Millimeter-Wave Technology Advances Since 1985 and Future Trends

Holger H. Meinel, *Senior Member, IEEE*

Abstract —The availability of hybrid and monolithic millimeter-wave integration techniques has fostered the use of millimeter-wave systems. Short-range radar and line-of-sight communication are the major application areas. Very stringent system requirements can be met using today's available hybrid technology. The finline technique, for example, has major advantages: almost all types of components can be realized, as a high level of integration and low-cost circuit design and development are combined. Even more important, the finline technique is suitable for small series production. An excellent example of this approach is the German AVES System, featuring a 60 GHz traffic monitoring sensor realized in finline technique.

However, to the extent available, monolithic technology will be applied using analog GaAs circuits as well as SIMMWIC, a silicon-based technology. Specific applications demand tailored approaches. Sensors operating at 94 GHz for collision avoidance and intelligent ammunition applications from Philips Microwave, U.K., and Telefunken SystemTechnik, Germany, are described to demonstrate the maturity of today's millimeter-wave technology.

I. Introduction

Although the application of millimeter-wave technology, i.e., the frequency range of 30 GHz and above, offers a number of commonly known advantages, widespread application has long been hampered by the lack of suitable power sources and the high cost of the components necessary. Worldwide research and development efforts in millimeter-wave technology are continuing. Today, the system requirements for solid-state millimeter-wave transmitters can for the most part be met, and hybrid and monolithic millimeter-wave integrated circuits have been developed with cost, size, and weight being the major system requirements.

Microstrip and finline are the most important planar or quasi-planar transmission media taken for millimeter-wave integration. The first of these, microstrip, is surveyed by D. Williams of GEC Plessey Semiconductors, Lincoln, U.K., in this issue.[1] This contribution will concentrate on finline or E-plane technology, since this technology has emerged as a front-runner for frequencies of about 25–150 GHz and is employed worldwide. Several examples, including AVES, a 61.5 GHz radar sensor for traffic data aquisition, are included here.

Monolithic integrated 60 and 94 GHz receiver circuits composed of a mixer and IF amplifier in compatible FET technology on GaAs will be presented to show the state of the art in this area. A new and promising approach to the use of silicon technology for monolithic millimeter-wave integrated circuits, called SIMMWIC, will be described as well.

As millimeter-wave technology has matured, increased interest has been generated for very specific applications:

- Commercial automotive applications such as intelligent cruise control and enhanced vision have attracted great interest, calling for a low-cost design approach.
- An almost classical application of millimeter-wave techniques is the field of radar seekers, e.g. for intelligent ammunitions, calling for high performance under extreme environmental conditions.

Two examples fulfilling these requirements will be described.

II. Applications

As Horton and Oxley pointed out in 1985 [1], "the successful development and application of millimeter-wave systems depends on the availability of low cost production techniques for both components and entire subsystem modules." The finline or E-plane technique was one of the most promising hybrid integration techniques at that time and thus research was being carried out worldwide [2], as this technology had emerged as a front-runner. The finline structure, which is a planar printed circuit enclosed in a waveguidelike split-block housing, has relatively low loss, and the conductor patterns are on circuit boards, which can be made reproducibly using conventional photolithographic techniques. In this way the tight mechanical tolerances are shifted to the printed substrates.

Not surprisingly, it lived up to these high expectations: entire systems were designed and realized using finline technology. Two successful implementations should be

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The author is with Deutsche Aerospace AG, Leopoldstrasse 175, D-8000 München 44, Germany.
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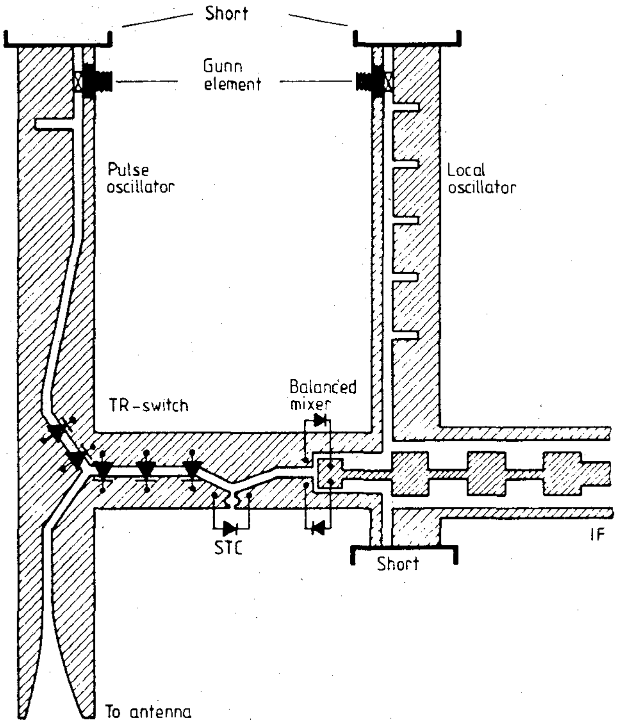

Fig. 1. Finline circuit layout for an integrated 35 GHz pulse radar front end.

presented here: a 35 GHz integrated radar sensor and a 29 GHz transceiver unit for communication purposes.

