Millimeter-Wave Research Activities in Japan

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***Abstract*— Millimeter-wave research activities in Japan are reviewed from various points of view. It is shown that a quarter of the papers presented at microwave sessions in the two major annual conferences of the Institute of Electronics, Information and Communications Engineers (IEICE), Japan, are millimeter-wave research papers. Monolithic microwave integrated circuit (MMIC) devices such as high-power amplifiers (HPA's), low-noise amplifiers (LNA's), and mixers developed by several companies are compared in terms of state-of-the-art performances. Unique cost-reduction techniques are also discussed. Two types of car collision-avoidance radar systems have been constructed using nonradiative dielectric waveguide (NRD-guide) technology peculiar to Japan. Topics presented at Microwave Photonics '96, Japan, are reviewed, with emphasis on the Japanese contributions to this field.**

I. Introduction

THIS paper is intended to give an insight into millimeter-wave research activities in Japan, particularly to readers abroad. Quasi-governmental and academic organizations for promoting millimeter-wave research and development will first be described. Then, state-of-the-art millimeter-wave techniques such as monolithic microwave integrated circuits (MMIC's), low-cost production techniques, and multichip module (MCM) techniques will be presented. Nonradiative dielectric waveguide (NRD-guide) technology will also be discussed since it shows great promise for practical applications.

Among many millimeter-wave applications systems which have been proposed to date, indoor local area networks (LAN's) and car collision-avoidance radar systems are nearing commercial availability. Another millimeter-wave application technology is millimeter-wave photonics, which may become a key technology for millimeter-wave mobile communications in the near future. In this connection, research presented at an international conference on microwave photonics (Microwave Photonics '96), held in Japan in December 1996, will be reviewed.

II. Projects and Organizations for Millimeter-Wave Research and Development

A. Quasi-Governmental Projects and Organizations

The first big project involving millimeter waves in Japan was the construction of circular-waveguide communications systems under the leadership of NTT during the period from the early 1950's to the middle 1970's [1]. Immediately after the project was terminated, due to the advent of practical optical fiber, the Communications Research Laboratories (CRL), Koganei-shi, Tokyo, Japan, started millimeter-wave propagation and scattering experiments for the exploitation of the unused frequency spectrum [2]. Recent projects at CRL are research and development of millimeter-wave indoor LAN's [3], millimeter-wave/submillimeter-wave devices [4], millimeter-wave remote sensing [5], and millimeter-wave propagation and communication experiments using satellites [6].

Millimeter-wave R and D companies such as ATR, Seika-cho, Kyoto, Japan, Milliwave, Yokohama-shi, Kanagawa, Japan, and Robotics, Ichikawa-shi, Chiba, Japan, were established around 1990 with funds from the governmental Japan Key Technology Center, Minato-ku, Tokyo, Japan, and have been engaged in the development of fiber-optic millimeter-wave subcarrier techniques [7], MMIC's [8], remote-control systems for unmanned vehicles, and so on. Though two of them have already finished their projects, ATR (now ATRI) is still engaged in a new project for developing advanced communications technologies.

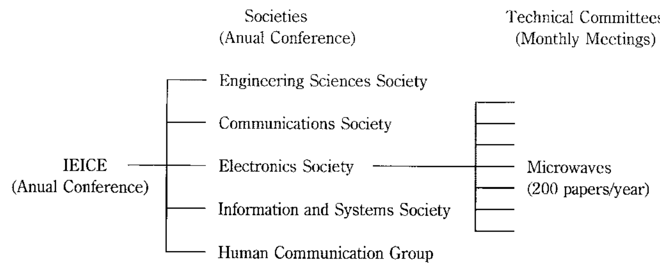

Fig. 1. Organization of IEICE.

B. Millimeter-Wave Research Activities in IEICE

The organization which is most strongly concerned with millimeter-wave research activities in Japan is the Institute of Electronics, Information and Communications Engineers (IEICE). As shown in Fig. 1, the Institute consists of four societies and one group, the group being a mini-society with a limited number of members and limited budget, and each society has several technical committees. The Technical Committee on Microwaves, which is the most active for millimeter-wave research, belongs to the Electronics Society. The Institute and each Society organize a General Conference and a Society Conference on an annual basis, respectively, and each technical committee holds monthly meetings. Over 100 papers are presented at microwave sessions of General and Society Conferences and over 200 papers are presented at

