Commercial Applications of Millimeterwaves History, Present Status, and Future Trends

Holger H. Meinel, *Senior Member, IEEE*

***Abstract*—The possibility to apply millimeterwaves for various applications in the commercial arena has a long history, as the advantages being offered by such systems have been known for more than three decades. Within the last five years the necessity of turning their attention away from the military sector towards commercial products has caused more and more companies to look at millimeterwave communications and automotive radar. By chance, this was accompanied by the advent of low-cost integration procedures, i.e., hybrid- and monolithic-integration techniques, respectively. Thus, the necessary technology is mature and available now, opening a wide field of deployment areas. Millimeterwave systems have found an ever increasing interest, due to their specific advantages, as well as the lack of frequencies for new services. While the military market is decreasing, commercial applications in the area of microwave tags, radio communication, and traffic control are increasing rapidly. The two most important application areas right now are: 38 GHz short-haul transmission links for PCN installations, an already valuable niche market, and 77 GHz automotive radar sensors—simple collision warning devices and intelligent cruise control sensors as well—which have the largest market potential for the very near future.**

I. Introduction

The advantages of millimeterwave systems are commonly known today, as they have been employed in specific, mostly military applications, for two decades at least. Two major commercial application areas may be distinguished, millimeterwave communications [1] and automotive traffic control [2], the latter including all aspects of road transport informatics (RTI). Since the early 1970's millimeterwave communications has been a focus of research in Japan, fostered and heavily supported by MITI, leading to mature and widespread 50 GHz radio links today. During the same time period, millimeterwave research was also pursued in the U.S., but mostly aimed at military applications, such as seekers for smart weapons, the adverse weather alternative to IR-guided systems. Due to the MIMIC[1] program a variety of monolithic integrated circuits at 35, 44, 60, or 94 GHz, respectively, are available today. Only recently, with the dramatic decline of military spending, has the focus of the millimeterwave industry in the U.S. turned to advanced vehicular technology, i.e., collision avoidance radar to start with. Further applications in the area of RTI are foreseen under the umbrella of the IVHS program. In Europe, the approach was twofold: while developing smart seekers, the first dual-mode, millimeterwave-IR seeker was flight tested by AEG in 1987, the commercial area was not at all forgotten. As early as 1975 AEG-Telefunken/Bosch and Daimler–Benz/SEL in Germany showed their first operating 35 GHz anticollision radar sensors, as did Lucas in the U.K. Radiotube communication at 40 GHz was tested in Germany in 1979, while 29 GHz transmission was implemented in the U.K. in the early 1980's, as 31 GHz communications were tested in France. Apart from the unique propagation behavior, millimeterwave applications take advantage of the highly directive nature of the propagated beam, thus millimeterwave systems are small in size and lightweight, compared to their microwave counterparts. However, it is only today that demand pull has taken over from the usual technology push. The lack of frequencies in the microwave bands commonly used is the important reason today to move into the higher frequency regime.

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The author is with the Daimler–Benz Aerospace AG, Postfach 80 11 09, D-81 663 München 80, Germany.

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[1] Microwave and millimeterwave monolithic integrated circuits (MIMIC), is a more than $500 million U.S. DARPA R&D program, initiated at the end of the 1980's; the follow-on program, MAFET, is currently under consideration.

II. Component Technology

The spreading application of millimeterwaves today has become possible due to rapidly advancing component technology being available, e.g., [3] and [4]. Some recent advances are reviewed.

A. Transmitter Performance

Millimeter-wave solid state source capability for local oscillator applications employing GaAs as well as InP GUNN elements, i.e., two terminal devices, is well developed, as are three terminal devices, like HEMT's or HBT's. A good overview is given in [5]. A 35 GHz VCO (HBT) delivers two mW of output with −80 dBc/Hz. High power solid state source capabilities are still somewhat limited. Silicon Impatt diodes for operation with 1 W of continuous and 42 W of pulsed output power have been demonstrated, using MBE grown silicon double drift diodes; however, for some system applications, this is still not enough. Here the development of mini-magnetrons with a volume of some tens of ccm, delivering more than 400 W of pulsed output power (about 1 W mean) out of a low voltage power supply (24 V only) in the 80 and 94 GHz bands [6], is significant.

B. Receiver Performance

Hybrid integrated receivers, employing beam-lead Schottky–Barrier GaAs diodes on finline or microstrip circuits are in production for frequencies up to 150 GHz. Noise figures of 7 dB are typical at 94 GHz. A microstrip hybrid integrated receiver unit, consisting of two STC/mixer circuits and LO

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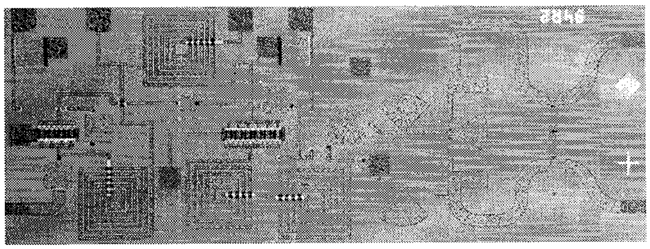

Fig. 1. 94 GHz MMIC receiver. (Courtesy of Daimler–Benz Aerospace AG.)

power divider built by Thomson-CSF of Malakoff, France exhibited very good reproducibility. A lot of about 40 mixer units showed an overall noise figure of 8.5 dB ± 1.5 dB, using GaAs Schottky–Barrier mixer diodes. However, this is only one way to realize integrated receivers. Fig. 1 presents a monolithic integrated 94 GHz receiver chip, consisting of a single balanced mixer and a single stage IF-amplifier, built by Daimler–Benz Aerospace AG of Ulm, Germany. This balanced mixer shows a minimum noise figure of 6.5 dB (dsb) at 94 GHz [7], while the amplifier gain was 20 dB over the 0.5–1.5 GHz IF band.

III. Millimeterwave Communications

Atmospheric propagation effects strongly influence considerations related to the application of millimeterwave transmission. Normally, such systems will be operated in the atmospheric windows around 35 and 94 GHz. For specific applications the maximum absorption range around 60 GHz may be used [8]; 50 GHz applications, taken as a compromise between atmospheric absorption and rain attenuation, have been especially fostered in Japan.

A. Early Research Systems

Early work in the area of point-to-point millimeter wave links has been carried out in Japan, and was published in in the late 1970's [9], [10]. Japan was preparing itself for the upcoming Information Technology Age in the late 1990's. Taking frequency availablity as a natural resource, new, up to then unused frequencies, had to be made available in order to prepare for future demands.

1) 40 GHz OKI System: The entire transceiver system, containing the RF-front end and the PCM-modem, was housed in a cabinet, measuring (500 × 500 × 580) mm (height × width × depth), the antenna being integrated. A simplified system design, using a single Impatt diode oscillator functioning as transmitter, frequency converter, and local oscillator simultaneously was built having the following performance [9].

Output power	200 mW
Receiver noise figure	8 dB
Antenna gain	43 dB.

According to the FCC regulations in the U.S., 14 duplex RF-channels (28 total) have been assigned between 38.6 and 40.0 GHz; the channel separation being 700 MHz.

2) 40 GHz NTT System: To ease transportation and installation work, antenna, RF-circuit, and FM-modem of the NTT system are integrated in a single ball-shaped container. Equipment economization was accomplished by simplifying the system design with the adoption of dual conversion receiver techniques [10]. System parameters, like

Output power	100 mW
Mixer noise figure	11.5 dB
Antenna gain	45.5 dB.

could be achieved. Power can be supplied either by converting 100 V AC commercial power or by a battery, having a capacity of two hours, if the main power supply should fail or be interrupted. Measurements being conducted in the city of Tokyo were quite promising. Arepeater spacing of 4 km is sufficient to cover almost the entire city.

These two first examples demonstrate that millimeterwave transmission is very well suited for telephone network enhancement and video transmission. Concerning densely populated areas, where the enlargement of normally used cable connections is very costly, this is a major advantage. Furthermore they show how thoughtful and adaptive circuit design, single oscillator approach or dual conversion techniques, can be used to simplify the system realization; i.e., to reduce the system cost.

Besides Japan, point-to-point millimeterwave communication has been under research in Europe, also.

3) 31 GHz CNET System: Taking advantage of the millimeterwave approach, compactness of the RF-components, narrow beamwidth with likewise small antenna apertures, etc., the 31 GHz CNET System was developed by Thomson–CSF under contract from the French Telecommunications Administration (CNET) to connect groups of less than 10 remote subscribers, thus, compared to the above, a very different application. It was introduced into the French network in 1983 [11].

The RF-equipment and the antenna are included in a cylinder measuring 20 cm in length and 25 cm in diameter. The millimeter set is associated with a digital multiplexer of 8 or 10 telephone lines. The major system parameters are

Transmitted power	50 mW
Receiver noise figure	12 dB
Antenna gain	35 dB.

A 9 km long link was developed in 1980. An important result was, that for −85 dBm received input power a BER of 10 exp (−4) could be achieved, demonstrating that millimeterwaves are well suited for connecting remote subscribers.

These three examples emphasize the versatility of the millimeterwave approach for communication links, operating in the lower millimeterwave regime, i.e., between 26 and 50 GHz, and are ideally suited to connect telephone subscribers at low cost, in densely populated as well as in remotely populated areas (OKI-/CNET-system). Ease of installation or mobility of color TV transmissions is another very important application (NTT-system).