A. Integrated 35 GHz Radar

Consequent use of finline technology rendered possible the realization of a complete Ka-band radar front end on a single substrate. This very compact, but high-resolution, lightweight and low-cost radar module was built by Telefunken SystemTechnik of Ulm, Germany [3]. Designed for commercial applications, this radar unit was used for distance measurements from a few meters up to a few hundred meters.

The basic assembly of the finline circuit is given in Fig. 1. All components are placed closely together; thus the line losses within the circuit itself could be smaller than with a conventional waveguide circuit. Performance data are:

peak output power	0.5 W
pulse width	50 ns
frequency	35.55 GHz
receiver NF (DSB)	8 dB.

Fig. 2 shows the realized finline module, which is integrated into a small radar sensor and tested for various applications, e.g. container yard automation [4].

B. 29 GHz Communication Link

A 29 GHz data and full-band video transmission system was developed by British Telecom Research Laboratories (BTRL) of Martlesham, England, the millimeter-wave

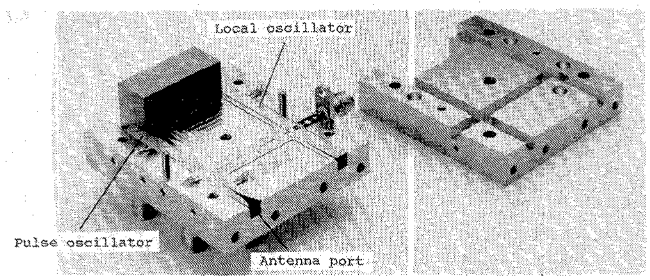

Fig. 2. Integrated 35 GHz pulse radar front end.

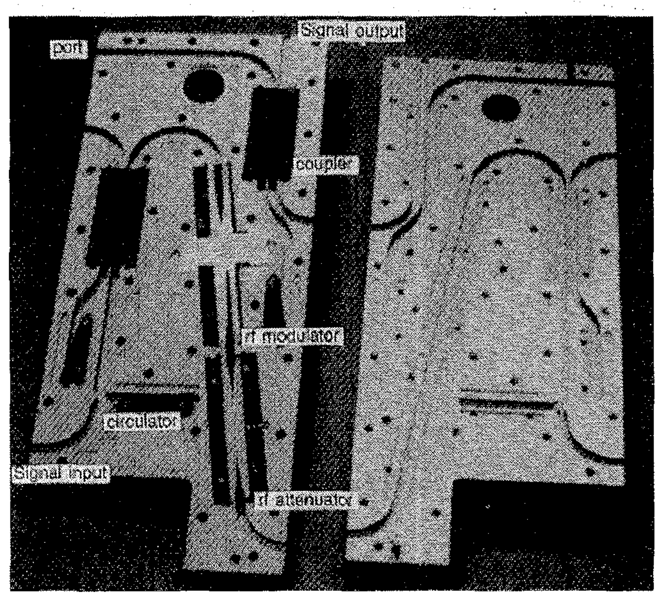

Fig. 3. 29 GHz communication link: integrated *E*-plane transmitter (courtesy of Philips Research).

components being engineered by Philips Mullard of Redhill, England [5].

The transmitter module contains several integrated finline circuits, as shown in Fig. 3. The Gunn diode local oscillator and the transmitter source, utilizing waveguide cavities, are mounted to this unit. For environmental reasons the entire RF assembly is desiccated. The major system characteristics of 70 prototype transceiver units being manufactured and shown here in Fig. 4 are as follows:

transmitted power:	150 mW
receiver noise figure:	8 dB
outage at BER 10 exp(−3)	less than 0.01%.

Operational since 1984 [6], this 29 GHz communication system has demonstrated its reliability.

The then available component technology, i.e., quasi-planar technology for hybrid integration, like finline, has fostered the growing application of millimeter waves in various areas [7]. Design and development examples of components and subsystems realized since 1985 as well as future trends will be presented in the following.

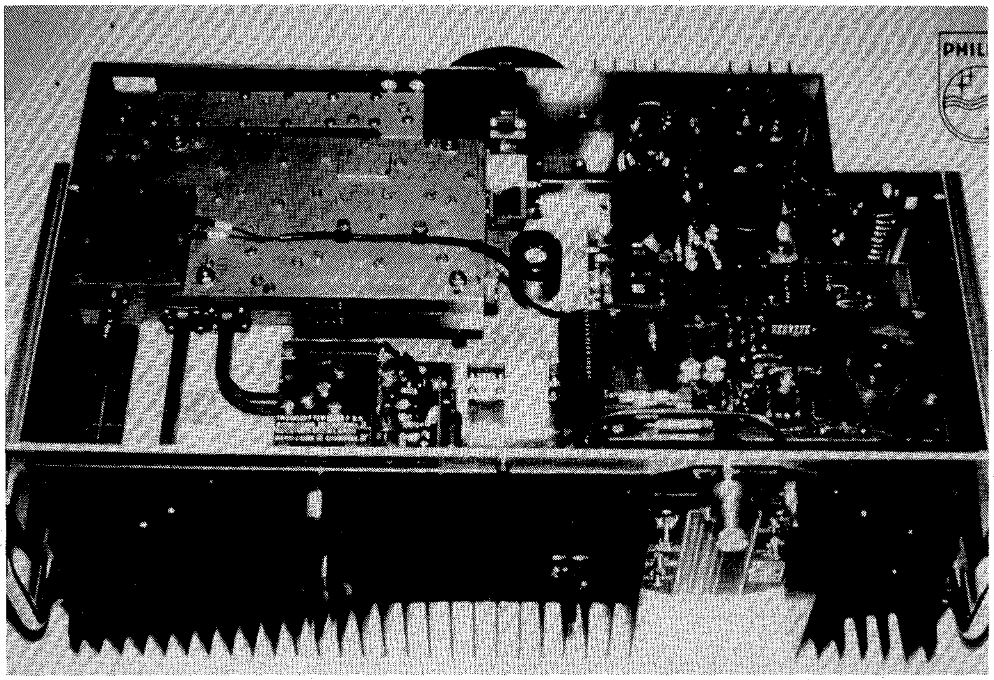

Fig. 4. 29 GHz communication link: assembled transceiver unit (courtesy of Philips Research).