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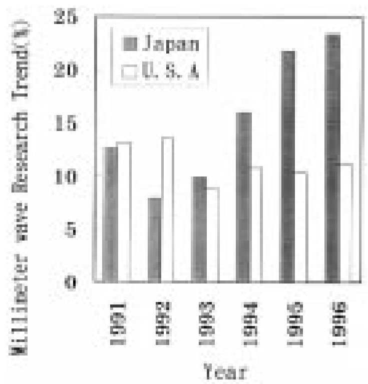


Fig. 2. Percentage of millimeter-wave papers presented at microwave sessions in IEICE conferences and MTT-S IMS.

monthly meetings of the Technical Committee on Microwaves every year.

Besides these domestic conferences and meetings, the microwave group in Japan is involved in the operation of a big international conference called the Asia–Pacific Microwave Conference (APMC), which is the Asia–Pacific region counterpart to International Microwave Symposium, (IMS) and European Microwave Conference (EuMC), and is held annually, in turn, by the regional countries. Japan has responsibility for APMC every four years and holds a three-day meeting called the Microwave Workshops and Exhibition (MWE) in years when the APMC is held outside of Japan. The efforts of many people in the field of microwave research and development from both the academic and industrial communities are united for the success of APMC and MWE.

C. Millimeter-Wave Research Trend

The trend of millimeter-wave research and development is considered, based on papers presented at the General and Society Conferences. Fig. 2 shows statistics which illustrate the fraction of millimeter-wave papers as a percentage of the total number of papers presented at microwave sessions. Comparison is made between Japan and the U.S. Data for the U.S. are taken from the IMS's held in recent years.

The drop seen in research activities in Japan around 1992 is, of course, due to the economical recession. In recent years, however, millimeter-wave research activities are recovering and a quarter of papers at the microwave sessions are related to millimeter waves. In the U.S., the percentage of millimeter-wave papers is fairly constant, but it should be noted that a considerable number of millimeter-wave papers are presented at the joint conference on MMIC's.

III. State-of-the-Art Millimeter-Wave Technologies [9]

A. MMIC Devices

Table I shows state-of-the-art performances of MMIC devices developed by Japanese electronics companies from 1994 to 1996.

TABLE I
State-of-the-Art Performance of MMIC Devices. (a) HPA's. (b) LNA's. (c) Mixers

COMPANIES	PERFORMANCES	REMARKS
MITSUBISHI	Gain 4.7dB P_0 23.0dBm @ 60GHz	AlGaAs/InGaAs PHEMT with Optimized Gate Width
TOSHIBA	Gain 42.6dB P_0 29.0dBm @ 41.5-42.0GHz	4-stage Pre-Amp. /4-stage Post-Amp.
NEC	Gain >20dB @ 48-60GHz	AlGaAs/InGaAs HJFEMT 3-stage Amp.
	Gain 7.0dB @ 94GHz	AlGaAs/InGaAs HBT
HITACHI	Gain 13dB @ 60GHz	GaAs PHET 3-stage Amp.
	Gain 16dB @ 77GHz	AlGaAs/InGaAs /GaAs 3-stage Amp.
MILLIWAVE/NEC	Gain 14dB P_0 17.1dBm @ 60GHz	AlGaAs/InGaAs HJFET 2-stage Amp.
	Gain 9.1dB P_0 16.8dBm @ 60GHz	30/60GHz Doubler 2-stage Amp.

(a)

COMPANIES	PERFORMANCES	REMARKS
MITSUBISHI	Gain 8.1dB NF 1.8dB @ 50GHz	AlGaAs/InGaAs PHEMT
	Gain 42.2dB NF 3.0dB @ 51GHz	PHEMT 4-stage Amp. in Hermetically Sealed Package.
TOSHIBA	Gain 7.6dB NF 0.9dB @ 57GHz	InAlAs/InGaAs PHEMT
	Gain 12.0dB NF 5.6dB Using MS @ W-band Gain 10.0dB NF 7.0db Using CPW @ W-band	AlGaAs/InGaAs/GaAs PHEMT 3-stage Amp.
NEC	Gain 11.5dB NF 3.0dB @ 59GHz	AlGaAs/InGaAs HJFET 2-stage Amp.
	Gain 17.2~18.3dB NF 3.2~3.7dB @ 58~62GHz	HJFET 3-stage Amp. with Single Bias Supply

(b)