B. State-of-the-Art Prototype Systems

Based on these promising results, customized digital distribution radios have been developed. More than 7,000 millimeterwave point-to-point radio links are already installed in Japan alone. The most important employment area for millimeterwave communication equipment today is in connecting

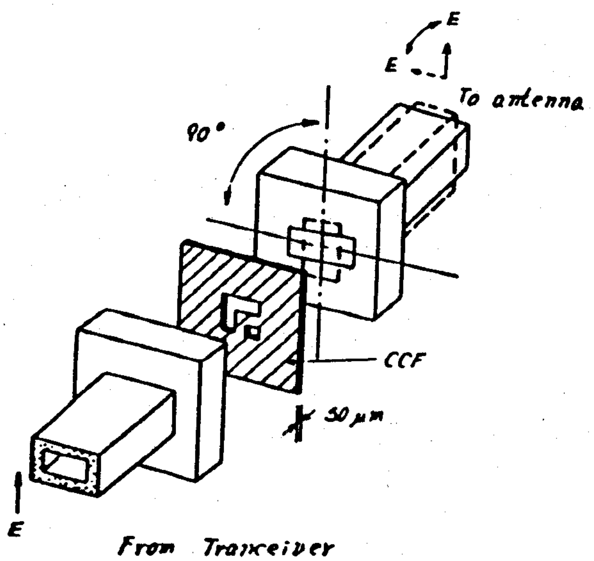

Fig. 2. FACOM 2160 cross coupling filter design (from: Dooi *et al.* [14]).

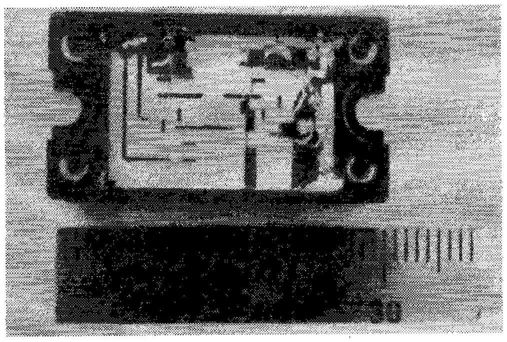

Fig. 3. 50 GHz Matsushita system 25 GHz FM modulator, realized (from: Ogawa *et al.* [15]).

subscribers, for example in private data, TV, and telephone circuits. Prototype developments aiming at this market are ongoing at 38 and 60 GHz, namely, at Alcatel-Telettra in Italy [12] and Alcatel-Telspace in France [13], respectively. The latter, turning its attention away from waveguide to hybrid technologies like microstrip and finline for the realization of the mixing devices, the filters, the switches, and the modulators, only the oscillator was built in waveguide, providing higher output power and better spectral purity, while the former is heading directly to MMIC's, i.e., monolithic integration. The different design and technology approaches to meet the inherently stringent low cost requirements, the above described early research systems made use of standard waveguide components for the realization of the RF-frontends, a technology too costly to be taken for production, as well as corresponding technical data of prototype and series systems will be presented.

1) FACOM 2160—50 GHz Fujitsu Radio System: Being either usuable for digital data transmission up to 20 Mb/s or for wide-band analog signals such as color TV, the FACOM 2160 system built by Fujitsu of Kawasaki, Japan [14], features 2–5 km of hop length, depending on the performance being required and the antenna being taken. The major data of this system are: An output power of 10 mW and a receiver noise figure of 17 dB. Two types of antennas, parabola, and horn, with a gain 40 and 22 dB, respectively, can be taken.

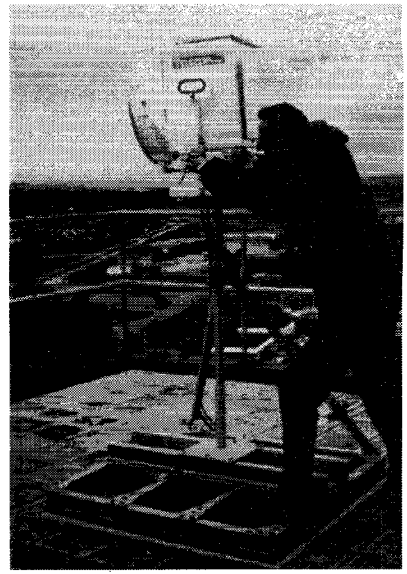

Fig. 4. 29 GHz BTRL system installation (courtesy of BT).

To prevent interference problems, if two or more transmitters on the same frequency are used in the same neighborhood, the FACOM 2160 features a unique, but simple solution: the cross-coupling filter (CCF), shown in Fig. 2. Horizontal or vertical polarization can be selected, simply by rotating the attached antenna by 90 degrees.

High resolution MIC technology on 0.2 mm alumina substrates is used for the integrated 50 GHz components [15] to allow low cost mass production of the RF-circuits; realizing the Varactor tuned DRO at 25 GHz with a doubler circuit following. Thus the circuitry is compatible with all HEMT MWMIC technology, leading to low power consumption, and low production costs.

2) 50 GHz Matsushita System: A good example for a transmission link making use of state-of-the-art hybrid microstrip technology is the 50 GHz Matsushita system, built by Matsushita Electric Ltd. of Osaka, Japan [15]. Having an output power of 10 mW and a receiver noise figure of 13 dB, a hop length of approximately 5 km can be achieved.

This system employs three-terminal devices only and takes advantage of hybrid MIC integration at 25 GHz with doubler circuits following. These GaAs FET frequency doublers exhibit a minimum conversion loss of 2.6 dB, while the 25 GHz FM modulator is frequency stabilized, using a dielectric resonator: 2 ppm/C from −20 to 60 C is achieved, the realized device being shown in Fig. 3. Newly developed miniature probe type microstrip-to-waveguide transitions with an insertion loss of less than 0.5 dB at 50 GHz allow the hermetic seal of this very compact RF-front end.

3) 29 GHz BTRL System: An example of a European point-to-point transmission link is the 29 GHz BTRL system. Early work at British Telecom Research Laboratories (BTRL) was concentrated on developing a 70 Mbit/s system for transmission of data and fullband video traffic [16]. Fig. 4 shows the installation. Corresponding system parameters are an output power of 150 mW and a receiver noise figure of 8 dB. The antenna gain was measured to be 41 dBi.

Philips Resarch at Redhill, England, who developed the RF components of this 29 GHz system, has chosen finline technology for the realization, as it has emerged as a front runner for frequencies of about 25–100 GHz. Finline technique features relatively low loss and the conductor patterns are on circuit boards, which can be made reproducibly using conventional photolithographic techniques.

The RF-front end contains the integrated finline modules, to which the GUNN diode local oscillator and the transmitter sources are mounted. The transmitter unit includes a biphase modulator, a voltage controlled attenuator, and a monitor coupler for checking power and frequency. The receiver unit contains a low noise balanced mixer with integrated IF preamplifier, an attenuator to adjust the LO level to the mixer, and a monitor coupler for oscillator power and frequency checking. The entire RF assembly is desiccated to avoid hermetic sealing. A maintanance interval of two years was foreseen. Seventy transceiver units of this type have been built in the early 1980's, and they have been operational ever since.

4) Pasolink 50—50 GHz NEC Radio System: The Pasolink 50 radio system built by NEC of Yokohama, Japan [17] was as well designed for transmitting various kinds of information: data, video, fax, and voice. The system is deployed within a water-resistant cabinet, the antenna being mounted onto the cabinet. The cabinet dimensions are: (180 x 120 x 260) mm, (width x height x length). With an output power of 100 mW, the receiver noise figure obained was 15 dB. Two types of antennas, parabola and horn, with a gain 40 and 20 dB, respectively, can be chosen.

Having a data rate of 1.544 and 6.312 Mb/s, respectively, a hop length up to 7 km can be achieved, depending on the outage time and the antenna, being allowable.

As far as applicable MIC technology was taken for the realization of this radio system. A quadrupled 13 GHz varactor tuned GaAs FET dielectric resonator oscillator (DRO) serves as transmitter, the single-ended mixer was realized on alumina substrate with a beam-lead type Schottky-Barrier diode. The chosen modular set-up of this system fits very nicely into the NEC's Microwave and VHF/UHF Communications Systems Menu [18].

These further examples testify to the maturity of different millimeterwave component design approaches, hybrid microstrip or finline, with HEMT or GaAs FET devices, hermetically sealed or desiccated, as well as the availability of well-adapted millimeterwave system designs, employing frequency doublers or quadruplers, to comply with already existing system designs to produce reliable and market fitting millimeterwave units. The applicability of the millimeterwave approach, based on demand pull, is undoubtlessly demonstrated.

C. Short-Haul Line-of-Sight Transmission Links for PCN's—The Actual Market

Today the field of mobile communication is moving rapidly. Crossborder agreements in Europe have paved the way for a group special mobile (GSM) pan-European digital mobile cellular network [19], because the demand for communication services that can be provided without the need for cable connections is growing. Potential users become aware of the advantages gained from services such as cordless telephone or mobile cellular radio.

The potential to use millimeterwave radio in such networks is great and may well become the major economic driver implementing such a network [20].

