4-2 Research on Millimeter-Wave Communication Devices Including Test and Measurement Techniques

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The CRL Millimeter-wave Device Group undertakes research to develop technologies for creating millimeter-wave (MMW) wireless communication devices with high performance and practicality. Such equipment is essential for use in future MMW communication systems and for their dissemination to the public. This research program addresses the development of high-performance MMW circuit components and innovation in MMW radio equipment construction. These activities are to be pursued in conjunction with the outcome of the concurrently undertaken Semiconductor Device Research program. Our research and development of MMW devices has the aim of establishing key technologies for widespread use of the millimeter-wave frequency spectrum and of enabling the features required for practical use – compactness, highperformance, and low cost. Testing and measurement methods are also addressed under this program as essential techniques in developing MMW communication devices. This report outlines our program on MMW communication device technologies.

Keywords

Millimeter-wave, Communication devices, Semiconductor devices, Antenna-circuit integration, Test and measurement techniques

1 Introduction

According to a ministerial report released in July 2001, more than 20-million computer users in Japan were estimated to access the Internet at home. Out of this figure, the number of subscribers using xDSL or coaxial cables is rising rapidly and remarkably, thus bringing about a variety in access methods and competitiveness among Internet carrier vendors. In this climate, broadband wireless access is also being developed worldwide for broadband Internet distribution services. In December 1998, three frequency bands, 22, 26, and 38 GHz, were released in this country for subscriber lines, followed by the commencement of fixed wireless access (FWA) services, which are being deployed using the 22-GHz band initially in urban areas. Meanwhile, in September 2001 the Information/Communications Commission of the Ministry of Public Management, Home Affairs, Posts and Telecommunications summarized the technical conditions for quasi-millimeter-wave broadband mobile access that would enable 100-Mbps outdoor transmission using 25 GHz. Thus, starting with the K/Ka bands, high-speed communication services using millimeter-wave frequencies are fast becoming a reality.

Despite long-term surveys and efforts made by researchers, the millimeter-wave (MMW) frequency spectrum has not yet been used for communication applications except for simple radio systems using the 50-GHz band. Since the MMW spectrum is extremely high in frequency, it by nature is suitable for broadband communications. Reflecting the background of exponentially growing demands for wireless communications and their widespread use during the past several years, the MMW frequency spectrum, with its advantageous characteristics as mentioned above, is gaining increasing importance as a valuable frequency resource for the future. These trends make it clear that the creation of communications systems using MMW frequency bands is becoming a crucial issue.

Conventional MMW devices has several negative features including bulky and complicated structures, high cost, and difficulty in handling, which to date have hindered their practical use for communications and their dissemination to the public as well. Recent progress in semiconductor devices and relevant MMW key technologies, however, has eliminated most of the problems. Key technologies for MMW communications systems such as semiconductor devices, monolithic microwave integrated circuits (MMICs), antennas, and filters have made remarkable advances in recent years, bringing about a steady accumulation of research results toward the creation of MMW communication systems. Such systems are well on the way toward becoming a reality, as symbolized by recent moves by the government toward the establishment of consecutive technical standards for 60-GHz indoor, wireless communications systems.

Moreover, the Japanese government, with the Communications Research Laboratory (CRL) playing the major role, has been focusing on national research programs such as the Stratospheric Wireless Platform, the Intelligent Transportation System (ITS), and the Wideband Inter Networking engineering and Demonstration Satellite (WINDS). These projects are essential in terms of public affairs policies and national infrastructures, and their outcome will influence the current communications systems as a whole, with high expectations for the development of practical applications. To incorporate these technologies into public use, it will be essential to develop new functions and high capabilities in MMW communication devices.

After the K/Ka bands, one candidate for future possible high-speed terrestrial and satellite communications applications is the 90-GHz band. This frequency band features low atmospheric attenuation (less than 1 dB/Km), and consequently to date has mainly been used in earth observation and sensing applications. Last year (2001), the U. S. Federal Communications Commission (FCC) began investigating the commercial use of the 92-95 GHz band, and service rules for this frequency band are now being made[1]. These events make it obvious that it is time for Japan to seriously consider the 90-GHz band for possible commercial use and to launch a study on communication systems using this band.

