an steadily increasing demand for gallium arsenide (GaAs) compound semiconductors - whose use is well advanced at high frequencies because of their excellent high-frequency characteristics, including high gain and low noise. An important feature of GaAs devices is excellent active device characteristics on a crystal substrate with semi-insulating properties. Thus the low-loss input/output impedance matching circuits that are indispensable in high frequency circuits can easily be formed on the substrate. GaAs MMICs enable most peripheral components to be fabricated on the chip. The wireless section can be made smaller, with assembly and adjustment eliminated—providing important advantages not possible with silicon LSIs. Hitachi has previously developed and produced a 1.9-MHz band GaAs MMIC chip-set incorporating a low-noise low-distortion GaAs FET and a spiral inductor fabricated by thick-film Au plating technology. Subsequently, to meet the needs of mobile phones for rapid size reduction, Hitachi succeeded in the development and mass production of the HA22022 MMIC extremely small low-noise amplifier in a small plastic package.

![Fig. 5—Block Diagram of Wireless Section of Mobile Phone. With an aim to making the assembly area even smaller, we developed the HA22032 Composite MMIC with LNA + MIX + Lo and matching circuits on chip.](image-url)
Now, to reduce size even more, Hitachi has developed and mass-produced the HA22032 MMIC that consolidates several receiver functions including low-noise amplifier, receiving mixer, and local oscillator amplifier together input/output matching circuits as shown in Fig. 5. Moreover the surface mount package used is an 8-pin thin small outline package (TSSOP) measuring only 6.4 \times 3 \text{ mm}.

The high-frequency characteristics of the HA22032 are shown in Fig. 6. When operating at 1.5\text{GHz}, the dual-gate metal-semiconductor FET (MESFET) with gate lengths of 0.4 \mu m provides high-gain and low-noise characteristics with a conversion gain of 26 dB, and a noise figure of 2 dB. For the same conditions, the third-order intercept point is 4 dBm, which provides excellent distortion characteristics. Use of this MMIC makes possible a size reduction to 1/2, including peripheral components, compared with previous Hitachi products.

In the future we will have to respond to mobile phone system requirements for multiplexing and even smaller size. Thus we believe that it will be necessary to produce highly integrated and multifunctional MMICs not only for the receiver section but also including the transmitter section.

Bi-CMOS Analog Signal Processing ICs

In urban areas there is increased demand for dual-band phones to solve the shortage of channels, resulting in a stronger desire for a higher level of...
The integration of the high-frequency signal processing section. Hitachi has already developed and produced single band ICs: HD155101BF for GSM and HD155111F for DCS-1800. These devices can be used in a dual-band phone, but the assembly area and power consumption will become large. Therefore Hitachi cooperated with TTP Communications Ltd of England to develop and produce a single chip that integrates GSM/DCS-1800 dual-band transmitting and receiving sections, the HD155121F high-frequency analog signal processing chip.

Configuration of the HD155121F

This IC uses the same 0.6-µm bipolar complementary metal oxide semiconductor (BiCMOS) process proven in single-band ICs, and has on-chip the majority of functions required in the dual-band transmitting and receiving high-frequency analog section, as shown in Fig. 7. It operates on 58.6 mA when receiving, 37 mA when transmitting. The package is the same 48-pin, 9 × 9-mm low profile quad flat package (LQFP) used for the single-band ICs, and it realizes a reduction in assembly area.

Receiving circuits

Two separate groups of circuits are used for the two frequency bands in the first mixer band, and structured to convert the received signals to the common intermediate frequency of 225 MHz. Thus the second mixer and succeeding circuits have the same structure as a single-band IC. Since operation at each frequency band has the same form as in a single frequency IC, users can utilize the same type of level diagram design as for a single band IC.

Other characteristics are as follows.

1. The negative-feedback bias circuit for the LNA is included on the chip greatly reducing the number of external components needed for the LNA.
2. The first and second mixers have a 2-stage gain-switching facility.
3. The digital-control variable-gain amplifier has 50 steps of 2 dB per step.
4. I and Q (I signal and Q signal) demodulators have an interference-signal suppression LPF on chip to reduce assembly area.

Transmitting circuits

The bandwidth of the offset PLL circuit that determines the transmitter output noise characteristics and phase accuracy is dependent on the product of the phase comparator output current (A/rad), loop filter propagation constant (V/A), and transmitter VCO sensitivity (Hz/V). Since the frequency bandwidth of GSM and DCS-1800 differs in the same manner as the frequency bands, the VCO sensitivity as measured in frequency change as a function of control voltage also differs.

Because this IC uses a shared phase comparator, loop filters with differing propagation constants would be necessary to enable use of an offset PLL with a fixed loop bandwidth. This requirement is avoided and a fixed loop bandwidth made possible by a configuration in which band selection and phase comparator output current level are simultaneously switched. Thus it is possible to use a shared filter, the filter bandwidth can be fixed, and reduction in the number of external components can be realized.

Other significantly advantageous characteristics are as follows. Use of the offset PLL method for frequency conversion results in a large reduction in out-of-band noise in the transmitted signal. Elimination of the need for a duplexer makes for a smaller assembly substrate to help realize lower cost.

Evaluation results

In addition to evaluating each block within the IC, evaluation of the entire system including baseband was carried out, and it was determined that the specifications are fully satisfied. As an example, receiver sensitivity characteristics of -106.3 dBm in the GSM band and -106 dBm in the DCS-1800 band are achieved, which provides more than adequate margin with respect to the specifications, as shown in Fig. 8.

Fig. 8—RBER as a Function of Received Signal.

Received signal sensitivity specifications for both GSM and DCS-1800 are exceeded.
PRODUCT PLANS

A 0.35-µm Bi-CMOS process triple-band IC is currently being developed to respond to the demand for even higher integration and lower power consumption. This IC has a triple-band specification to implement GSM, DCS-1800, and additionally Personal Communications Services 1900 (PCS1900); and our goal is to have both LNA and PLL synthesizers on the same chip. We are also considering using this technology as the basis for extending development to W-CDMA and other systems.

CONCLUSIONS

We have described mobile phone systems trends, requirements, and work on high-frequency semiconductor development ongoing at Hitachi. High-frequency semiconductors greatly influence the realization of mobile phones featuring smaller size, lighter weight, and longer talk-time, and strong demand exists for devices with higher efficiency, higher performance, and higher integration. We expect to continue our progress in developing high-frequency semiconductors suitable for many types of communications systems.

REFERENCES