Mobile telephones communicate at 0.9 or 1.8 GHz within cell sizes of 1 to 5 km in diameter. Groups of five to 20 of these cells have to be linked to a base station and this is the valuable niche market, where millimeterwave radio fits in. Depending on the hop length being necessary topologywise, 23, 38, or 55 GHz usage is appropriate. For the new German DCS 1800 mobile telephone network called E-plus, for instance, a total requirement of 16 000 38 GHz-T/R-units has been estimated to be necessary before completion of the installation in 1998. Spare units for maintenance and redundancy for hot spots are not yet taken into account. Thus, the commercial exploitation of this greatly underutilized region of the frequency spectrum is upcoming.

Until today, in most cases, hybrid millimeterwave technology was employed predominantly. However, MMIC technology is incorporated now, as it has become available. Alpha Industries of Methuen, MA, alone has shipped more than 2000 monolithic 38 GHz chip-sets worldwide in 1994 [21]. Fig. 5 displays the unique situation of Alpha Industries as a key-player in this field, providing 38 GHz chipsets for most of the major equipment manufacturers.

1) 40 DR–38 GHz Northern Telecom System: A recent example for a transmission link taking advantage of this state-of-the-art MMIC technology is the 40 DR communication system at 38 GHz delivered by Northern Telecom Europe, Ltd. of Paignton, England [22] and manufactured by MRC (Microwave Radio Corporation), a subsidary of California Microwave in the U.S. The integrated GaAs MMIC type components of which are being supplied by Alpha Industries of Methuen, MA [23]. The 40 DR Digital Millimetric Radio System consists of a lightweight outdoor RF unit, a high performance antenna, and an indoor digital interface unit. The modular design allows the user to upgrade the system in the field according to the specific needs of the customer.

The transmitter module is based on two MMIC's, a voltage controlled oscillator, and a power amplifier, the other components within the (26 x 15 x 13) mm module being for temperature compensation and bias regulation. The receiver module, Fig. 6 shows the realization, is actually slightly larger, and it draws on a combination of GaAs MESFET, Schottky, and Si MMIC technologies. The mixer is a GaAs MMIC; a Schottky-diode based rat race-balanced device with an IF frequency range between 10 MHz and 1 GHz. A Si MMIC was used for the IF amplifier. The resulting DSB phase noise is quoted at 5.5 dB.

The RF unit is housed in a weatherproof enclosure, that can be mounted directly on the antenna or separately to a tower support or wall. Connection to the antenna is made by rigid or flexible waveguide. Precision high performance antennas, being of the center fed reflector type, are available in diameters of 300 and 600 mm. The 300 mm diameter antenna, for example, has 37 dBi of gain and maximum sidelobe levels 23 dB down at ± 5 degrees from boresite at 38 GHz.

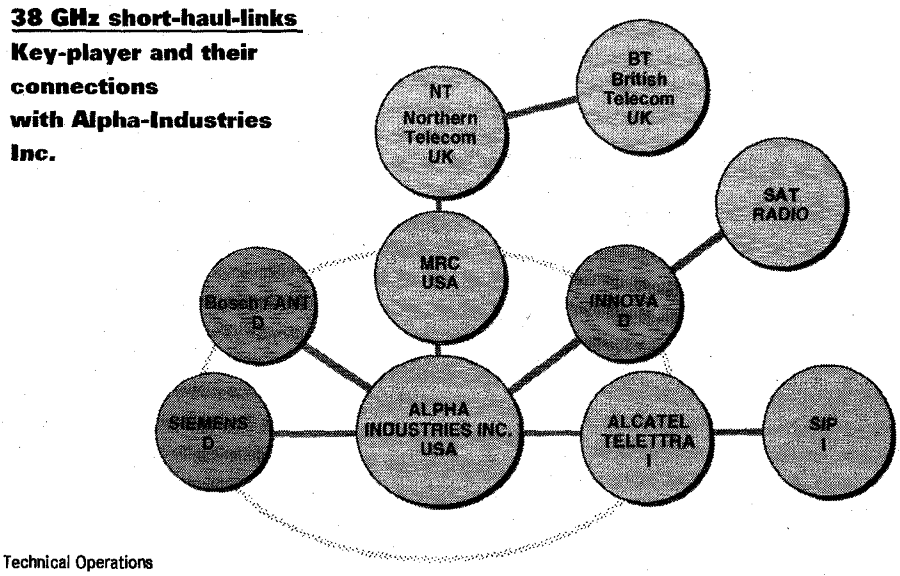

Fig. 5. 38 GHz short-haul transmission-links worldwide key-players and their connection to Alpha-Industries.

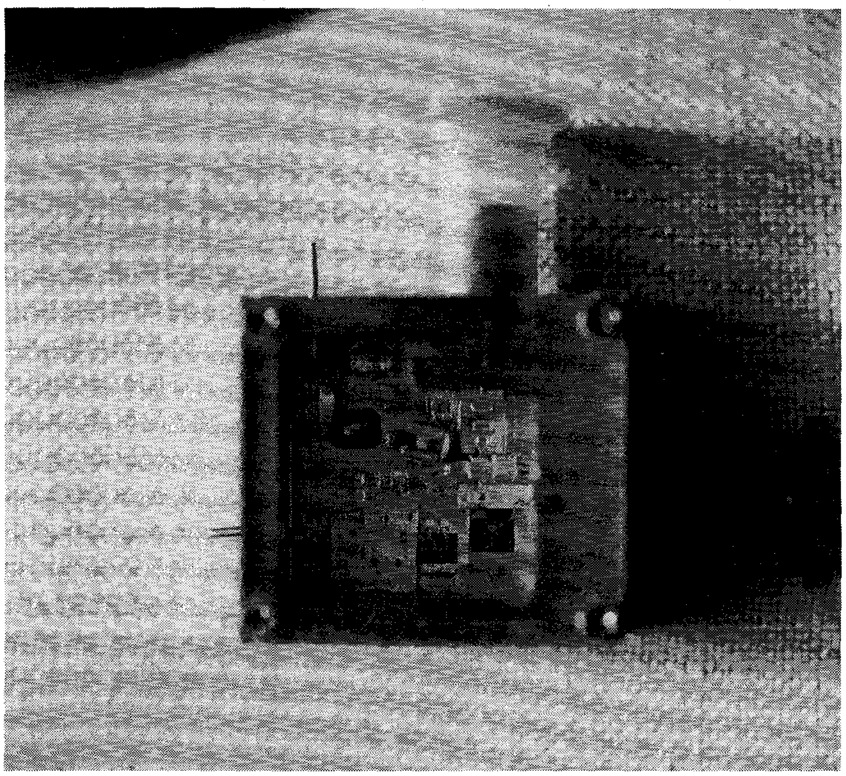

Fig. 6. Ka-band MMIC receiver realized unit (from: Raffaelli [23]).

Being built according to CCITT Rec. G. 703, 742, and 823 regulations [22], the available voice channel capability spans from 30–120, depending on the installed digital interface—CEPT 1 or CEPT 2.

2) MDL 38–38 GHz Philips-TRT System: Another vendor suppling 38 GHz short-haul communication units is Philips-TRT of Paris, France [24]. Fig. 7 displays the MDL 38 with a 36 dB parabolic dish antenna, being able to transmit 1 to 4 x 2.048 Mbit/s signals. The guaranteed receive threshhold at BER 10^{-3} is -85 dBm for 4 x 2 Mbit/s and -88 dBm for 2 x 2 Mbit/s. The assigned operating frequency range of 37–39.5 GHz is compliant to the ETSI/ETS pr 300 197 standard.

Philips claims to have delivered 575 units of the MDL 38 in 1993 and 1994 worldwide. The viability of the millimeterwave approach for point-to-point communication within more complex personal communication networks like GSM, i.e., the easy to install gateways, is clearly demonstrated. 23 and 38 GHz short-haul communication links are already a valuable niche market today.

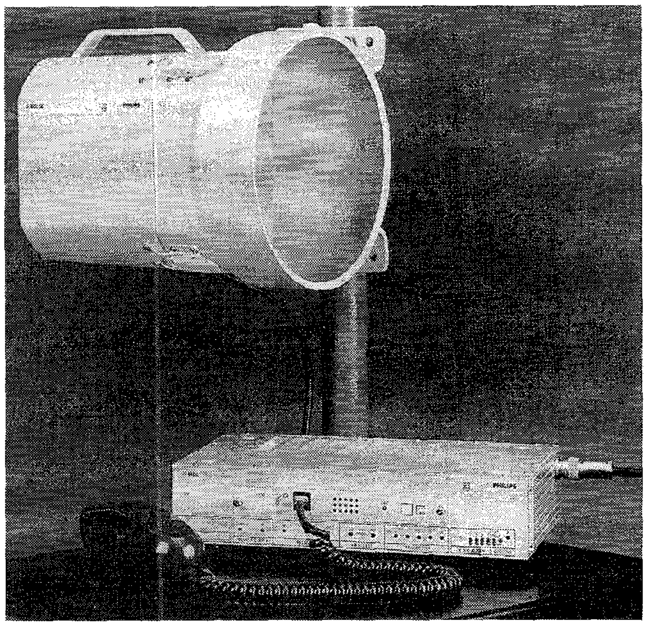

Fig. 7. MDL 38 terminal with standard antenna and engineer order wire (EOW) option (from: Brillard *et al.* [24]).