The architectures for future communication systems and their creation for commercial use, including the use of the MMW frequency spectrum, highly depend on the MMW device capabilities; ranging from semiconductor device and high-frequency circuit component technologies to wireless equipment construction. In addition, their dissemination to the public depends on the development of MMW device technologies that would bring about downsizing, high performance, and cost reduction in equipment through mass production. In this report we describe our research programs to develop high-performance MMW circuit components and construction technologies for creating new MMW wireless communications devices which will be pursued in coordination with results obtained in the concurrent Semiconductor Devices Research program. Our aim in doing so is to establish the core technologies in MMW communication equipment needed to put the equipment to practical use. We also address the topic of research on developing testing and measurement techniques, which are essential in developing MMW wireless communications devices under this program. We intend to play a major role as a global hub in MMW device technology research. The details of our research programs are overviewed in the following sections.

2 Millimeter-Wave Circuit Technology

Creating high-performance millimeter-wave (MMW) communication devices requires development of structuring technology, i. e. , integration of MMW circuit components while achieving excellent performance in the overall structure along with improved capabilities in each building block. Fig.1 schematically shows a typical configuration for MMW front-end modules. Millimeter-wave wireless communications equipment, consisting of a number of components, is based on a wide range of technical factors: high capability in each component, analysis and design arts, and test and measurement techniques along with innovations in electronic devices and materials. We are concurrently undertaking the MMW Transistor Research program, which aims to ensure provision of essential electronic device technologies for realizing high performance in functional circuit components such as amplifiers, mixers, frequency multipliers, and oscillators. To manufacture high-performance MMW components and equipment, we are employing a flip-chip bonding technique for interconnecting devices and circuits, and will also incorporate micromachining including possible use of multi-layered structures. Low insertion losses and high return losses are to be attained in these structures to prevent degradation of device characteristics.

Crucial technical issues in creating MMW front-end modules will be overviewed in the sub-sections to follow.

2.1 Millimeter-Wave Amplifiers

One of the basic techniques commonly used in constructing communication equipment is amplification. Performance of MMW amplifiers, particularly those of higher than 60GHz, critically relies on the characteristics of MMW transistors such as HEMTs. The indium-phosphide (InP) HEMTs developed by CRL have attained a world-record cutoff-frequency (f_T) of 472 GHz in current gain[2]. Devices with 50-nm-long gate structures exhibited 15dB and 10dB of maximum small-signal gains at 60 GHz and 90 GHz, respectively[3]. Since InP HEMTs thus promise higher gain at high frequencies than conventional GaAs-based counterparts do, a smaller number of amplifier stages will suffice to