III. Hybrid Integration

Ease of fabrication, low cost, and the ability to integrate a wide range of circuit functions, as well as specific performance features, are of prime importance for system design and realization. Today it is common knowledge that this normally cannot be met by a single technology. A trade-off between different options, such as microstrip, coplanar line, suspended stripline, finline, and dielectric image line, to mention some of the most widely used planar (or quasi-planar) transmission lines, based on a performance comparison is necessary to arrive at a final choice.

A. Discrete Components

Almost every type of component has been realized using the finline integration technique, since finline exhibits a number of advantages, e.g. easy implementation of semiconductors, especially beam lead devices, flexible design (incorporating CAD), and the combinations that are possible with other types of planar transmission media. An in-depth overview is given in [8] and [9].

As a state-of-the-art example of an integrated component the performance of a W-band p-i-n diode switch, manufactured by Telefunken SystemTechnik [10], is given in Fig. 5. Employing six diodes, an isolation of better than 70 dB was achieved at 94 GHz, the insertion loss being only 1.8 dB. Six SPST-type p-i-n diode attenuators/switches are displayed in Fig. 6, lying on a photomask with the typical finline pattern for this application. The units shown are designed for different waveguide bands, ranging from K band (18–26.5 GHz, back left) to T band (110–180 GHz, front right).

B. Integrated Subsystems

1) 61.5 GHz AVES System: 61.5 GHz vehicle sensors based on the Doppler principle have been applied successfully for traffic jam avoidance or warning. Fig. 7 shows the application scheme in general. This system, called AVES (AEG Verkehrs Erfassungs System), obtains specific traffic information from appropriate Doppler signal processing (built by Telefunken SystemTechnik [11]). The chosen frequency of operation—61.5 GHz—offers several advantages:

- The frequency band is available for this application, namely the ISM (industrial, scientific, medical) band in Europe [12].
- Because of the high frequency, small antenna dimensions allow good focusing; individual lanes can be illuminated. Owing to its short range application, it is not hampered by high atmospheric absorption. It affords economic reuse of frequencies.

The sensor is relatively small, approximately 150 mm × 150 mm × 150 mm, and can be mounted easily on signposts and bridges. Thus, it is not necessary to install the system underground, as is done with inductive loops. This makes these sensors especially suited for mobile installations, e.g. road construction sites.

The basic block diagram is given in Fig. 8. The concept for this radar sensor is to utilize a millimeter-wave transmitter/receiver operating continously and unmodulated at 61.25 GHz. Direct mixing is employed to obtain the Doppler signal. Transmitter and receiver are polarized differently to reduce rain clutter. The available output power is 5 mW; antenna beam widths were chosen to be 3° and 13° in the vertical and horizontal directions, re-

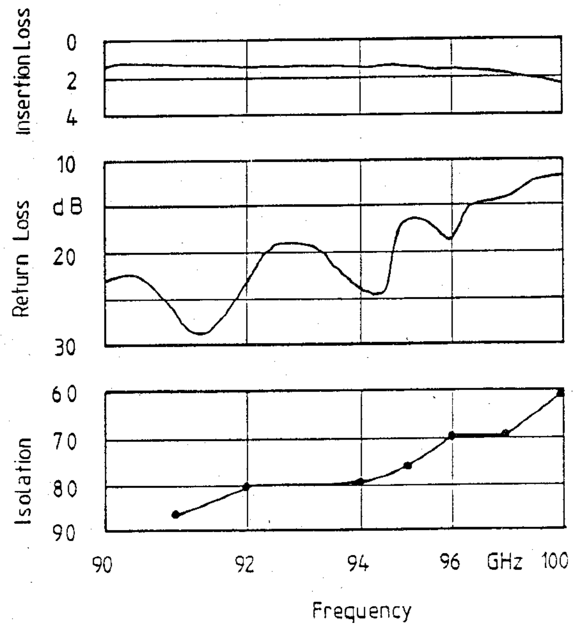

Fig. 5. 94 GHz p-i-n diode switch: switching performance.