COMPANIES	PERFORMANCES	REMARKS
SHARP	Lc 9dB @ 60GHz	InGaP/GaAs HBT Single Mixer
MITSUBISHI	Lc <16dB @ 54~60GHz	Image Rejection Harmonic Mixer
	Lc 8.4-12.5dB P_{LO} -2~0dBm @ 55~60GHz	InP HEMT Low Local Power Resistive Mixer
NTT	Lc 6±1dB P_{LO} -7dBm @ 55~66GHz	PHEMT Uniplanar Resistive Mixer RF Amp., LO Amp., Mixer on Chip
NEC	Lc 7.7dB @ 40GHz P_{LO} 10dBm @ 10GHz	Subharmonically Pumping Mixer with Multiplier
MILLIWAVE/FUJITSU	Gc >20dB NF <3.6dB P_{LO} 5dBm @ 59-61GHz	InGaP/InGaAs HEMT Mixer with 4-stage LNA

(c)

1) High-Power Amplifiers (HPA's): Mitsubishi, Kamakura-shi, Kanagawa, Japan, has developed an HPA with an output power of 23 dBm at 60 GHz by carefully optimizing the gatewidth of an AlGaAs/InGaAs pseudomorphic high electron-mobility transistor (PHEMT). Toshiba, Kawasaki-shi, Kanagawa, Japan, has obtained an output power of about 1 W by means of a four-stage preamplifier followed by a four-stage post-amplifier at 42 GHz. This HPA was developed for use in the short-range field pickup of television broadcasting at the Nagano Winter Olympics. NEC, Tsukuba-shi, Ibaragi, Japan, has used an AlGaAs/InGaAs heterojunction bipolar transistor (HBT) for the construction of a power amplifier with a gain of 7.0 dB at 94 GHz. Milliwave/NEC have demonstrated that the combination of a 30-GHz/60-GHz doubler and a two-stage amplifier can produce an output power of 16.8 dBm at 60 GHz.

2) Low-Noise Amplifiers (LNA's): Mitsubishi reported a record minimum noise figure (NF) of 1.8 dB for GaAs high electron-mobility transistors (HEMT's) at 50 GHz. Immediately after Mitsubishi's achievement, Toshiba obtained a better NF of 0.9 dB at 57 dB using an InAlAs/InGaAs PHEMT. An LNA developed by NEC features a single-bias voltage supply.

3) Mixers: Mitsubishi's InP HEMT mixer requires only a low LO power for operation. NTT, Yokosuka-shi, Kanagawa, Japan, has fabricated a uniplanar type of mixer together with RF and LO amplifiers on one chip. The required LO power is as low as −7.0 dBm for operation over a 10-GHz frequency range from 55 to 66 GHz. A mixer developed by Milliwave/Fujitsu, Kawasaki-shi, Kanagawa, Japan, is backed up by a four-stage LNA, and has a conversion gain in excess of 20 dB, as well as an NF less than 3.6 dB.

B. Low-Cost Millimeter-Wave Manufacturing Techniques

Though MMIC technologies have been developed, they are still not practical for consumer applications because of the high cost required for production. A new keyword in the field of millimeter waves is "low cost." Two symposia were recently held at annual conferences to discuss low-cost millimeter-wave manufacturing techniques. Topics presented there are summarized below.

1) Uniplanar MMIC's: A novel technique for fabricating uniplanar MMIC's has been proposed at NTT Wireless Systems Laboratories, Yokosuka-shi, Kanagawa, Japan [10]. As shown in Fig. 3, it employs coplanar waveguides (CPW's) and slotlines instead of conventional microstrip lines. It has been proven that uniplanar MMIC's require a smaller linewidth and smaller line spacing than their microstrip counterparts. In addition, there is no need for polishing the bottom of the substrate and for making via holes in the uniplanar structure. Thus, a one-fifth reduction of both chip size and device cost can be achieved.

2) Multilayer MMIC's: It has been proposed at ATRI that the bump–bonding technique can be applied to multilayer MMIC's. Each layer is shielded by an upper and a lower metal sheet and is connected by bumps in a stacked manner, as shown in Fig. 4. This technique is useful for constructing multilayer MMIC's at low cost, as well as for reducing parasitic reactances associated with interconnection between layers.