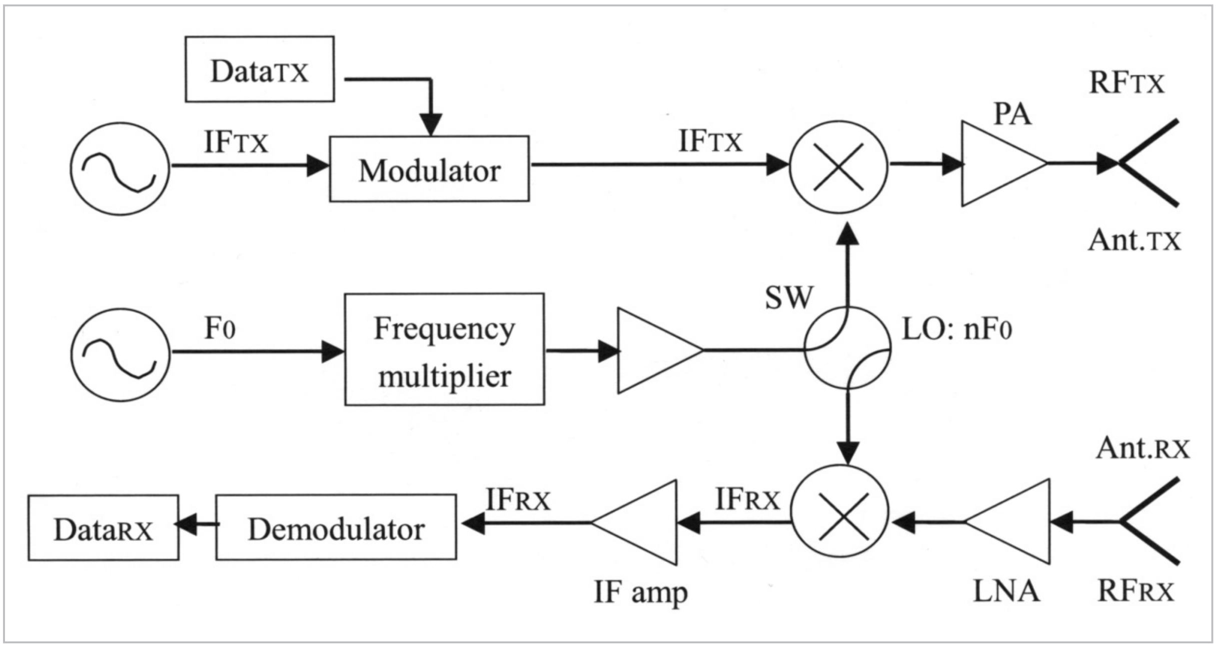

Fig. 1 A typical configuration for MMW front-end modules

achieve a specified gain. Indium phosphide HEMTs also work effectively in improving receiver noise performance. The total receiver noise factor, F_{12}, is expressed by

$$F_{12} = F_1 + (F_2 - 1)/G_1, \tag{1}$$

which is known as the Friis formula[4]. Here F_1 and F_2 are noise factors of the first-stage amplifier and of the following receiver circuits respectively, while G_1 is power gain of the first-stage amplifier. The noise factor, F, is related to the noise figure, NF, by NF [dB] = 10 logF. Formula (1) suggests that both high gain and low noise performance in a device used for the first-stage amplifier contribute to reducing the total receiver noise figure. The CRL in-house HEMTs exhibited a minimum noise figure of lower than 0.7 dB at 30 GHz, suggesting feasible ultra-low-noise MMW receivers using these devices. We will conduct research to develop MMW low-noise amplifiers, minimizing insertion losses that are associated with matching networks and interconnections. We plan to develop high-precision test and measurement techniques to obtain device parameters in the 90-150 GHz band, and based on these techniques will develop amplifiers in that frequency range as basic building blocks for future short-millimeter-wave equipment.

One problem is that due to their reduced sizes, single-element electronic devices for MMW applications have limited power capacities. This poses a serious issue in amplifier power handling and efficiency as the operation frequency increases. To cope with this difficulty, we will undertake the High-Power MMW Amplifier program to achieve high output power in the MMW frequency region through the incorporation of spatial power combining techniques. This will be concurrently undertaken with the High-Power HEMT program, which will undertake the exploration of nitride-based compound semiconductors.

2.2 Signal Sources

Recent high-speed digital communications systems require low phase-noise carriers. To transmit QPSK signals, for instance, a phase noise of lower than -90 dBc/Hz is assumed at 100 kHz off the carrier frequency[5]. Oscillator phase noise is mainly caused by 1/f noise, the so-called flicker noise in devices, which is dominant in the low frequency domain. In this regard, heterojunction bipolar transistors (HBTs) are known to be superior to HEMTs. Advanced HBTs in recent years have resulted in improved phase-noise performance in MMW oscillators, particularly when operated with dielectric resonators. Another traditional approach to generate signal sources is through frequency multiplication. Phase noise degrades in 20 log(N) (N: multiplication factor) by frequency multiplication, or in proportion to the square of the frequency; whereas phase noise performance in microwave and MMW oscillators reportedly degrades in a manner greater than the square of the frequency. This suggests that employing frequency multipliers is effective for generating MMW signals as far as spurious issues can be alleviated.

2.2.1 HEMT Frequency Multipliers

High electron mobility transistors are commonly used as frequency multipliers to generate MMW signals. Since the conversion efficiency in second-harmonic generation is the highest among the harmonics generated by HEMTs, cascade frequency doublers may well result in efficient generation of even-order harmonic signals. We prototyped and tested three-stage frequency multiplier (×8) to 29 GHz using GaAs-based HEMTs, showing excellent overall performance including conversion gain[6]. The degraded phase noise resulting from the three consecutive frequency doubling was measured and found to be 18 dB. This was consistent with the theoretically predicted value, and thus the effectiveness of the frequency-multiplication approach was demonstrated.