TABLE I
CHANNEL PLAN AND EQUIPMENT REGULATORY SPECIFICATIONS (FROM [29])

	FREQUENCY BAND		
TRAFFIC CAPACITY	38GHz	55GHZ	58GHz
	CHANNEL SPACING (MHz)		
2Mbit/sec	14	25	100
8Mbit/sec	28	50	100
34Mbit/sec	56	75	100
140/155Mbit/sec	140	150	*
NARROWBAND TV	28	*	100
COLOUR TV/RADAR REMOTING	56	*	100
GO/RETURN SPACING (MHz)	1260	> 500	N/A
FREQUENCY STABILITY (+/- MHz)	4	9	36

* NOT YET DEFINED

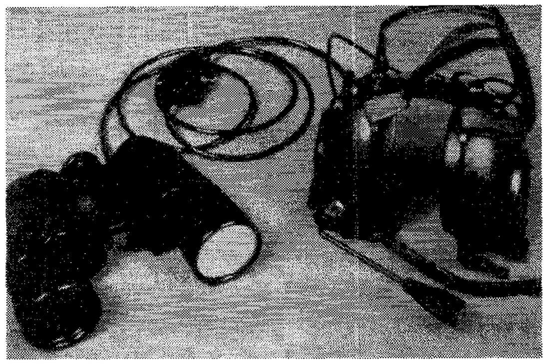

Fig. 8. 60 GHz Binocular Radio realized equipment (from: Brigginshaw *et al.* [32]).

D. Mobile Communication

Besides the described point-to-point and point-to-multipoint applications, the millimeterwave range may be used for mobile communication purposes, too.

1) Radiotube Applications: The operation of modern railway systems with speeds as high as 300 km/h requires a high degree of safety and reliability. This can be accomplished by the introduction of mobile communications. As there is a worldwide lack of frequencies for conventional mobile radio bands, millimeterwave frequencies were chosen. Propagation measurements carried out in the late 1970's [25] have shown the unique performance of this approach. The millimeterwave range enables highly focused radio beams to be transmitted. Due to their quasi-optical propagation only a limited zone of influence, the Radiotube, is formed.

Two German firms, Siemens [26] and AEG-Telefunken [27], respectively, were involved in the development of a millimeterwave railway communication system for the German Federal Railway, the Deutsche Bundesbahn, in the late 1970's and early 1980's. According to the system requirements, stationary, and mobile transceiver units have been developed for the 40 GHz AEG-Telefunken system. Both types have been constructed similarly. Only the transmit/receive frequencies were interchanged and different antennas have been used with the mobile unit. Several measurement campaigns have been carried out. Data rates between 1.2 kbits/s and 64 kbits/s were realized. The corresponding bit error rate was less than $10 * \exp(-5)$ for a data rate of 1.2 kbits/s. Besides data transmission measurements, train control via 40 GHz transmission was demonstrated successfully.

Based on these early results and the corresponding system design, a 40 GHz communication system for the TVE, the German experimental Maglev Transportation System, is currently under construction at Daimler–Benz Aerospace AG of Ulm, Germany [28].

2) Local Cellular Radio Network (LCRN) Applications: Local cellular radio networks (LCRN), have been a major investigation effort in England. The extensively used lower frequency bands have led to the exploitation of the millimeterwave bands based on the recommendations of the Radiocommunications Agency, London, U.K. [29]. Two groups of researchers in England from the Universities of London [30] and Bristol [31], respectively, have investigated the 55/60 GHz range. The feasibility of the 60 GHz range approach, despite interference and blocking effects due to the city environment, could be shown, according to 60 GHz transmission measurements carried out in the City of Bristol. The allocation of 38, 55, and 58 GHz bands for commercial communication use in the U.K., as shown in Table I, is only consequent.

Based on these initial measurements it appears to be very likely to establish LCRN's in the millimeterwave range. Thus the commercial exploitation of this greatly under utilized region of the frequency spectrum is coming up. For the moment both research groups have used commercially available 60 GHz equipment (Standard Waveguide type), being not suitable for future system realizations.

3) 60 GHz Marconi Binocular Radio: A state-of-the-art 60 GHz product developed for military purposes is displayed in Fig. 8. This prototype voice communication link, realized by Marconi of Stanmore, England [32], consists of three units, the battery box, and power supply, the headset with microphone and the binoculars, containing the transmitting and receiving circuitry as well as the optical sight. System parameters are

Output power	50 mW
Mixer noise figure	7 dB
Antenna gain	25 dB.

Employing hybrid integration technique on quartz MIC made it possible to integrate the entire RF unit, six discrete components, within one half of a standard binocular. Thus, a complex system realization, incorporating modulator, iso-circulator, separate LO-path, etc., could be accomplished.

This noncommercial example shows what can be done at 60 GHz, using the already developed, i.e., existing, technology.

4) WLAN's—Wireless Radio LAN's (Local Area Networks): In recent years, there has been a continuing trend towards ever cheaper, smaller, and more portable computers. Alongside this has been a similar trend towards ever smaller and more portable telecommunications equipment, providing an opportunity to meet the demand for local networking of computing facilities via wireless access [33]. The principal benefits are:

1) Ease and speed of installing or altering LAN systems.
2) Portability/mobility—so that a portable terminal can be moved around a site and still have access to the LAN.
3) Reliability (if well designed)—the cabling in current LAN's is responsible for the majority of faults [34].
4) Cost—it is claimed that Wireless LAN's (WLAN's) can be cheaper than cabled LAN systems. Although there may be little or no savings in the initial installation cost of WLAN's, the real benefits will be long term, when costs of extending, altering, and maintaining cabled LAN's are taken into account.
5) WLAN's can be used where cables cannot be installed, e.g. in listed buildings.

As the radio frequency spectrum is a limited natural resource, there is considerable competition for its use. As the lower bands become more and more congested, new frequencies can only be made available by moving higher and higher in frequency. This trend has a number of consequences, especially in the area of WLAN's:

1) At higher frequencies, the wavelength decreases and hence the physical size of the transceiver equipment becomes advantageously smaller.
2) The technology is less well proven, involving greater development costs and technical risks.
3) Higher frequency wave propagation becomes increasingly line-of-sight and there is greater attenuation from walls, partitions, etc.
4) Around 60 GHz, radio waves are significantly attenuated by absorption due to the oxygen content of the atmosphere. This will be of benefit in system design, since interfering signals have a very short range and hence frequencies can be reused more efficiently.

5) RACE project 2067—Mobile Broadband System (MBS): The RACE project 2067—mobile broadband system (MBS), being jointly under development by 18 European partners, including Daimler–Benz Aerospace AG of Ulm, Germany, [35], [36], addresses the 60 GHz system concept, the techniques and the technologies required for the set-up of the MBS, as well as market and economical issues, related to the widespread introduction of corresponding systems and services. The demonstrator consists of a mobile transmitter and a base station receiver, which together are able to perform high data rate (32 Mbit/s) video transmission. The main program objective is to specify, design, simulate, fabricate, and test the building blocks of this transceiver working in the 62–66 GHz band, and using GaAs MMIC technology. Three building blocks, 1) phase locked, low noise local oscillator, the realized chip being shown in Fig. 9, 2) high dynamic range upconverter, and 3) low noise down converter, are under development at this time. First results for the upconverter (2) exhibit a conversion gain of 0 dB (± 1 dB) for an input power of 10 dBm over an IF range of 5.2–6.2 GHz with good agreement between simulated and measured results [37].

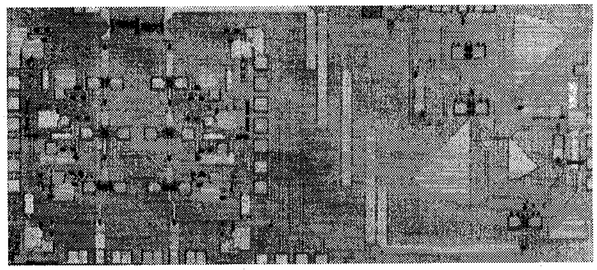

Fig. 9. RACE project 2067 MBS local oscillator chip (from: Fernandes *et al.* [34]).

6) Optic Microwave Hybrid LAN's: The employment of fiber-optical distribution for LAN's was, to the author's knowledge, first proposed by ALCATEL-SEL of Pforzheim, Germany [38], and CNET of Lannion, France [39]. Following the so-dubbed optic microwave hybrid approach a mobile broadband communication system can be realized economically attractive. A large number of very simple base stations (BS), Fig. 10, requiring only low power and being easily upgradeable to higher capacity are connected to the main base unit by means of optical fibers. Wireless transmission takes place in the microwave (2.45 GHz CNET) or millimeterwave (40/60 GHz, Alcatel-Sel) region. The general problems of this approach and their different solutions are discussed thoroughly in [40].

7) RACE project 2005—MODAL: Within the RACE Project 2005—microwave optical duplex antenna link (MODAL) [38], the generation of the millimeterwave carrier is performed indirectly. Two optical carriers with a frequency difference equal to the desired millimeterwave frequency, 40 GHz, are generated; one of which being modulated in amplitude, frequency, or phase. Being transported to the micro-BS via the fiber-network, the optical carriers are heterodyned, using a PIN-diode. The downconverted millimeterwave signal is amplified and radiated. Employing Erbium-doped fiber-optic amplifiers, transmission over 8, 20, and 40 km was tested. No degradation of the millimeterwave signal was observed.