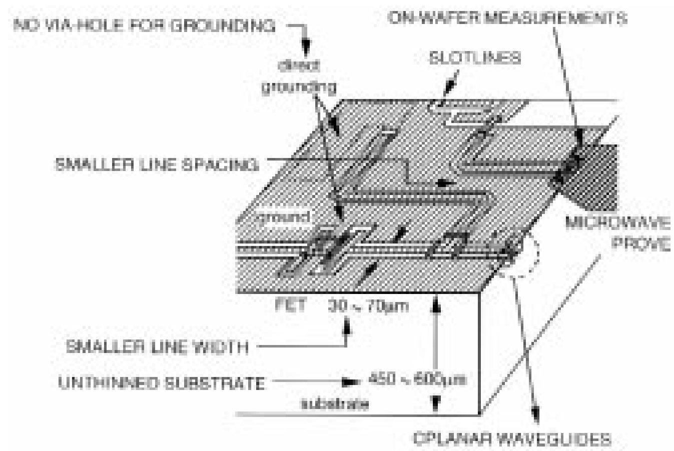


Fig. 3. Advantages of uniplanar MMIC.

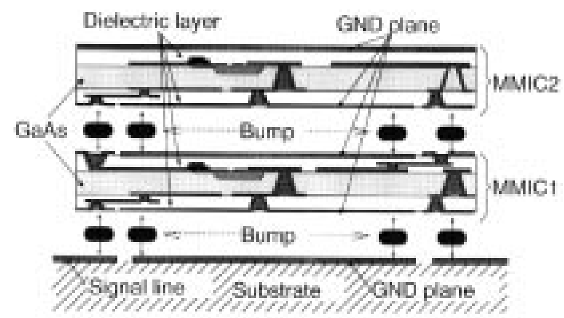


Fig. 4. Stacked multilayer MMIC.

3) Masterslice MMIC's: The concept of masterslice MMIC's has been proposed by researchers at NTT Wireless Systems Laboratories [11]. The master array, which contains transistors, metal–insulator–metal (MIM) capacitors and resistors, is created in the bottom layer, and transmission lines are built in the upper layers, as shown in Fig. 5. MMIC's can be fabricated by making connections between transmission lines and necessary components selectively. By using this technique, a one-chip receiver has been built for microwave frequency. It may be expected that the masterslice technique can be extended to the millimeter-wave frequency range in the near future.

4) Flip-Chip Technique: The flip-chip technique is becoming increasingly popular and important in the field of millimeter waves. The Matsushita Group, Kawasaki-shi, Kanagawa, Japan, has developed a unique and innovative flip-chip technique which uses the micro-bump bonding (MBB) technique and benzocyclobutene (BCB) for the substrate instead of SiO_2 [12]. Transmission loss of the microstripline on BCB is one-third of that on its SiO_2 counterpart. No thermal bonding is needed for MBB. Bonding is carried out by placing gold bumps and transistor chips on microstrip lines, adding light-setting insulating resin, and finally, illuminating the resin by light, as shown in Fig. 6. The resin is shrunk and hardened by light illumination to hold bumps and chips in position. Thus, low-cost as well as low-parasitic connections can be achieved

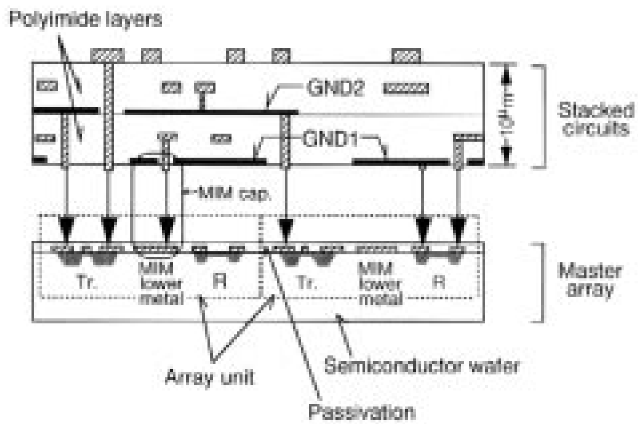


Fig. 5. Masterslice three-dimensional (3-D) MMIC.