We plan to develop frequency multipliers with MMW output signals using InP-based HEMTs, which will promise higher conversion efficiencies in frequency multiplication into the MMW frequency domain.

2.2.2 Quantum-Barrier Varactor Frequency Multipliers

The quantum-barrier varactor (QBV) is a two-terminal device, i. e. a diode that contains an electric barrier layer in thin-film crystalline structures formed on a semiconductor substrate and consisting of different atom combinations. The depletion region thickness changes with the voltage between the two terminals, resulting in decreased capacitance as the applied voltage increases. This device thus acts as a varactor diode. Since the QBV features a symmetrical capacitance-voltage characteristic (i. e. , the capacitance has the same value regardless of the voltage polarity), it can be used for efficiently generating odd-order frequency harmonics ($3f_0$, $5f_0$,$\cdots$). A further benefit is that no DC biasing is required.

The QBV also features an extendable dynamic range realized by stacking the varactor structures during the crystalline growth process using a molecular-beam epitaxy (MBE) system. In addition, the varactor impedance can be adjusted by varying the varactor size in the fabrication process. Since these advantages enable cut-off frequency to be in the tera-hertz domain, the QBV is very promising as a device for creating signal sources with possible high output-power levels in the millimeter-wave and sub-millimeter-wave frequency regions. To date we have investigated the frequency tripler characteristics in the 30-GHz band, and demonstrated techniques for improving frequency conversion efficiency[7]. We will optimize the device structure along with the peripheral circuits, and will conduct research for applying the QBV to practical signal sources in the MMW frequency region and higher.

2.2.3 Millimeter-Wave Power Combining

IMPATT and Gunn oscillators are two types of conventional solid-state MMW signal sources. Although neither of these devices is very efficient compared to vacuum-tube oscillators, they operate at lower voltages and are easier to manipulate. In particular, Gunn diodes have been widespread for MMW oscillators since they generate high purity spectra. With recent advances in transistor technology, however, they are being replaced by transistor-based oscillators, which promise high dc-to-rf conversion efficiencies and even easier manipulation. This has resulted in a rapidly diminished supply of Gunn diodes over the past few years, causing a scarcity of InP-based Gunn diodes in particular. Since the latter have been widely used as local oscillators in radio astronomical observation or spectroscopy experiment systems in the MMW and submillimeter-wave frequency regions, an alternative to them is required, especially in the 100-140 GHz band. These circumstances are spurring the development of 50-mW-class signal sources in this frequency range, including the possible use of InP HEMTs and even power-combining techniques. We plan to create short-millimeter-wave signal sources through efficient power combining as well as by employing frequency multiplication or direct oscillation with transistors.

2.3 Frequency Conversion Circuits

The mllimeter-wave HEMT is capable of mixing the low-frequency baseband signal or the intermediate frequency signal with the MMW local signal, thereby upconverting the former to the RF signal for MMW transmitters. Another mode of operating the HEMT mixer is downconversion in receivers, translating the millimeter-wave RF signal to the low-frequency signal. Employing InP-based HEMTs will result in possible conversion gain in millimeter-wave and even in short-millimeter-wave mixers. We will develop MMW mixer circuits and integrate them with peripheral circuit elements, thus further developing MMW device technology.

2.4 Filter Circuits

Frequency filtering, performed in conjunction with MMW planar circuit components, is an essential technique commonly used in a number of MMW circuits. There are various types of filter circuits that are indispensable for use in such circuits as amplifiers, mixers, frequency multipliers, and oscillators, including low-pass, high-pass, band-pass, and band-rejection filters and combinations of these. In communication equipment configurations, where these circuit components are connected to each other, the major causes of degraded communication equipment performance are thought to be deviation from the ideal frequency characteristics of the filter and the interactions between filters and circuit components. By incorporating highly-controlled bonding techniques, we plan to develop high-performance MMW planar filters, particularly high-Q filters, that are compatible with multi-layered or integrated structures.