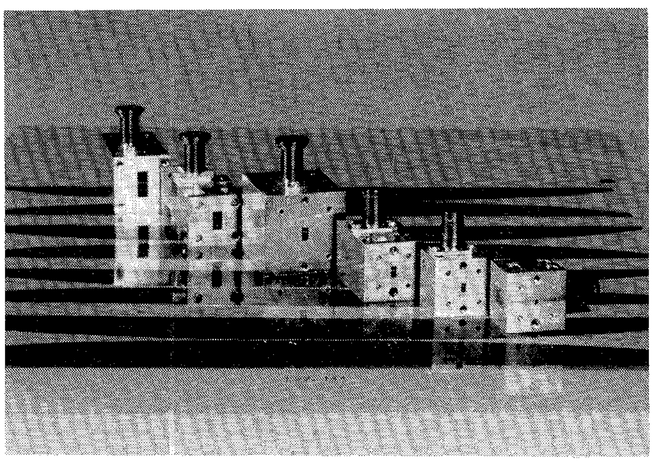

Fig. 6. Millimeter-wave p-i-n diode attenuators for different waveguide bands, ranging from K band (18–26.5 GHz) to T band (110–180 GHz).

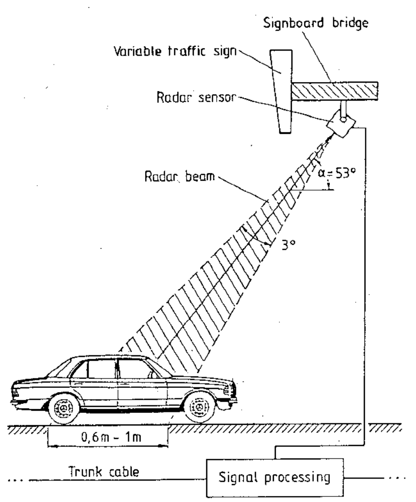

Fig. 7. 61.5 GHz AVES system: application scheme.

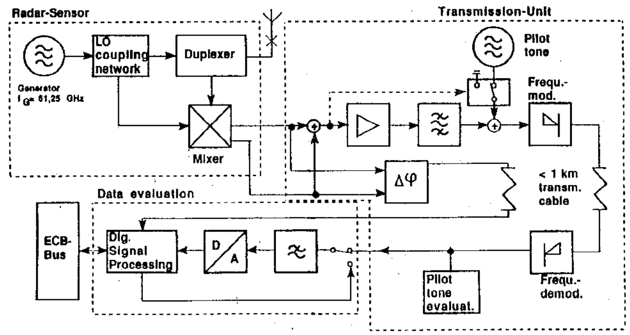

Fig. 8. 61.5 GHz AVES system: basic block diagram.

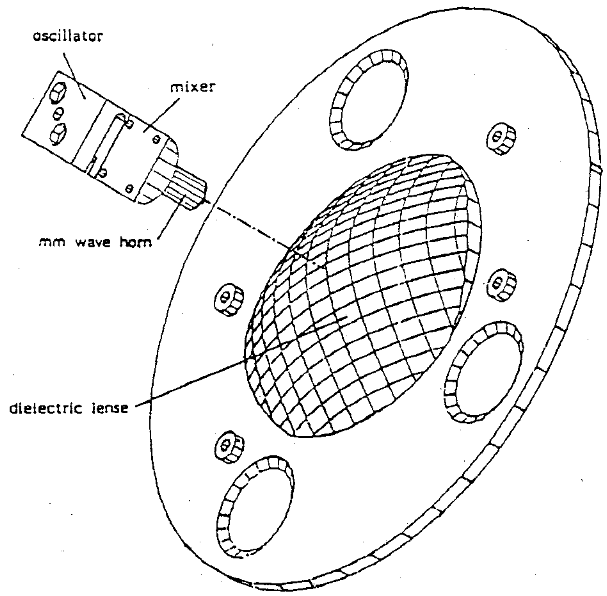

Fig. 9. 61.5 GHz AVES system: schematic setup of the millimeter-wave components.

spectively. A schematic setup of the RF components is shown in Fig. 9. Hybrid integration was implemented, combining finline and waveguide. The realization is described in detail in [11].

As vehicle speed, vehicle length, and the distance between vehicles is obtained employing the AVES sensor, a very good overview of the actual traffic situation can be derived. Using suitable algorithms [13], measures to optimize traffic flow can be provided.

The AVES system was tested successfully on German highways as well as on a private test road, outperforming a competing IR system. The system was finally approved by the German Bundesanstalt fuer Strassenwesen. A production contract for the first lot of 1000 units has recently been placed.

2) 94 GHz AEG Seeker Front Ends—Waveguide Split Block Technology: Very stringent system requirements for high-performance FM CW radar sensors at 94 GHz, i.e., the best transmitter/receiver isolation available, led to the rebirth of the three-dimensional design approach in the millimeter-wave range. Multimode waveguide antenna

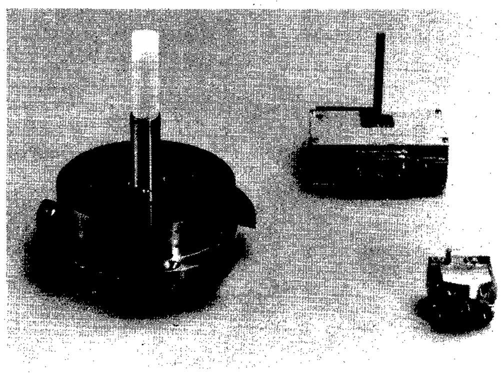

Fig. 10. 94 GHz FM CW radar sensors: *left*: dual-polarization monopulse front end; *above*: dual-polarization front end; *right*: combined FM CW/radiometer front end.

feeds, combined with planar or quasi-planar integrated receivers, offer the best results [14].