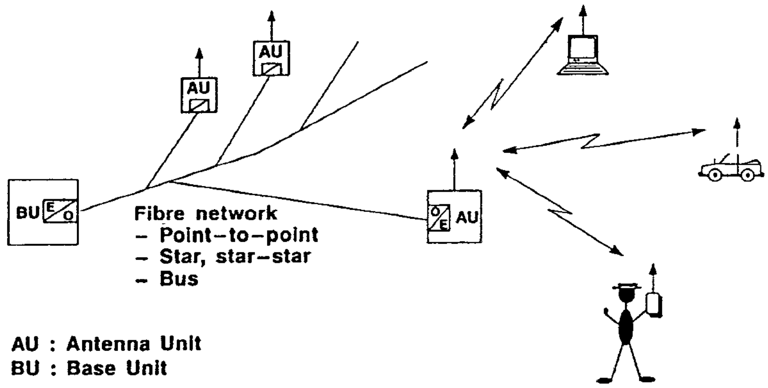

Fig. 10. RACE project 2005 MODAL basic architecture of optic microwave hybrid distribution system (from: Heidemann *et al.* [38]).

Generally following the same optic microwave hybrid approach, but incorporating passive terminal stations at 2.45 GHz for the micro-BS, tests were carried out by CNET [39], giving more than promising results: a BER of 10^{-7} was achieved for a bit rate of 192 kbits/s.

The area of mobile communication will be another successful commercial market for millimeterwaves within the near- to midterm future. Networking without cabling is the driving demand in this field. New application areas, like fully automated process control and production in industry comes within reach; the car production factory of the future cannot be thought of without mobile networking.

E. Wireless Cable Applications

Unlike conventional cable, wireless cable systems do not require hardwire infrastructure or signal amplification. The system uses an addressable, multichannel, high-frequency signal, operating along a line-of-sight path to a customer's antenna. Using the 27.5–29.5 GHz band, a virtually unused segment of the spectrum previously reserved for point-to-point commercial networks. CellularVision of New York (Freehold, NJ) is currently providing a point-to-multipoint distribution system with 49 video channels in the Brighton Beach section of Brooklyn. The system uses a 12.7 cm flat plate antenna at the user's premises. Service prices are significantly lower than that of cable [41]. The potential to use millimeter radio for wireless CATV is great and may very well become another valuable niche market.

All these examples testify to the viability of the millimeterwave approach for communication purposes, point-to-point and point-to-multipoint communication links at 38 and 55 GHz will complement already existing microwave transmission systems. Such links will be taken as easy to install gateways within more complex personal communication networks like GSM, being a valuable niche market already. The frequency range of 58 or 62–66 GHz will be used for short range WLAN's, and various indoor and outdoor applications are upcoming.

Table I shows the corresponding Channel Plan and Equipment Regulatory Specifications, being proposed in 1990 by the Radiocommunication Agency of London, U.K. [29], which is used as a general standard for industry in countries with no official frequency assignment yet.

IV. Traffic Control

Micro- and millimeterwave techniques offer the means of sensing vehicles and communicating with them, while they have the advantage of being immune to changing weather conditions. Three major areas of deployment may be distinguished in the area of traffic control: road transport informatics (RTI), including automatic toll debiting systems (ADS), is a mostly communication type application, while microwave doppler sensing (MDS), and automotive collision avoidance sensors for intelligent cruise control (ICC) are radar type approaches.

A. Road Transport Informatics (RTI)

Early work in this field has been carried out in Japan. Already in 1980 vehicle-to-roadside communication was tested intensively within MITI's so-called Large Scale Project, using 60 GHz. Today, it is Fujitsu, developing fully monolithic 60 GHz RF-ID chips for this purpose. The major concern of RTI in Europe is vehicle-to-vehicle and vehicle-to-roadside communication. One example is the 61 GHz DACAR system, a joint European project within the DRIVE program. Other systems, like the improved German AVES (AEG Verkehrs Erfassungs System) operate as well at 61 GHz, while, for example, the RDS-TMC—Radio Data System-Traffic Message Channel of Robert Bosch GmbH of Hildesheim, Germany [43], is under development and test at 5.8 GHz. With 5.8 GHz being the most frequently used operating frequency today, the already deployed toll debiting systems, like Telepass in Italy or Telepeage in France, use this frequency. It is yet open, if this frequency approach, which has a somewhat limited bandwidth capability, is sufficient under all operational aspects, especially under the view of a pan-European usability requirement.

The 61.5 GHz vehicle sensors based on the Doppler-principle have been applied successfully for traffic jam avoidance or warning since the late 1980's, as the chosen frequency of operation, 61.5 GHz, offers several favorable advantages:

1) The frequency band is available for this application industrial, scientific and medical (ISM)-band in Europe [44].
2) Due to the high frequency small antenna dimensions allow good focusingonly individual lanes are illuminated.
3) Short range application thus not hampered by high atmospheric absorption.

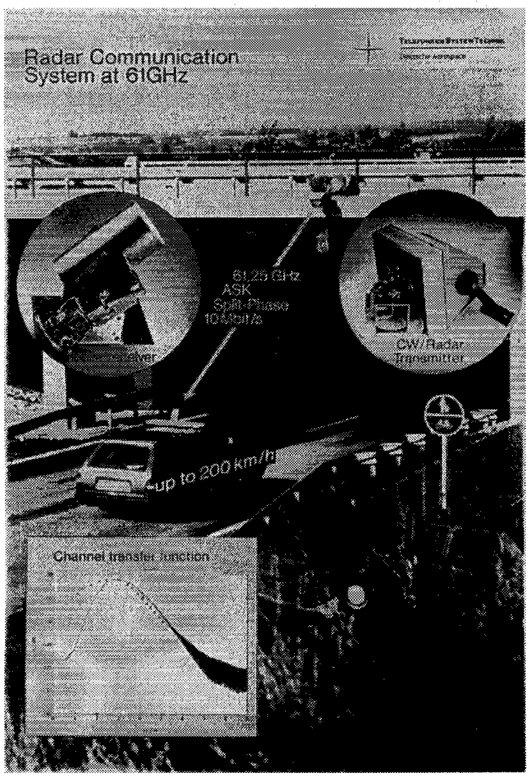

Fig. 11. 61 GHz beacon system typical test site and realized breadboard units (Courtesy of Daimler–Benz Aerospace AG).

4) Economic reuse of frequencies due to high atmospheric absorption.
5) High bandwidth capability regionally different operational requirements can be implemented into a single pan-European system.

1) 61 GHz DACAR System: The data acquisition and communication techniques and their assessment for road transport system (DACAR) within the DRIVE program is a joint effort of Marconi-CCS in Leicester, England, ALCATEL-SEL in Stuttgart, Germany and eight further European partners [45]. Communication occurs at 61 GHz over a token prototype bandwidth of 500 MHz. Differential phase shift keying (DPSK) with error detecting and correcting coding was applied. This leads to a more than promissing bit error rate (BER) of $5 \times 10\exp(-10)$ after demodulation, as multiple tests trials, being carried out in May/June 1991 have shown.

2) 61.5 GHz Deutsche Aerospace AG Beacon System: The AVES (AEG Verkehrs Erfassungs System) was built to obtain specific traffic information from appropriate Doppler signal processing by the former Telefunken SystemTechnik of Ulm, Germany.The sensor was relatively small, approximately (150 x 150 x 150) mm, and could be mounted easily on already existing signposts and bridges. Exhibiting an antenna beamwidth of 3×13 degrees, the output power amounted to 5 mW. Hybrid integration was implemented, combining finline and waveguide to meet the stringent low cost demand, as is the employment of a second harmonic type GUNN oscillator and the implementation of Ku-band devices for the single balanced mixer.

Recently the performance of the AVES system was enlarged to roadside-vehicle communication, incorporating a vehicle receiver; Fig. 11 showing the realized breadboard units as well as the test site setting. Using a 61.5 GHz GUNN reflection type preamplifier 17 dB of gain could be obtained. With an antenna beamwidth of 20 x 20 degrees the sensitivity amounts to -56 dBm. The test results are quite promissing, using ASK and data rates up to 2.5 Mbit/sec successful data exchange was achieved for passing speeds up to 145 km/h [46].

The DRIVE II project, communication using millimeter-wave systems (COMIS), is investigating and demonstrating the feasibility of the 60 GHz approach for RTI communication further more.

Under the view of more advanced traffic control and traffic dispatching systems for the future, e.g., the concept of co-operative driving, the vehicle-to-vehicle communication feature of the just described RTI-systems, like DACAR or COMIS, becomes most important. Due to bandwidth limitations, vehicle-to-vehicle communication cannot be accomplished using the already existing and deployed 5.8 GHz systems. Thus, the 60 GHz approach for RTI purposes can be successfully commercialized in the not too far future, within 5 to 10 years, approximately. The corresponding European ETSI-Standard for 63 GHz-RTI-Communication is due to be ready by the end of 1997. (For comparison: there is no European ETSI-Standard for 5.8 GHz-Communication yet and, due to existing uncompatible national standards, it is not very likely for such a standard to come into being shortly.)