2.5 Micromachining for High-Frequency Applications

Technologies for forming fine structures using Si-based processing methods have recently attracted considerable attention. One of these is micromachining. Exhaustive research is being conducted to apply this technology to a variety of fields including micromechanics, pharmacy, and medical science. Micromachining will also find new possible applications in constitution technologies for microwave and MMW devices. With this in mind, we are conducting basic research on micromachine-based, high-frequency components such as low-insertion-loss switches, variable frequency filters, and low-loss transmission lines. Micromachining technology is considered particularly crucial in the short-millimeter-wave and submillimeter-wave frequency ranges. Accordingly, we intend to construct micromachined passive components and high-performance devices in the short-millimeter-wave frequency range, making most use of the performance in semiconductor devices.

3 Wireless Communication Devices

Among other crucial issues in constructing millimeter-wave (MMW) communication devices are antenna structuring, e. g. , in MMW front-end modules, and antenna-RF circuit interface technology. In conventional microwave and MMW radio equipment, RF circuits and antennas have been independently developed as though they belong to different technical fields, which has often required coaxial connectors or waveguide flanges for transforming sections. This conventional approach, however, poses several problems, including:

(1) Since transmission-line losses rapidly increase in the MMW frequency region, the addition of transforming sections, causing extra electrical lengths along with imperfect impedance matching, would result in degraded performance;

(2) The construction of transforming sections creates difficulties in reducing the size, weight, and cost of communication equipment.

Taking these problems into account, in this report we identify the integration of RF circuits and planar antennas as a vital technical issue. Techniques need to be developed to alleviate electromagnetic interaction between adjacently-located antennas and RF circuits, as well as to manufacture reproducible, high-quality equipment. Research topics related to wireless communications equipment, including antenna technologies, are stated in the following sub-sections.

3.1 Millimeter-Wave Planar Antennas

We proposed a coplanar-waveguide (CPW) patch antenna, which can be suitably integrated with CPW-based MMW circuits and photonic devices[8]. Using microwave-scale models, we studied ways to make the antenna more sophisticated, e. g. , broadening its bandwidth[9], and also prototyped millimeter-wave versions of the antenna at 38 and 60 GHz[10]. We investigated, meanwhile, 60-GHz microstrip patch antennas as primary feeders for quasi-optical antennas, and successfully developed and tested 60-GHz Gaussian-beam antennas.

We will focus on integrating these antennas with microwave and MMW circuits, and on developing module and equipment technologies.

3.2 Quasi-Optical Antennas

Increased feeder losses at MMW frequencies seriously degrade radiation efficiency of conventional planar array antennas designed for achieving high gain numbers. Techniques to simultaneously attain high radiation efficiencies and high gains have been utilized in slot-arrays[11] and leaky-wave antennas[12]. By making use of quasi-optical techniques such as Fabry-Perot resonators and focusing effects caused by adjacently located dielectrics, we have developed MMW antennas that feature high radiation efficiencies and low sidelobe levels[13][14]. We will pursue integration of these antennas with MMW circuits in multi-layered structures, aiming to develop high-capability modules for MMW communications systems.

3.3 Radiating Oscillators

Radiating oscillators are a type of radio equipment that functions as both an oscillator and an antenna by means of a resonator for both oscillating and radiating electromagnetic waves. In the MMW frequency region, where transmission-line loss is a serious problem, an oscillator and antenna integrated in a one-body structure, thus simplifying construction, is considered advantageous for creating new, efficient equipment configurations. We have pursued two approaches to reduce oscillator phase noise, namely, by means of a unique Fabry-Perot resonator[15] and of two-dimensional array configurations[16]. With the latter approach we attained high efficiencies in power combining. The fairly straightforward configurations of radiating oscillators should enable new radio equipment applications to be found for them. Efficient power combining is, meanwhile, a critical issue for creating high-power MMW transmitter signal sources with high efficiencies. We intend to pursue these techniques and apply them to practical MMW communication devices.