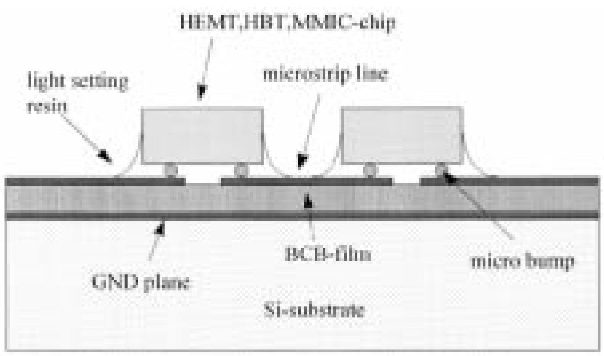


Fig. 6. Technique of micro-bump bonding.

simultaneously. This is an innovative low-cost millimeter-wave production technique recently developed in Japan.

5) Multichip Modules (MCM's): The MCM technique was discussed in comparison with hybrid integrated circuit (HIC) and MMIC techniques at a symposium held jointly with the Society Conference in 1996. It was discussed from the viewpoints of development cycle, performance, size, cost, and RF skills required. The general conclusion was that the MCM technique is preferable to the other two competitive techniques for all items at the subsystem level, though MMIC's have the advantage in small-size devices.

C. NRD-Guide Technology

NRD-guide is the rectangular dielectric waveguide inserted in a below-cutoff parallel-plate waveguide. Unwanted radiation, if any, is suppressed by the cutoff nature of the parallel-plate waveguide [13]. Though the NRD-guide is practical, it contains two nonradiating modes, one being the LSM_{01} mode and the other being the LSE_{01} mode. The LSM_{01} mode is chosen as the operating mode due to its smaller transmission loss, but its cutoff frequency is higher than that for the parasitic LSE_{01} mode. This causes trouble at curved sections of the waveguide because these two modes couple with each other if the bending radius is too small.

An innovation has recently been made by Murata Company Ltd., Nagaokakyo-shi, Kyoto, Japan. They have proposed a grooved NRD-guide to hold dielectric strips in position and have calculated cutoff frequencies of the two nonradiating modes against the depth of groove, as shown in Fig. 7. Crossover of the two dispersion curves takes place at a certain depth of groove. If the frequency and groove depth are chosen to be, say, 55 GHz and 0.6 mm, respectively, a single-mode operation is possible with the LSM_{01} mode. Thus, the coupling phenomenon at curved sections disappears and a very sharp bend can be created. This grooved NRD-guide is called the Hyper NRD-guide by Murata.

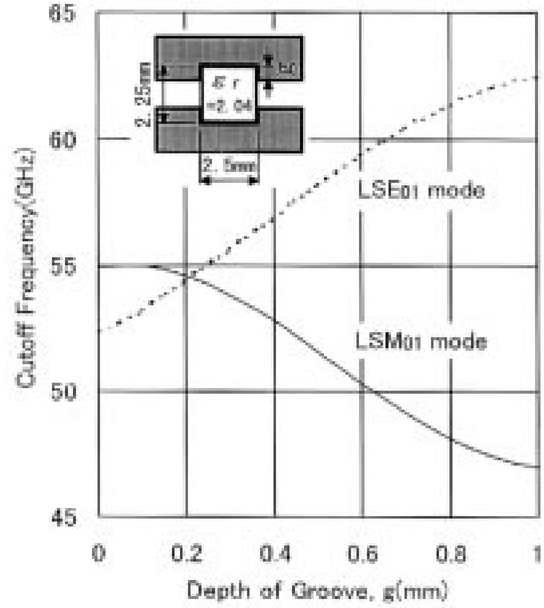


Fig. 7. Cutoff frequencies of hyper NRD-guide modes.

Actually, the grooved NRD-guide was previously studied both in Japan and China, but the grooves were found to be too shallow. An NRD-guide with shallow grooves is worse in performance than the normal type of NRD-guide because cutoff frequencies of the relevant two modes are closer to each other and coupling becomes more problematic.

IV. Millimeter-Wave Applications

Though many millimeter-wave applications systems have been proposed, indoor LAN's and car collision-avoidance radar systems have the greatest potential demand and are the most promising. A research project on millimeter-wave indoor LAN's is currently in progress at the CRL, while car collision-avoidance radar systems are being fabricated at several companies using MMIC and NRD-guide technology. Millimeter-wave photonics is a challenging and emerging technology, and is expected to produce entirely new millimeter-wave applications in conjunction with optoelectronic technology.

