Integrated Millimeter-Wave Systems and Subsystems Using Finline and Related *E*-Plane Technologies

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Abstract —Reduced production costs is one of the most important requirements for the successful and widespread application of millimeter-wave systems in the future. Finline integration techniques, combined with *E*-plane- or milled-block waveguide technology, provide a suitable solution. Three already realized millimeter-wave sensors, using this design approach will be described:

— a 61-GHz Doppler sensor, being used to determine the top dead center in combustion engines, accuracy being a few angle minutes;
— A dual-polarization front-end for a frequency-agile 94-GHz Pulse-Doppler-radar featuring an overall conversion loss of 11 dB (pin-diode switch, filter, diplexer-circulator, and mixer losses are included);
— a 66-GHz radar front-end for a helicopter obstacle warning radar with only four separated millimeter-wave "Super" components (the provided output power is 1.5 W peak, the achieved receiver conversion loss is less than 7 dB).

I. Introduction

The successful development and application of millimeter-wave systems depends on the availability of low-cost production techniques for both components and entire modules. Finline integration techniques combined with related component realization methods like *E*-plane or milled-block waveguide techniques provide the required advantages, for example, reduced manufacturing costs, light weight, and small dimensions.

Finline is a kind of a shielded slotline; or from another point of view, finline resembles a double-ridge waveguide with very thin ridges printed on a dielectric substrate. Due to the double-ridge waveguide structure, finline provides the design base for a variety of components [1]. Nearly all circuit functions are performed using printed structures on the dielectric substrate; thus, the requirements for tight tolerances are shifted into the printing process, which has been well established in industry for years now. This approach will reduce the production costs significantly.

For those components for which the finline technique is not suited, such as filters or oscillators with tight specifications requiring high stability or second-harmonic operation, other fabrication techniques have been selected. These techniques can be combined with finline very easily (for example, the *E*-plane or the milled-block waveguide techniques).

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In the following sections, some examples will be shown describing this design approach in more detail. These are:

— 61-GHz Doppler sensor for piston location measurements of combustion engines,
— 94-GHz dual-polarization receiver front-end,
— 66-GHz radar front-end of an obstacle warning system for helicopters.

II. 61-GHz Doppler Sensor for Piston Location Measurements

The measurement of the locus of the piston in a combustion engine, especially the exact turn around point, is of great importance for fuel-efficient car ignition systems. This turn around point can be determined exactly by employing a 61-GHz Doppler radar sensor [2]. The advantage of the high-frequency approach for this application is the possible wave propagation through the spark plug itself. Only a suitable adapter has to be designed.

The Doppler sensor consists of a Gunn oscillator, a 3-dB coupler used as a transmit–receive diplexer, and a video detector. The latter two are realized in finline techniques on a single substrate (see Fig. 1). A beam-lead-type Schottky-barrier diode was used for the video detector. The employed Gunn oscillator is a second-harmonic device, realized in waveguide techniques with a radial cap resonator; the rated output power is 20 mW.

This design approach of the oscillator has the advantage of being insensitive against pushing and pulling effects of the piston movement, since the fundamental frequency of 30.5 GHz cannot be influenced by these factors. As displayed in Fig. 1, the entire sensor unit furthermore includes a power supply circuit for the Gunn oscillator and a video amplifier.

By means of this sensor, which has been developed for and delivered to Volkswagen AG of Germany, the top dead center can be measured with an accuracy of a few angle minutes.

III. 94-GHz Dual Polarization Receiver Front-End

Compared to infrared systems, millimeter-wave radar systems operating at 94 GHz provide high resolution combined with small antenna diameters, while still maintaining

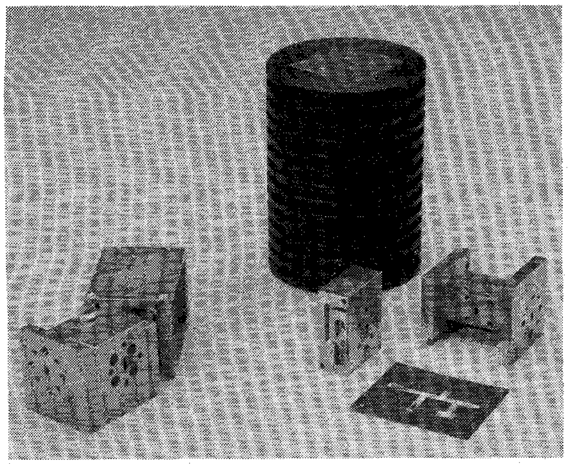

Fig. 1. 61-GHz Doppler sensor for piston location measurements. Below right: RF-components. Left: RF-unit with power-supply and video amplifier. Top: Assembled sensor.