3.4 Millimeter-Wave Photonics

The current trend in millimeter-wave (MMW) wireless communications systems is to fuse MMW and optical-wave technologies to create broadband communication systems over today’s fiber-optic backbone networks. These systems employ both basic RF technology and a new technology called radio-over-fiber (ROF), which is a synergistic mixture of optical and RF technologies. One of the key system components is a device to generate MMW signals from optical waves. This conversion device is a common and indispensable element, and plays an important role in such wireless communication systems as the intelligent transportation system (ITS), where signals are transmitted both between the vehicles and between the vehicle and the road, in fixed wireless access (FWA) services, and in wireless distribution systems for CATV. In recent years we have been working on the development of high-performance optical/millimeter-wave converters with high conversion efficiency and high RF output. Using an efficient photodiode in experiments on optical-waves modulated with a MMW subcarrier, we successfully obtained MMW frequency signals (60 and 38 GHz) with output power levels of higher than 10 mW[17]. Furthermore, based on these experimental results, we introduced a new concept relative to integrating the conversion device and the MMW antenna. Directly integrating the device and the antenna will enable us to construct a simple and reliable optical millimeter-wave-communications system that is free from the serious loss levels associated with MMW signal transmission, thus simultaneously achieving relatively high output power without employing any extra RF circuits. We will conduct research to develop a fully integrated device module and to realize practical applications for it.

3.5 Adaptive Antennas

Among other important antenna-related issues is adaptive-antenna technology for MMW applications. Our intent is to conduct a basic study on engineering new antennas that can handle switchings in radiation pattern and beam directivity, thus making them suitable for use in subscriber distribution systems, indoor LANs, and other communication systems. We will also aim at developing innovative integration technology that will enable high-speed digital control and analog devices to be incorporated into antennas and RF circuits.

The conceptual image of MMW communication devices we envision is illustrated in Fig.2.

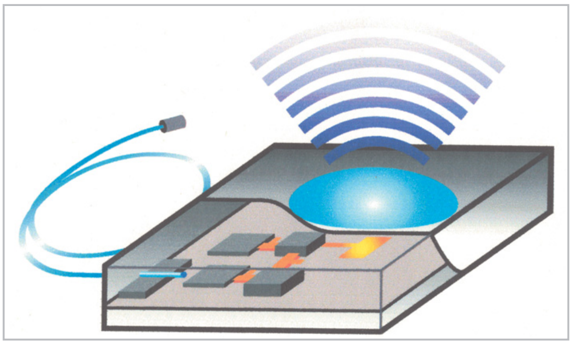

Fig.2 A conceptual image of MMW communication devices

4 Millimeter-Wave Test and Measurement Techniques

New measurement methods and testing techniques need to be developed in the course of undertaking research on new electronic devices as well as on high-performance millimeter-wave (MMW) circuit components and wireless communications equipment. Major test and measurement techniques in the MMW frequency region are overviewed in the subsections to follow.

4.1 Device Parameter Measurements

A crucial factor in circuit design is accurate understanding of the small-signal characteristics of devices. Small-signal equivalent circuit parameters for devices such as HEMTs and quantum-barrier varactors can be extracted by analyzing measured scattering parameters (S parameters), which feature high-frequency characteristics, along with data collected through dc measurements. To improve accuracy in extracting some of the parameters, we intend to make improvements to our current measurement system and analytical methodology. We also plan to develop a high-precision system for measuring device parameters in the 90-150 GHz band, a system that will be necessary to develop high-performance short-millimeter-wave devices in the future.

4.2 Noise Parameter Measurements

A transistor device’s signal impedance to provide the minimum noise figure, or NF_{min}, is generally different from that to provide impedance matching in the input network. Obtaining the conditions for NF_{min} directly through measurement is therefore crucial in the design of low-noise amplifiers. Noise-parameter measurements consist of several procedures: calibrating the measurement system, acquiring noise-figure data while changing the device signal-impedance through such means as a mechanical tuner, and, finally, deducing the noise parameters from NF measurement data for several signal-impedance settings. Since these procedures involve a series of measurement and computation processes, error analysis is a topic of prime concern. Uncertainties associated only with noise-figure measurements, let alone those as a result of the whole process of noise-parameter measurements, are likely to be significant in the V band and higher because of insufficient capabilities in available measurement systems in these frequency ranges. We plan to engineer an apparatus that will provide higher measurement sensitivity, thus improving test and measurement techniques.

4.3 Load-Pull Measurements

When a device is operated in a circuit with power higher than small-signal levels, the behaviors of the device deviate from those predicted by S parameters. Thus it is essential for circuit designers to be able to determine device characteristics under the exact operation power levels. Load-pull measurements consist of measuring output power levels while modifying the load and/or signal impedance(s) through such means as a mechanical tuner, thereby enabling optimum conditions to be ascertained directly through measurement. We plan to engineer a measurement apparatus that will provide improved measurement accuracy in the MMW frequency bands. We will use the system to obtain load-pull data and then incorporate the large-signal data into the circuit-design process to obtain more accurate designs. This approach should be effective in helping us to create high-powered MMW devices.