B. Microwave Doppler Sensors (MDS)

Future onboard traffic control systems require true ground speed information for ABS, ASC, or car navigation systems. This field was pioneered as early as 1972 by Texas Instruments of Dallas, TX, in cooperation with General Motors [47], designing and testing a 55 GHz speedometer, utilizing Si-based semiconductors, Impatt's and Schottky–Barrier diodes, respectively. Using Doppler systems at 24 and 61 GHz, respectively, today it has been shown, that at least two independent sensors have to be employed, looking forward and backward, to correct the systematic measurement error due to vehicle movements. Several sensors have been developed at different institutes and companies in cooperation with the major car manufacturers in Europe.

A 24 GHz prototype MDS module was designed and tested by Volkswagen AG of Wolfsburg, Germany [48] for a measurement range of 2.5–200 km/h (300 km/h optional) the sensitivity amounts to 20 Hz per km/h ($\pm 1\%$) and 13.9 mm per pulse ($\pm 0.1\%$) for velocity and distance, respectively. Being tested over several 1000 km under adverse weather conditions, including winter in Scandinavia, the sensor has shown good sensitivity without failures. Another 24 GHz MDS sensor was developed by the University of Karlsruhe, Germany [49]. Such 24 GHz sensor modules fulfill the requirements for car integration. Due to ongoing developments in the high frequency satellite broadcasting systems area at 12 GHz, the cost for the presented hybrid version will be lowered correspondingly.

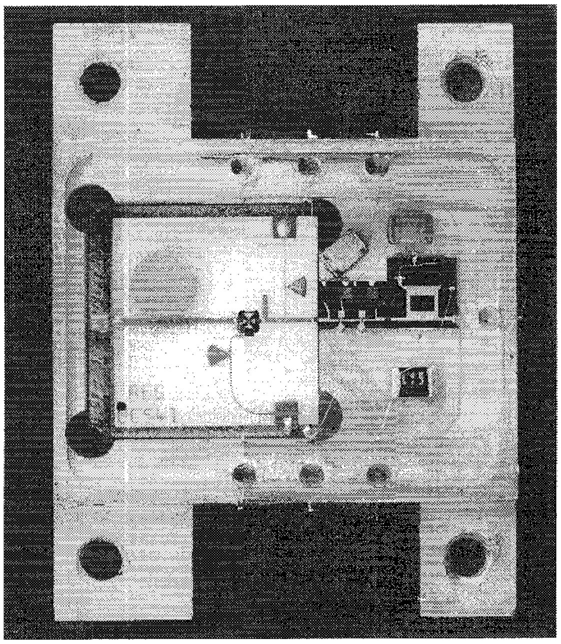

Fig. 12. 24 GHz Daimler–Benz MDS system component realization (from: Colquhoun *et al.* [49]).

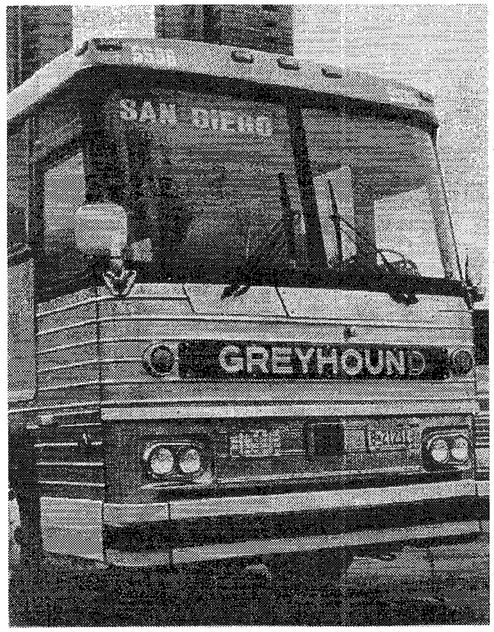

Fig. 13. 24 GHz Vorad radar warning device Greyhound bus installation (Courtesy of EATON/VORAD).

1) 24 GHz Daimler-Benz MDS Module: The low-cost, very high volume production of microwave Doppler sensors has to rely on the availability of corresponding GaAs MMIC's. A 24 GHz MDS module using monolithic integration techniques based on quarter micron GaAs MESFET's was developed at the Daimler–Benz Research Institute of Ulm, Germany [50]. Employing a three-chip design for flexibility and optimization purposes, oscillator, two stage buffer-amplifier and coupler/mixer. The first prototype realization is depicted in Fig. 12, still utilizing a hybrid oscillator. Having an output power of 11 dBm (± 1.5), the spectral purity amounts to 80 dBc/Hz at $f = 10$ kHz. The achieved conversion loss is less than 11 dB.

The technical feasibility of this approach was demonstrated. An entirely integrated sensor chip designed in microstrip techniques will have an area of <9 mm^2. Incorporating a hybrid integrated patch antenna, 15 x 11.5 degrees of beamwidth related to 18.5 dB of gain, the described MDS module was road tested successfully.

2) 61 GHz Doppler Velocity Sensor: Fig. 15 depicts the schematic set up of a Doppler sensor using inverted strip dielectric waveguide developed by the University of Ulm, Germany, [51]. A simple GUNN element serves as the transmitter as well as (self-oscillating) mixer and gives an output power of a few mW. Beamwidths of 5 and 18.5 degrees in E- and H-plane, respectively, are obtained with the chosen grating type antenna. Being mounted to a standard car, the first test results were quite promissing. However, to increase the dynamic range, the antenna sidelobe levels should be reduced.

3) 61 GHz Displacement Sensor for Automotive Application: A 61 GHz Doppler radar system has been developed at the University of München, Germany, [52], being able to measure the lateral and longitudinal speed of an automobile. This knowledge gives a better understanding of the vehicle's dynamic behavior in critical situations. A GUNN-oscillator with an output power of 20 dBm was used as transmitter, while two appropriately arranged mixers were employed to extract positive and negative Doppler frequency components, in order to compensate for pitch and roll. A leaky wave antenna with 2.1 degrees lateral and 19.6 degrees longitudinal beamwidth was incorporated. The already achieved measurement accuracy makes this radar unit a promising device to further investigate the vehicle's dynamic behavior more thoroughly.

A. Automotive Collision Avoidance Radar

The use of radar for automotive collision avoidance or intelligent cruise control is not new. Many companies, institutions and laboratories experimented with various millimeterwave frequency pulse- and/or FM-CW radar systems in the past two decades [53], [54]. Table II gives a summary of these efforts. Small size antennas can fit into the front of a car. Such radars are built for short range use only, up to 200 m maximum can be achieved easily, even under adverse weather conditions.

1) System Considerations: Normally an automotive collision avoidance radar is thought to be a simple forward-looking sensor with a starring, i.e., body-fixed antenna directly leading to automotive collision warning devices. Fig. 13 depicts the installation of such a simple collision warning sensor built by Vorad Safety Systems, Inc. in San Diego, CA, and being used in 3500 Greyhound overland buses. This sensor operates at 24.125 GHz with an output power of 0 dBm. A quite simple realization, employing bias sweeping for frequency modulation was chosen. The FCC-licensed system has an operating range of .3–110 m typical. A much more sophisticated approach, the automotive obstacle warning radar (OWR), to warn the driver of potential hazards in his path, has to generate a radar map of the scene and, incorporating a suitable man-machine-interface, leads to cooperative driving, the ultimate future.

TABLE II
HISTORICAL OVERVIEW OF AUTOMOTIVE RADAR EXPERIMENTS IN THE MILLIMETERWAVE RANGE (NOT COMPLETE)

1970	Bendix	16 GHz diplex CW		
1972	RCA	10 GHz FM-CW		
1974	AEG-TFK	35 GHz pulsed	LUCAS Ltd.	32 GHz FM-CW
1975	SEL	16.5 GHz FM-CW		
1976	AEG-TFK	50 GHz pulsed		
1977	Bendix	36 GHz diplex CW		
1978	SEL	35 GHz FM-CW	NISSAN	24 GHz pulsed / FM
1980	TOYOTA Fujitsu	50 GHz FM-CW		
1982	NISSAN	60 GHz pulse-FM NRD - guide		
1984				
1986				
1988	Philips	94 GHz FM-CW LwCst Hybrid		
1990	Univ. de Lille	94 GHz quasi-optical		
	SMA	38.5 GHz pulsed, noncoherent		
1991	Philips	77 GHz FM-CW LwCst Hybrid		
1992	GEC-Plessey Semiconductors	77 GHz FM-CW quasi-optical	Univ. München	61 GHz PN coding
	Fujitsu	60 GHz FM-CW	TEMIC / DASA	77 GHz / MMIC coherent pulse
	TRW	94 GHz FM-CW 1 chip MMIC	LUCAS Ltd.	77 GHz FM-CW hybrid
1993	millitech	76.5 GHz pulsed / FM-CW	DASA	77 GHz FM-CW LwCst Hybrid
1994	CelsiusTech	77 GHz FM-CW hybrid	HINO Motors	60 GHz FM-CW NRD - guide
	HIT	77 GHz FM-CW	Philips	77 GHz frequency scan

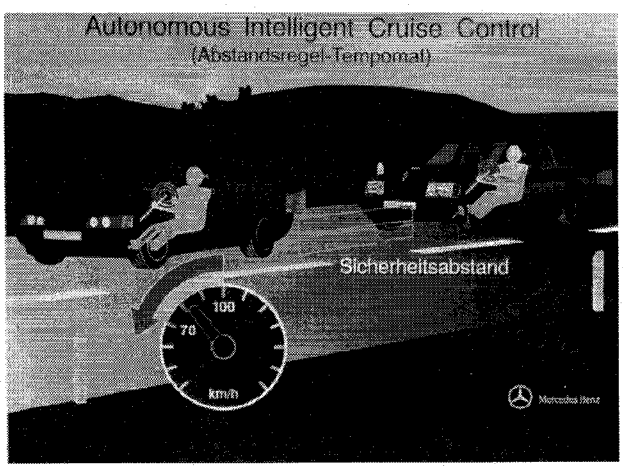

Fig. 14. Autonomous intelligent cruise control (AICC) principle of operation (Courtesy of Daimler–Benz AG.)