A. Millimeter-Wave Indoor LAN's

A large-scale facility for the millimeter-wave indoor LAN experiments has been built at CRL. By using NRD-guide transceivers with a bit rate in excess of 100 Mb/s at 60 GHz, intensive experiments have been carried out for investigating

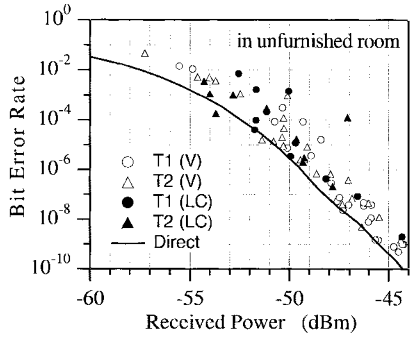
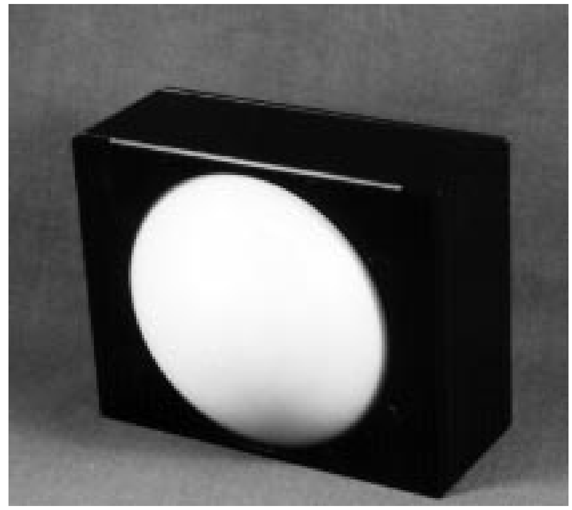


Fig. 8. Received power and bit error rate in indoor LAN. V: Vertical polarization. LC: Left-handed circular polarization. Direct: Direct connection of transmitter and receiver.

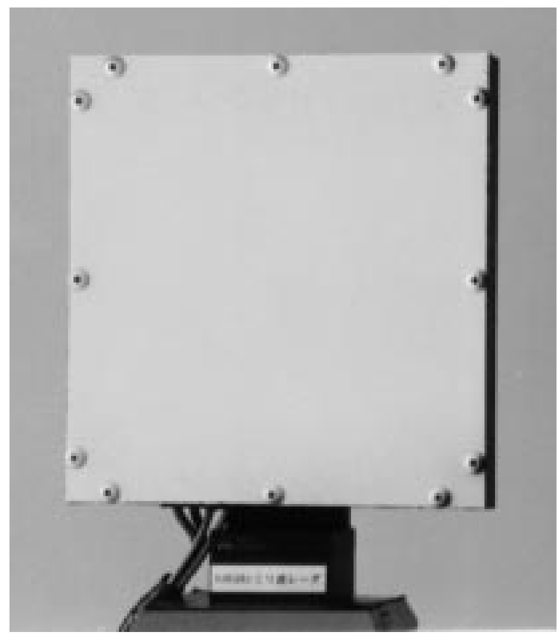
the feasibility of indoor LAN's under various propagation conditions [3]. Typical results of measurements indicate a close correlation between bit error rate and received power, suggesting that the larger the received power, the smaller the bit error rate, as shown in Fig. 8. The conclusion obtained from these experiments is that a bit error rate lower than 10^{-8} can be attained, provided that the received power is larger than -45 dBm under line-of-sight propagation.

B. Car Collision-Avoidance Radar

The practical use of car collision-avoidance radar is just around the corner. The Fujitsu group has developed a 60-GHz band front end for frequency modulation–continuous wave (FM–CW) radar, which features small transmission power achieved with the aid of the switching heterodyne technique [14]. NRD-guide technology is also a promising candidate for collision-avoidance radar systems. Murata Company Ltd. uses a hyper NRD-guide and a dielectric lens antenna to fabricate a compact FM–CW radar front end at 60 GHz, as shown in Fig. 9(a) [15]. An NRD-guide has also been applied to build a planar antenna which has sufficient space to implement a radar front end. The planar antenna with a built-in front end is smaller than the number plate of a car in area and is 10 mm in thickness, as shown in Fig. 9(b). The gain is 31 dBi, and the half-power beamwidths are 2.1° in the E-plane and 2.8° in the H-plane, respectively [16].



(a)



(b)

Fig. 9. Car collision-avoidance radar systems with (a) lens antenna and (b) planar antenna.