4.4 Dielectric Material Measurements

Various kinds of substrate materials are used for MMW planar circuits and antennas. The dielectric properties of the substrates are a key factor for determining essential parameters in the design of circuit components, and therefore it is vital to acquire accurate permittivity and dielectric-loss data. Circuit or circuit component designers, however, often do not have enough data on the MMW properties of substrates during the design process. The dielectric properties of the substrates are a key factor for determining essential parameters in the design of circuit components, and therefore it is vital to acquire accurate dielectric constant data. Inaccurately determined permittivity results in deviation from design values in such important circuit parameters as characteristic impedance and resonance frequency, while the dielectric loss causes transmission-line losses and degrades filter performance.

These problems spurred the development of more reliable dielectric measurement techniques for use in designing MMW planar circuit components. One well-known technique is the Fabry-Perot resonator method. We invented a unique resonator of the Fabry-Perot type[18] and applied it to a system for conducting dielectric measurements at MMW frequencies[19]. The system is now being remodeled to make it easier to operate. We plan to use the new version of the system to perform high-precision MMW measurements on a variety of dielectric substrates, and will incorporate the data obtained with it into the circuit component development process. We will also amass a large volume of data to help us contribute to the standardization of dielectric measurement methods in the MMW frequency region.

4.5 High-Frequency Surface Impedance Measurements

The high-frequency conductor loss associated with metallic materials is another factor that affects transmission-line characteristics at high frequencies, particularly in the MMW frequency region. A variety of metallic films are used for transmission lines, and the conductor loss of the films depends on the film type and thickness as well as the film quality obtained in the fabrication process. This indicates the importance of measuring metallic characteristics at MMW frequencies. We developed an exclusive measurement system that can derive conductor losses in absolute values with high accuracy[20]. After remodeling the system to make it easier to take measurements, we plan to use it to measure the properties of a variety of metallic films, and will incorporate the data obtained with it into the MMW circuit component development process.

5 Conclusions

This report described our research program on millimeter-wave (MMW) devices as the basic technology for practical establishment and dissemination of MMW communication systems in the future. It also outlined research and development subjects on testing and measurement techniques, which are essential for developing MMW communication devices in the course of undertaking this research program.

Critical factors for making technological progress aimed at practical use of the MMW frequency spectrum are (1) the development of various key technologies such as semiconductor devices, high-frequency circuit components, and wireless equipment, and (2) integrating these technologies into the invention of new devices and equipment engineering methods. Under this program, we aspire to create high capabilities in MMW circuit components and to develop new MMW wireless equipment technology, making use of the outstanding results that have been obtained in the concurrently undertaken Semiconductor Devices Research program. In this way, we aim to establish the core technologies for MMW equipment needed to put them to practical use. We are undertaking research programs on a wide range of MMW device technologies in cooperation with researchers from private sectors and from academic communities both domestic and overseas. A number of graduate students are also participating in the programs.

The recent economic downturn has resulted in a rather inactive state in the telecommunication industry with respect to the research and development of MMW technologies. In consequence public-sector organizations very likely will play a significant role in promoting research to develop MMW communication equipment. The Communications Research Laboratory, as one such organization, is committed to exploring the possible applications of the MMW frequency spectrum, in particular the 90-GHz band and higher. We are also committed to carrying out feasibility studies on new applications for it. As a global hub in MMW device technology research, we will continue to expand, re-organize, and improve our research system, thus enabling us to establish key technologies for and make significant technological contributions to practical use of the MMW frequency spectrum.

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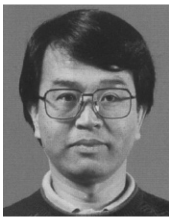

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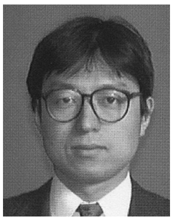
Millimeter-Wave devices High Frequency Measurements



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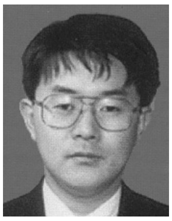
Millimeter-Wave Devices



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