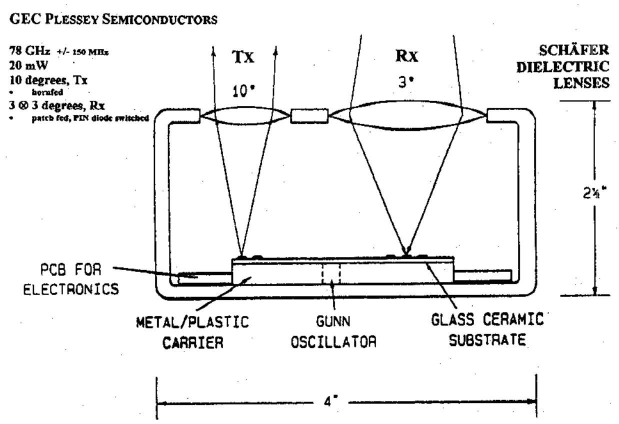

Fig. 15. 77 GHz quasi-optical scanning transceiver (from: Williams [55]).

In between those two extremes lies the autonomous intelligent cruise control (AICC) radar sensor approach, the principle of operation being presented in Fig. 14. The technical realization of AICC needs antenna scanning. Preferrably this should be done electronically, Fig. 15 shows a design proposed by GEC-Plessey-Semiconductors of Lincoln, U.K. [55]. The receiver antenna can be scanned electronically by sequential switching employing PIN-diodes. The FM-CW sensor, having an output power of 15 mW, features a frequency linearity of 0.5%; automatic target acquisition and tracking is part of the deployed processing system. Another approach, being pursued by the University of Munich, Germany [56] is to design an automotive collision avoidance radar in such a way, that due to PN-coding, wave-reconstruction can be accomplished.

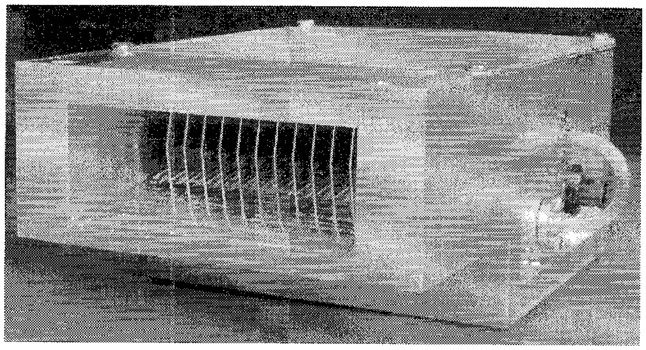

Fig. 16. 77 GHz frequency beam scanning radar view into the aperture (from: [58]).

Fig. 17. 77 GHz Tempomat-Radar Sensor brassboard A-model installed behind the license plate. (Courtesy of Daimler–Benz Aerospace AG.)

2) *Technology Considerations:* Currently available technology demands the antenna to be manufactured either as dish or lens with waveguide feed. Similarly, the most efficient millimeter wave oscillators utilize waveguide cavities. All the remaining front-end components can be conveniently manufactured in a single hybrid assembly using finline technology, for example. A 94 GHz radar demonstrator following this approach was realized by Philips Microwave of Stockport, England, showing very promising results [57]. The projected cost of a metallized mold will be less than £10, thus providing the base for a millimeterwave radar product ideally suited to the needs of the automotive industry in the short to medium term future. While Philips-Microwave of Stockport, England has moved on to a new sensor design, incorporating frequency scanning, Fig. 16, [58], Celsius Tech of Järfälla, Sweden deployed this 77 GHz finline-hybrid sensor into a mechanically scanned AICC sensor [59].

Split-block technique, employing remarkable low cost planar hybrid microstrip integration, was chosen by Daimler–Benz Aerospace AG of Ulm, Germany, for the realization of the Tempomat-Radar, a 77 GHz ICC-sensor [60]. FM-CW transmission is combined with amplitude monopulse techniques, incorporated into a three-beam design. With an average output power of 300 mW an operating range of 135 m can be achieved, with a corresponding resolution of 1 m. Fig. 17 shows an installed unit, which was successfully road tested during the last year by several car companies and automotive suppliers. Fig. 18 shows the new B-model design.

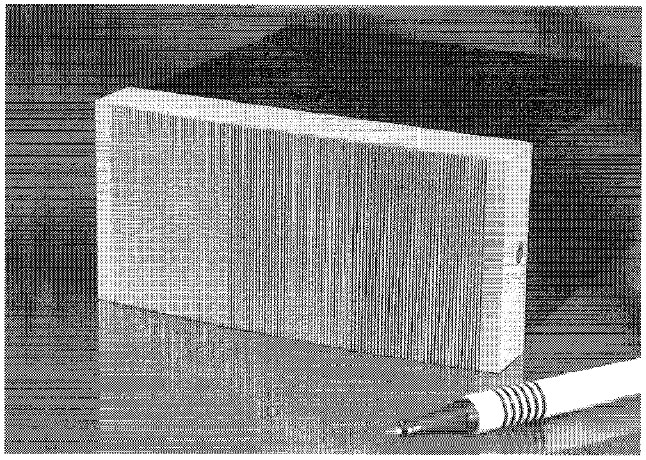

Fig. 18. 77 GHz Tempomat-Radar Sensor the new brassboard B-model design. (Courtesy of Daimler–Benz Aerospace AG.)

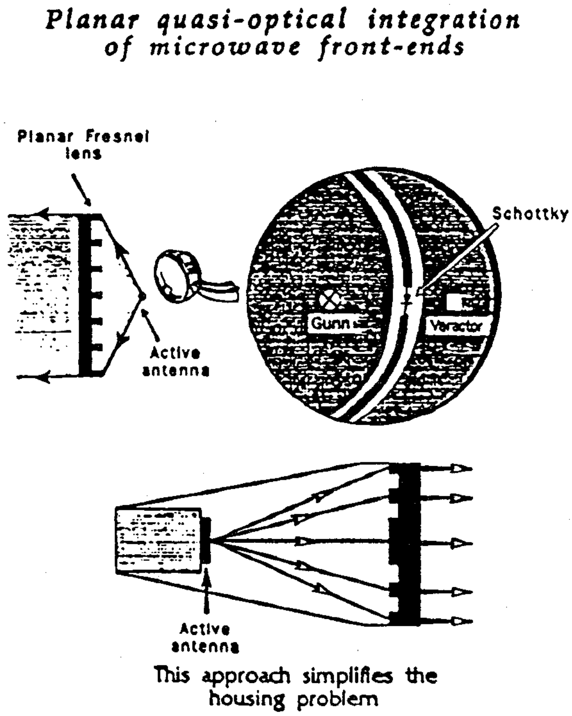

Fig. 19. Quasi-optical automotive radar sensor principle schematic (from: Rolland *et al.* [61]).

3) *Quasi-Optical Technology:* As millimeter wave systems progress to higher frequencies and complexities, the engineer may be forced to simplify components and to combine functions whenever possible. Rather than scaling low frequency techniques to shorter wavelengths, a completely new approach is needed. Quasi-optical components provide a solution to this problem by combining, for example, the function of an antenna and a functional component such as an oscillator or mixer into a single entity.

An example of this approach are two anticollision radar prototypes at 60 and 86 GHz, using a pulsed GUNN and an FM-CW Impatt oscillator, respectively, developed by the Universite de Lille, France [61]. Fig. 19 shows the principle realization scheme.

The active antenna consists of a circular patch, fed by a two-terminal device, radiating the TM 11 mode. Using slots

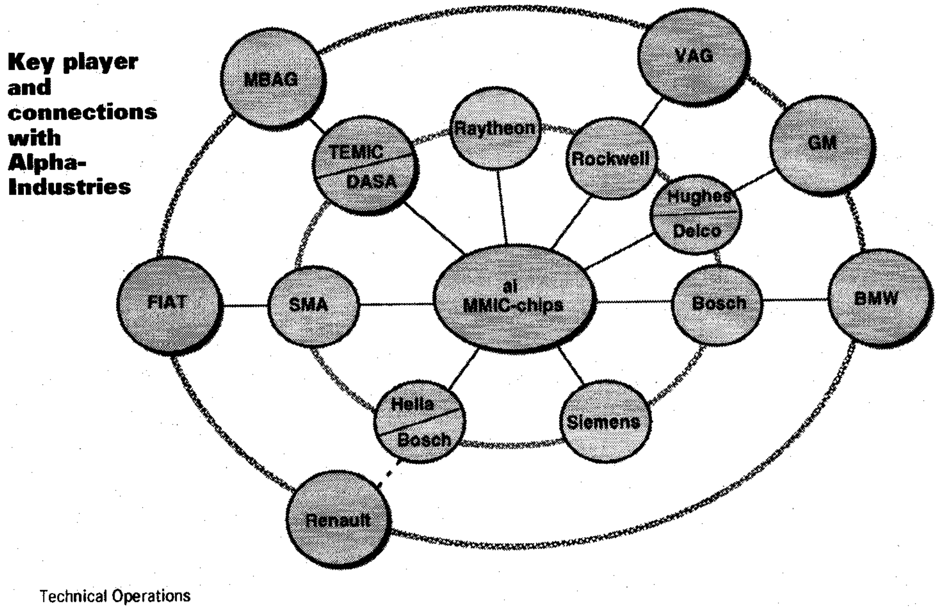

Fig. 20. 77 GHz car radar systems worldwide key players and their connection to Alpha-Industries.

following the TM 11 current lines, a varactor for frequency tuning and a mixer diode for receiving can be incorporated as well. This active antenna is placed in front of a fresnel lens. The 60 GHz pulsed GUNN radar unit gave excellent results for ranges up to 150 m, while the 86 GHz FM-CW Impatt unit exhibited lower sensitivity. Due to the inherent simplicity of the mechanical structure quasi-optical technology can be employed usefully for various industrial and commercial purposes, especially as realizations like the one just described, are compatible to monolithic integration; consequently a version employing three-terminal devices only is under development.