C. Millimeter-Wave Photonics

Millimeter-wave photonics is an interdisciplinary research field involving both millimeter-wave technology and optoelectronics. It includes the fiber-optic millimeter-wave subcarrier technique for microcell and picocell mobile systems and LAN's, optically controlled phased-array antennas, on-chip optical characterization of MMIC's, and so on. The Topical Meeting on Microwave Photonics was held in Japan in December 1996. Over 200 participants, including 50 from abroad, attended the meeting [17]. In order to give a brief insight into the meeting, papers presented by Japanese invited speakers will be reviewed.

1) TV-Signal Reception: The first topic presented by the Tokin Corporation Group, Tsukuba-shi, Ibaragi, Japan. was concerned with TV-signal reception rather than millimeter waves [18]. A receiving antenna is provided with an electrooptic modulator having input and output optic fibers running to the satellite station. Optical waves in their round trip from the station are modulated by radio waves which are received by the antenna, and the radio waves are recovered with a carrier noise (C/N) ratio of about 50 dB at the station for delivery to each TV viewer. This technique can be applied to TV-signal relay in an isolated area. Since the antenna and the station are connected by optic fiber instead of coaxial cable, serious damage by lighting can be avoided.

2) Inter-Satellite Optical Links: Researchers at CRL have discussed technical bases and requirements for constructing inter-satellite optical links [19]. They also presented data obtained by the first ground-to-satellite communications experiments performed from December 1994 to July 1996 using the ETS-VI satellite to study the feasibility of space laser communications.

3)Pulse Generation: Experiments on ultrashort pulse generation have been carried out by a research group from OKI Company, Ltd., Hachioji-shi, Tokyo, Japan, by using a newly fabricated mode-locked semiconductor laser [20]. A train of optical pulses with a duration of 2.3 ps has been produced from the laser diode at a high repetition rate of over 33 GHz. Subpicosecond pulses at high repetition rates of 400, 800 GHz, and 1.5 THz with an output power of 16 mW have also been obtained by harmonic passive mode locking. The timing jitter of the mode-locked laser is reduced to less than 1 ps by electrical- and optical-signal injection techniques.

4) Optical Devices: Ultrahigh-speed optical devices have been developed for future optical-fiber communications systems at NTT Opto-Electronics Laboratories, Atsugi-shi, Kanagawa, Japan [21]. These devices are a ridge-type $LiNbO_3$ Mach–Zehnder optical modulator, an electroabsorption multiple quantum well (MQW) semiconductor modulator, and a mushroom–mesa multimode waveguide photodetector. Performances of the fabricated optical devices are summarized as follows: the $LiNbO_3$ modulator exhibits a 100-GHz band, 5-V driving-voltage operation, and a 45-GHz band, 3.3-V driving-voltage operation depending on broad-band design and low-voltage design, respectively. The MQW semiconductor device has a 40-GHz band and a 1.8-V driving-voltage operation which has been found to be sufficient to conduct optical transmission experiments of 40 Gb/s. The photodetector has a 3-dB bandwidth of 110 GHz and an external quantum efficiency of 50% at 1.55 μm with a lensed fiber.

5) Modeling: The last topic presented by Koshiba and Tsuji [22] is concerned with design and modeling of microwave photonic devices. Using the quasi-TEM finite-element method (FEM) and the full-wave vector FEM (VFEM) for a millimeter-wave waveguide problem and the scalar FEM (SFEM) for an optical-waveguide problem, modulation characteristics of a traveling-wave (TW) $LiNbO_3$ optical modulator with a ridge structure were successfully simulated. For the first time, the VFEM solver was applied to the full-wave analysis of millimeter-wave propagation characteristics in TW optical modulators. These solvers are expected to be applicable to modeling of other millimeter-wave photonic devices such as semiconductor modulators and photodetectors.

Microwave/millimeter-wave photonics is an emerging technology in which millimeter waves are expected to play an important role.

V. Conclusions

Millimeter-wave research activities in Japan have been reviewed from a variety of viewpoints. Indoor LAN's and car collission-avoidance radar systems are the most promising millimeter-wave applications, but high-cost components and devices prevent their wide use. The key issue for the promotion of millimeter-wave consumer applications is the development of low-cost techniques. Various approaches being pursued in Japan were reviewed in this paper.

Some materials referred to in this paper are taken from the Digests of General and Society Conferences of the IEICE over the last three years. Though they are written in Japanese, some of them are expected to appear in English soon.

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