Fig. 10 presents different 94 GHz FM CW radar seeker RF front ends built by Telefunken SystemTechnik using integrated milled block technology, as this approach is called. A dual-polarization monopulse front end is shown at the very left:

output power	300 mW
transmit	RHCP or LHCP, switchable
receive	4 channels, simultaneous linear

Another dual-polarization front end is displayed in the upper part of Fig. 10:

output power	20–30 mW
transmit	circularly polarized
receive	simultaneous linear
number of units built	8
linearity	< 0.1% (not measurable!)

while a combined FM CW radar/radiometer module can be seen in the lower right:

output power	30 mW
active/passive channel separation	filters.

Developed for a "low cost" application, this combined radar/radiometer sensor makes use of favorable features of both principles. Radar and radiometer information can be separated in the frequency domain by filtering and can be processed independently. A logical combination offers excellent target detection and false target rejection capabilities [15].

A-145-mm diameter Cassegrain antenna with a fixed subreflector is connected to a circulator acting as a duplexer [16]. The Gunn oscillator provides transmitting power for radar operation as well as local oscillator power for the mixer. The received signal is down-converted to video frequency, which, after being amplified, is separated into radiometer and radar channels by means of high-pass and band-pass filters, respectively. The entire RF unit is very compact and measures only 20 mm$\times$20 mm$\times$23 mm. These 94 GHz FM CW sensors described here were originally developed for military purposes. However, today they are under consideration for automotive radar applications, as performance and technology can be easily applied for such an application. The low cost constraints for automotive use may be even easier to achieve with these designs.

IV. Monolithic Integration

A. GaAs Technology

The low-cost, very high volume production of millimeter-wave systems has to rely on the availability of millimeter-wave MMIC's. During the past few years great efforts have been made to push the frequency limits of the key components to higher frequencies. In addition, technologies which allow the integration of different circuit functions in a monolithic way will be of great advantage. On the basis of earlier results, a new GaAs technology has been developed which allows the integration of Schottky diodes ($f_t = 2300$ GHz), varactor diodes, and MESFET's ($f_{max} = 70$ GHz) on the same chip. With this technology it is possible to integrate diode mixers, IF amplifiers, and local oscillators—the key components of a receiver front end—on one chip [17].

A single balanced mixer chip was developed for 60 GHz and is shown in Fig. 11 [18]. A conversion loss of 6 dB and a minimum noise figure of 3.3 dB were achieved. An IF amplifier using the same compatible GaAs technology has a gain of 20.6 dB combined with a minimum noise figure of 1.7 dB at 4 GHz. The overall noise behavior is given in Fig. 12.

A 94 GHz single balanced mixer was fabricated as well [19]. Fig. 13 displays the layout. These mixer chips show conversion losses of less than 8 dB combined with noise figure values below 6 dB (DSB) (Fig. 14).

B. SIMMWIC

The application of molecular beam epitaxy (MBE) and X-ray lithography for the fabrication of monolithic integrated millimeter-wave devices on high-resistivity silicon is very promising and has been proven [20]. Discrete IMPATT and Schottky diodes fabricated from this material have shown excellent performance in the 100 GHz range.

Hybrid integrated transmitters using the SIMMWIC (silicon monolithic millimeter-wave integrated circuits) approach have delivered a maximum CW output power of 200 mW at 73 GHz. A completely monolithically integrated transmitting element using a planar IMPATT diode in a coplanar structure was realized recently, demonstrating the feasibility. Without the use of additional heatsinking, the output of this first unit was low, 0 dBm only. Thus, more work has to be done.

The integration of a coplanar Schottky diode with a microstrip antenna yields a simple monolithic detector