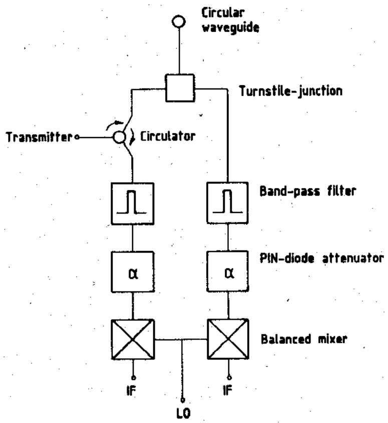

Fig. 2. Principle block diagram of a 94-GHz dual polarization receiver front-end.

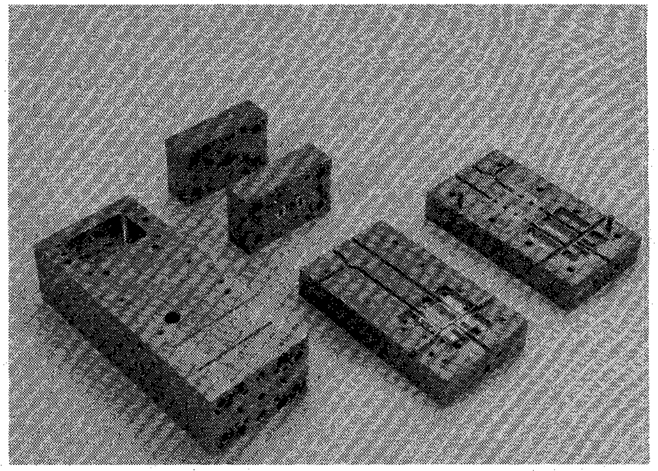

Fig. 3. 94-GHz dual polarization receiver front-end. Right: Dissembled circulator, STC/units and power-divider circuit. Upper Left: Turnstile junction. Lower Left: Assembled front-end.

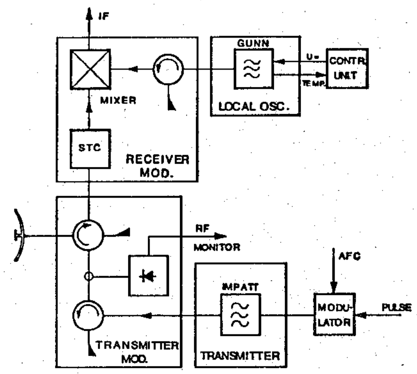

Fig. 4. Principle block diagram of a 66-GHz radar front-end for a helicopter obstacle warning device.

acceptable atmospheric attenuation and far better penetration into obscurants such as clouds, fog, or dust.

Therefore, a dual-channel receiver front-end for a 94-GHz radar with dual-polarization capabilities has been developed [3]. The front-end consists of polarizer, circulator, filters, STC pin-diode switches, balanced mixers, and a power divider for the LO power distribution (Fig. 2).

Standard waveguide techniques were used for the realization of the polarization diplexer, a turnstile junction. The remainder of the circuit was built using *E*-plane techniques, being integrated in a single split-block mount. An *E*-plane-type waveguide circulator [4] is employed as the transmit–receive diplexer in one channel. The two filters make use of metal inserts in the *E*-plane, while switches, mixers, and an LO power divider are built using finline techniques on a single substrate, employing beam-lead-type pin and Schottky-barrier diodes, respectively.

Fig. 3 shows the disassembled receiver parts, as well as the completed front-end; the outer dimensions are $76\times 32 \times 20$ mm.

The minimum overall conversion loss of this front-end is 11 dB. This loss is composed of 8.5 dB of the pin diode switch/balanced mixer configuration, 0.6 dB from filter, 0.5 dB from the circulator, and a few tenths of a decibel from additional line losses. The required LO power is 5 mW for each mixer, combined with 2 mA of dc-bias, and is supplied using a second-harmonic Gunn oscillator.

IV. 66-GHz Radar Front-End for a Helicopter Obstacle Warning System

The use of helicopters for various civil applications, as well as in the military field, has resulted in demands for an obstacle warning device. This can be done efficiently, employing a 60-GHz-range radar sensor, as extended flight tests in 1982 have shown [5].

The implementation of the employed millimeter-wave front-end was quite expensive, as it consisted of eight different mechanically separated parts, including three oscillators, four circulators, and the already integrated STC/balanced mixer unit. Thus, reduced manufacturing costs, lower power consumption, and light weight were the main requirements that applied to the development of the new millimeter-wave front-end.