4) Monolithic Integration: The low-cost, very high volume production of collision avoidance sensors has to rely on the availability of millimeterwave GaAs MMIC's, which have become a reality today. During the past few years great efforts have been made to push the frequency limits of the key components to higher frequencies [49], [62]. Alpha Industries of Methuen, MA, is once again one of the key players in this field, as Fig. 20 is showing. Others are TRW in the U.S., Mitsubishi in Japan, or the Daimler–Benz GaAs foundry in Germany, respectively [63].

5) 77 GHz TEMIC GmbH Automotive Obstacle Detection System: A very promising concept for a 77 GHz automotive obstacle detection system is presently under development at Temic–Telefunken microelectronic GmbH of Friedrichshafen, Germany in cooperation with Daimler–Benz Aerospace of Ulm, Germany [64]. It comprises a highly miniaturized coherent-pulse-radar front end at 77 GHz, incorporating a dielectric lens antenna system, and a monolithic 77 GHz GaAs RF-module. Fig. 21 shows a cut open view of the radar front-end. At a frequency of 77 GHz an average output power 200 mW is obtained. The antenna beam width, with three switchable beams was chosen to be three degrees. Incorporating this RF-front-end into an automotive obstacle detection system, safety distance is calculated and displayed, warning the driver whenever necessary. Thus driving safety and comfort are improved without taking the action out of the driver's hands. Extensive road tests are ongoing at this time, incorporating the direct actuation of accelerator and brakes.

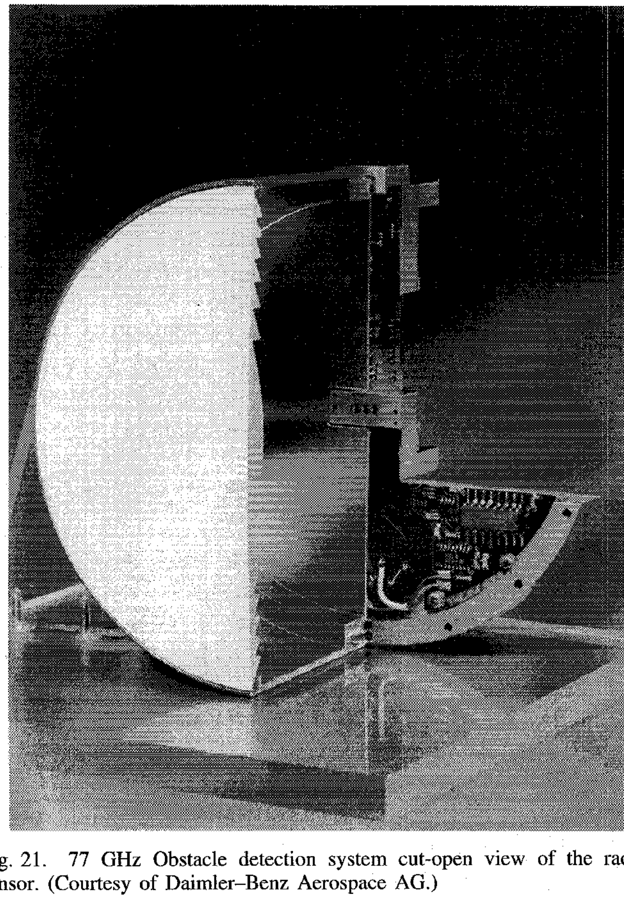

Fig. 21. 77 GHz Obstacle detection system cut-open view of the radar sensor. (Courtesy of Daimler–Benz Aerospace AG.)

Besides millitech in the U.S. and GEC-Plessey in England, the TEMIC/DASA development in Germany is the only other one, to the authors knowledge, having fully achieved the brassboard B-type development status.

Traffic control and especially automotive radar sensors, is the second largest millimeterwave application area today, and exhibits the largest market potential for the very near future. The unique physical advantages of the millimeterwave approach can be deployed. Ideally and successfully in this field. Before too long, within the next five years to be more precise, we will see thousands of cars on our roads, comforting the driver with 77 GHz AICC radar sensors; even warning the driver of potential hazards on the road in front of him is no longer a fairy tale. Based on these pushing market demands, MMIC's play a major role in this field, and have to be further developed, i.e., commerciallized, accordingly. However, clever and customized circuit (system) designs are still needed to reduce production and maintenance costs. This will be the key for future success.

V. Industrial Process Control

In industry, millimeterwave radar can be employed in any situation where motions or distances have to be measured in a contact-free manner [65]. Doppler sensing will be used to obtain information for automatic process control. An example of the latter is the top-dead-center measurement of combustion engines. The exact turn around point of the piston in an engine is of great importance for fuel efficient car ignition. The top dead center can be measured with an accuracy of a few minutes of arc. This can be accomplished using Doppler sensing [66]. The millimeterwave approach—again the 60 GHz range ISM-band—makes use of wave propagation through the spark plug. No separate holes in the motorblock itself are necessary. The sensor was developed by AEG of Ulm, Germany together with Volkswagen AG of Wolfsburg, Germany.

It should be mentioned that the just described Doppler sensor was built quite similar to the previously described vehicle sensor, showing that sensor standardization will be possible in spite of very different applications.

VI. Conclusion

This discussion shows that millimeter wave technology to meet even outstanding system requirements is available today. Short-haul communication at 38 and 55 GHz is a reality and a very valuable niche market today. LCRN's in the 60 GHz range, or vehicle-to-roadside and vehicle-to-vehicle communication at 63 GHz are no longer research topics. The 77 GHz AICC radar sensors will make driving more comfortable and safer in the very near future.

The ground for a successful and effective innovation process in the microwave industry has been prepared, but there is still an urgent need for more creative and active collaboration between the experts, particularly in the automotive and the electronic industry. Time-to-market has become one of the most important driving factors in this field. The gap between manufacturer and customer, and even more the end user, has still to be closed. Millimeter-wave applications and technologies, being initiated, fostered and pushed by military needs first, have arrived in the commercial arena and will be the backbone for the future.

Acknowledgment

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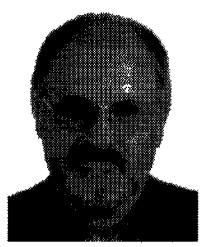

Holger H. Meinel (A'79–SM'84) joined the AEG-Telefunken Advanced Technology Department in Ulm, Germany, in 1973, after receiving the Dipl.Ing. from the RWTH AACHEN in Aachen, Germany.

As a Research and Development Engineer, he has designed components for a 35 GHz anticollision radar for cars. He was Supervisor of Radar Sub-Systems and of the Millimeterwave Integration Group, in 1976, responsible for the development of hybrid technology for millimeterwave radar and communication systems with emphasis on commercial and scientific application. He then became the Manager of the RF-Systems Department in the Radar Division of AEG-Telefunken in 1983, having been responsible for the development of ECM and Radar Systems up to the millimeterwave range. From February 1985 to December 1986 and March 1987 to May 1988 he was on-leave from AEG, working with MDTT, Inc. in Orlando, FL, and Thomson-CSF in Malakoff near Paris, France, respectively, on the development of a W-Band radar seeker. Subsequently he was in Ulm, Germany, as Manager of Marketing and Project Control for millimeterwave programs in the Guidance and Control Systems Division of Telefunken Systemtechnik, the current name of the company. From April 1990 to February 1995, he was with Daimler–Benz Aerospace AG in Munich, Germany, responsible for research and technology concerning Electronics and System Techniques within the Directorate of Corporate Technology of this newly formed company within the Daimler–Benz group. Since March 1995 he has been with the Daimler–Benz Research Institute in Ulm, Germany. His current research interests are in design and research on future traffic control and enhancements systems, especially on the next generation of automotive radar. He is author and coauthor of over 100 technical papers, mostly on millimeterwave integration and application and holds eight patents.

In 1985, Dr. Meinel was awarded the Walter Blohm Prize of the German Aircraft Industries Association (BDLI) for the development of a 60 GHz range helicopter obstacle warning radar. Since 1993 he served as Guest Lecturer on millimeterwave techniques at the Technical University of Ilmenau, Germany.