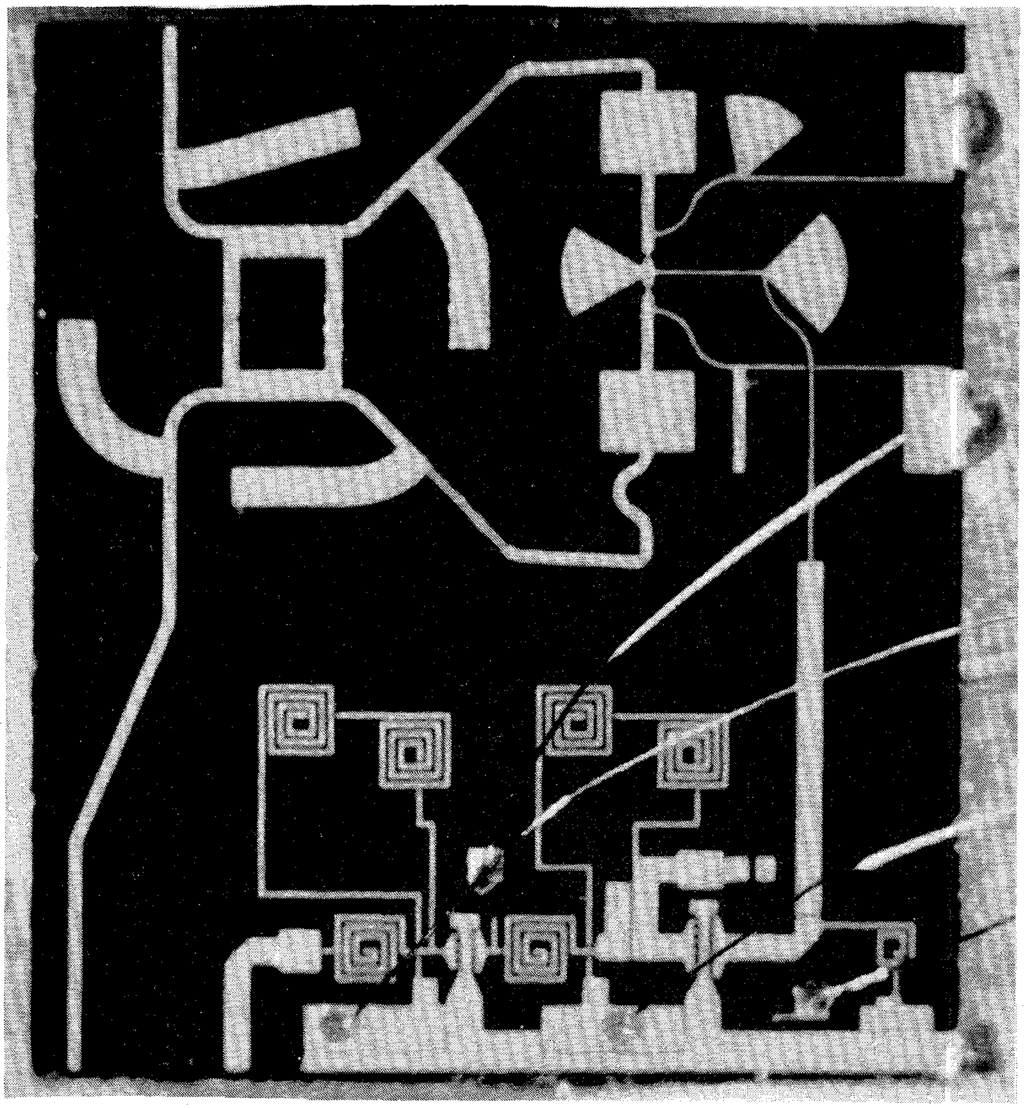

Fig. 11. 60 GHz integrated receiver chip on GaAs. Chip size: 4 mm × 4.5 × 0.15 mm.

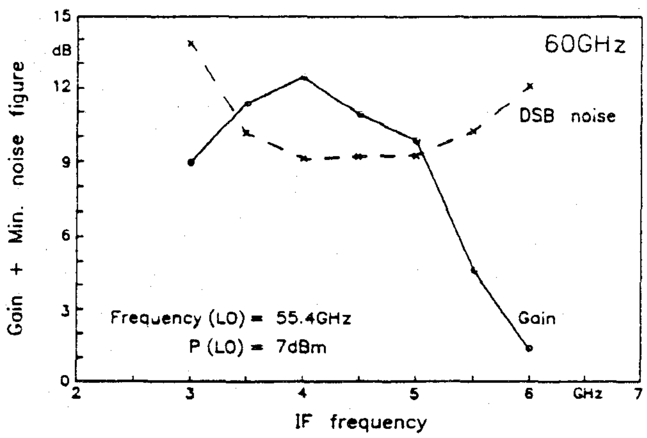

Fig. 12. 60 GHz integrated receiver: conversion gain and overall noise figure (DSB).

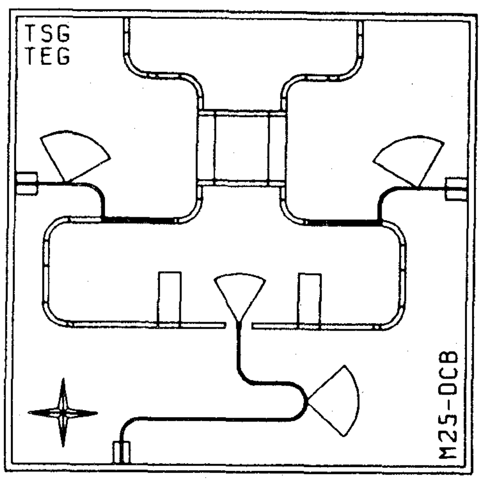

Fig. 13. 94 GHz integrated mixer: schematic layout.

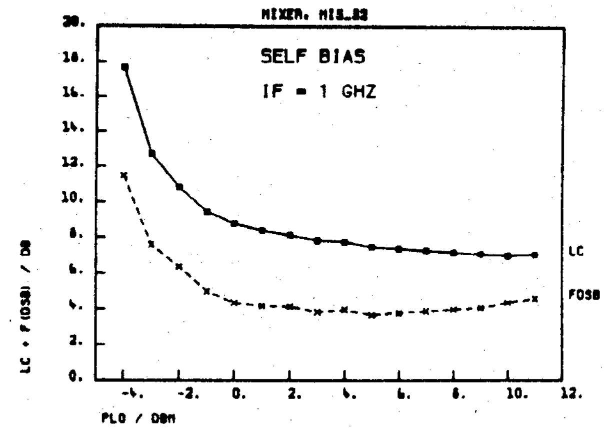

Fig. 14. 94 GHz integrated mixer: conversion loss and noise figure versus LO power.