Manufacturing as well as assembly are quite cost-intensive today. Obviously, it is necessary to reduce the expense by integrating the components. But doing this, one has to bear in mind also that practical measurements have to be

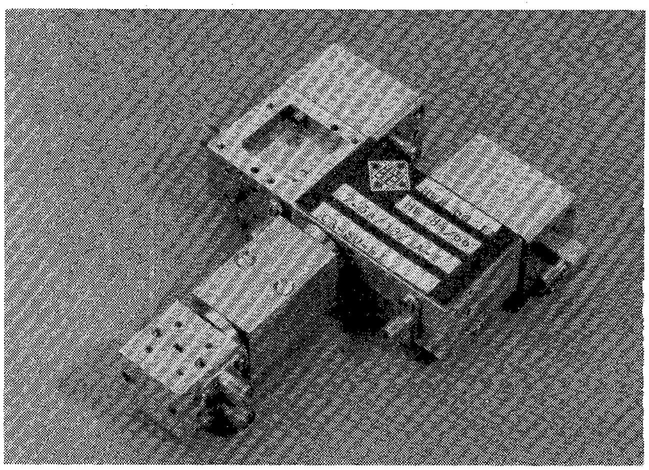

Fig. 5. 66-GHz radar front-end. Upper Right: IMPATT transmitter. Lower right: Transmitter module. Left: Receiver module. Upper Left: GUNN-LO. Lower Left: Twist and pin-diode SPDT (not used here).

made. Highly integrated "Super" components for millimeter-wave applications can be developed, as shown before [6]. But as long as the reproducibility of semi-conductors for the millimeter-wave range remains as poor as it is today, maintainability in terms of measurability will continue to be of high importance in systems design. Thus, the decision as to which integration level is necessary and suitable to meet certain system requirements has to be carried out very carefully. On the basis of these considerations, a comprehensive millimeter-wave front-end was developed [7]. Fig. 4 shows the overall schematic block diagram. The transmitter, an IMPATT oscillator with an output power of 1.5 W (peak), drives the antenna via the transmitter module. The required frequency stability of the IMPATT oscillator is not achieved by means of injection-locking, but is due to control of the IMPATT frequency by an IF-based AFC circuit. The transmitter module contains two circulators and an RF-monitoring detector for BITE purposes. On the receiver side, the receiver module and the LO complete the front-end, the module containing the pin-diode STC, mixer, and circulator for LO matching. The LO, a second-harmonic-type Gunn oscillator with an output power of 20 mW, is temperature stabilized by controlling the operating voltage; a stability of $1.5 \cdot 10^{-6}$ K was achieved over the temperature range from -30 to $+70°$ C. Thus, the total number of mechanically separated millimeter-wave "Super" components could be reduced to four.

Fig. 5 shows the realized components: transmitter (upper right), transmitter module (lower right), receiver module (left), and LO (upper left). Also shown are components on the lower left, a twist and a pin-diode SPDT, which are not used in the system described here. The transmiter module has an insertion loss of 1.2 and 0.6 dB for the transmit and the receive channel, respectively. The transmit/receive decoupling amounts to 15 dB. All three ports are matched to better than 18-dB return loss. The monitor detector has an overall sensitivity of 0.9 mV/mW.

The pin-diode STC, as well as the balanced mixer in the receiver module, was built using finline techniques employ-

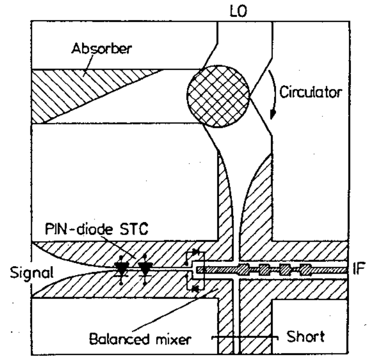

Fig. 6 Realization of the receiver module. Top: E-plane waveguide circulator. Below: Bottom: STC/balanced unit in finline technique.

ing beam-lead-type pin and Schotty-barrier diodes, respectively, while the circulator is of the E-plane waveguide type [4]. Fig. 6 shows the module construction. An overall conversion loss of less then 7 dB, including the STC insertion loss, was achieved. The required LO power is 10-mW minimum and the LO/RF decoupling is greater than 20 dB.

V. Conclusion

These examples demonstrate successfully the practicability of building integrated millimeter-wave components using finline and related E-plane techniques. Besides size, weight, and cost reduction on one hand and design flexibility on the other, an even more important advantage should be expressed: finline circuits on an RT-Duroid substrate are reported to withstand shock accelerations up to 4000 gs [8], and a balanced mixer on a quartz substrate has been tested up to 30000 gs without failure.

Employing finline techniques for the realization of components thus can be the key for the cost-effective development of future millimeter-wave systems (for example, for radar warning — and seeker — systems or portable communication equipment). Finline techniques are also suited for small and large series production, are an already developed and mature technology, and thus, instantly available today.

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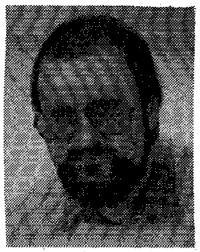

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