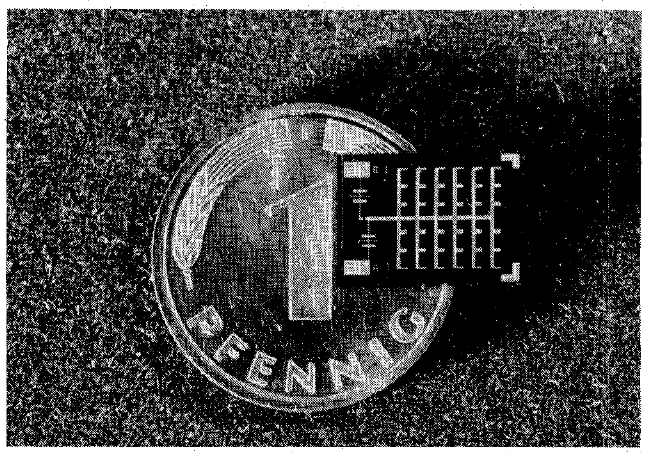

Fig. 15. Second generation SIMMWIC: monolithic integrated receiver on Si.

receiver chip and is shown in Fig. 15. The Schottky diode is terminated by a quarter-wave microstrip line; there are two dc networks for biasing and for decoupling the received signal. For operation the Schottky diode was biased with 270 mV. A receiver sensitivity of 65 μV/μWcm was obtained at 94 GHz.

V. "Special" Technology Approaches

As millimeter-wave technology has matured, increased interest has been generated for very specific applications. Commercial automotive applications such as intelligent cruise control and enhanced vision have attracted great interest. The limiting factor here in meeting market requirements is not performance but rather cost. Component cost, in particular the housing, is currently identified as a prime determinant for product competitiveness.

An almost classical application of millimeter-wave techniques is the field of radar seekers, e.g. for intelligent ammunitions. The limiting factor here is not cost but rather performance. Depending on the carrier accelerations up to 22000g have to be overcome.

These two examples show how specifically chosen technology approaches can be used to cope with such unusual system requirements.

A. Cost-Driven Technology

Present technology demands that the antenna be manufactured as either a dish or a lens with waveguide feed. Similarly, the most efficient millimeter-wave oscillators utilize cavities. All the remaining front-end components can be conveniently manufactured in a single hybrid assembly. The use of E-plane technology readily allows the optimum manufacturing process to be used for each circuit function.

The overall performance of such a unit is determined by the conducting housing, forming the surrounding waveguide. Plastics have received a great deal of attention as a low-cost solution for mass production. However, machined plastic components do not show a significant cost reduction. Polymer injection molding, however, is an attractive high-volume mass-production technique that brings with it a considerable background of process information.

The mass production of compact discs with micron surface features (a more stringent requirement than millimeter-wave radar) was accomplished using a metal-plated polymer injection molding process pioneered by Philips.

The 94 GHz radar seeker demonstrator, realized by Philips Microwave of Stockport, England [21], comprises a frequency swept Gunn oscillator, driving the antenna via a duplexer/circulator. Returned signals are coupled to the single balanced mixer via the same duplexer/circulator and are mixed with a coupled sample of the transmitted power by means of a branch guide coupler. The entire unit was realized employing finline technology. The performance data are:

output power	35 mW
frequency	94 GHz
sweep range	800 MHz
linearity	less than 1%
weight	less than 50 g.

Component values and layout design of this first demonstrator unit are not optimum for radar use, as it was necessary to have electrical access to each component for experimental purposes. However, the feasibility of this design approach was proven. Fig. 16 shows a prototype unit.

The housing was manufactured using metallized plastics (acrylic glass), giving no significant cost reduction. The projected cost of the equivalent metal-plated injection molded assembly is less than 10 pounds sterling, with a production rate of 45 s per housing. Fig. 17 displays the molded parts, providing a millimeter-wave radar product ideally suited to the needs of the automotive industry.

B. Performance-Driven Technology

Millimeter-wave components and systems for applications with inherently high accelerations must offer spe-

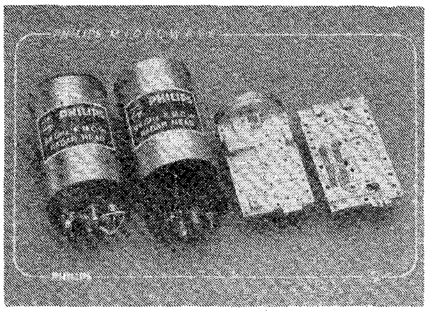

Fig. 16. Opened finline module of a 94 GHz radar seeker demonstrator (courtesy of Philips Microwave).

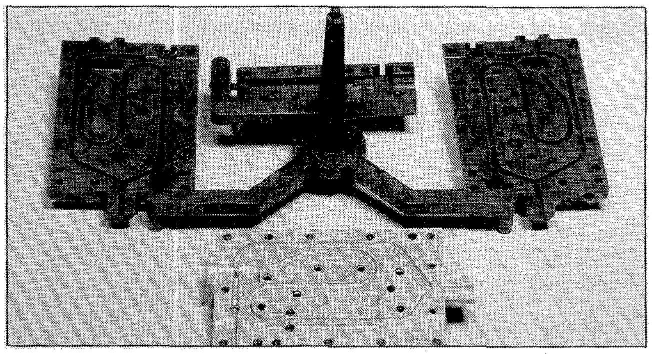

Fig. 17. 94 GHz radar seeker demonstrator: structural polymer components (courtesy of Philips Microwave).

cific mechanical features, with excellent electrical performance being taken for granted. Depending on the carrier, axial accelerations up to $20\,000g$ have to be overcome, while the radial acceleration due to twist amounts to 400 000 rad per second squared. These accelerations last only for milliseconds. However, because of these requirements the number of applicable millimeter-wave technologies is drastically reduced. Presently, the technology most suited to meet these demands is integrated waveguide milled block technology, being developed at Telefunken SystemTechnik.

This technology has been under development for more than a decade [14]; it provides low attenuation, mechanical rigidity, and excellent reproducibility for the 90 GHz range. The latest CAD procedures and NC milling machines are used for designing and manufacturing sophisticated "gun-hardened" components.

Only soft substrate materials are used, and design methods have been developed to realize components with inherently adequate electrical performance, as no tuning elements can be allowed. Moreover, the possibility of integrating these components into a complex radar front end has to be addressed.

A band-pass filter using this technology has been developed using the classical inductive window direct coupled resonator design. Fig. 18 shows a typical unit. A five-section filter [22] shows an insertion loss of 1.5 dB over a bandwidth of 4.5 GHz at 94 GHz. The far-off suppression

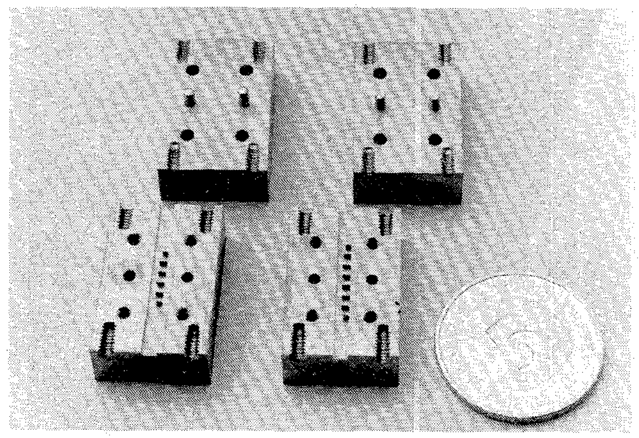

Fig. 18. Integrated milled block technology: realized 94 GHz passband filter.

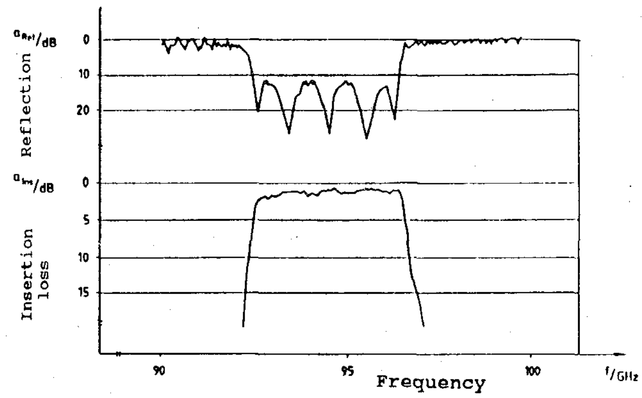

Fig. 19. Frequency response of a 94 GHz passband filter using integrated milled block technology.

is better than 60 dB over the entire W band, as displayed in Fig. 19.

Millimeter-wave components that are able to withstand extreme accelerations can be realized, as demonstrated. However, more engineering work has still to be done for component- to system-level integration.

VI. Conclusion

This short survey has shown that millimeter-wave technology to meet even extraordinary system requirements is available today. For different applications different technologies will be applied. Hybrid millimeter-wave technology is mature today and is used worldwide; MMIC components have been or will be incorporated into systems as soon as they are available. A good example of this approach is the aforementioned 29 GHz BTRL communication system: after several years of operational tests, the frequency was recently reallocated to 41 GHz and the entire front end will be redesigned now, incorporating monolithic circuits [23]. Millimeter-wave technology developed in response to military needs, but the availability of today's mature component and subsystem technology is fostering a spreading commercial market.

Acknowledgment

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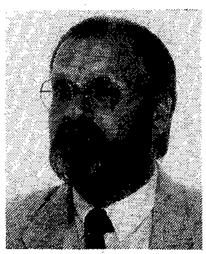

Holger H. Meinel (SM'84) joined the Advanced Technology Department of AEG-Telefunken, in ULM, FRG, in 1973 after graduating from RWTH Aachen. In 1976 he was appointed supervisor of the radar subsystems and millimeter-wave integration group responsible for the development of hybrid technology for millimeter-wave radar and communication systems with emphasis on commercial and scientific applications.

He became 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 millimeter-wave range. He was seconded from AEG in February 1985 for nearly two years to work with MDTT Inc. in Orlando, FL, and again in March 1987 to Thomson-CSF in Malakoff, near Paris, France, to work on the development of a W-band radar seeker. Returning to Germany in May 1988, he became manager of marketing and project control for millimeter-wave programs in the guidance and control systems division of Telefunken SystemTechnik (previously AEG-Telefunken). April 1990 saw a move to Deutsche Aerospace AG in Munich, where he is responsible for the commercial and business development strategies of this newly formed company within the Daimler–Benz group.

Mr. Meinel is the author or coauthor of more than 60 technical papers, mostly on millimeter-wave integration and applications. He holds eight patents. In 1985 he was awarded the Walther Blohm Prize by the German Aircraft Industries Association (BDLI) for the development of a 60 GHz range helicopter obstacle warning radar.