A 77-GHz FM/CW Radar Front-End with a Low-Profile Low-Loss Printed Antenna

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***Abstract*— Design and results of a 77-GHz frequency-modulation/continuous-wave radar sensor based on a simple waveguide circuitry and a novel type of printed, low-profile, and low-loss antenna are presented. A Gunn voltage-controlled oscillator and a finline mixer act as transmitter and receiver, respectively, connected by two E-plane couplers. The folded reflector-type antenna consists of a printed slot array and another planar substrate, which, at the same time, provides twisting of the polarization and focusing of the incident wave. The performance of the radar is described, together with the initial results of a scanning of the antenna beam.**

***Index Terms*—Automotive radar, integrated circuits, millimeter wave, millimeter-wave radar, printed circuit antenna, reflector antenna, scanning antenna.**

I. Introduction

In the last years, a number of efforts have been spent to develop automotive radars in the 76–77-GHz frequency range for autonomous cruise control or collision warning, [1]–[9]. As these sensors have to be integrated into the front part of a car, very compact RF and antenna arrangements are required, which, at the same time, must be suited for a low-cost mass production. With respect to the millimeter-wave front-end, this leads to great challenges for both transmitter/receiver circuitry and the antenna. Waveguide or hybrid integrated circuits as well as monolithic integrated circuits, e.g. [2], [9], and [10], have been developed for the millimeter-wave front-end.

The antenna diameter and beamwidth of such a sensor are determined by the system requirements, typically resulting in a beamwidth of 2°–3° and an antenna diameter of around 100 mm in this frequency range. Due to post, telephone, telegraph (PTT) limitations of the effective isotropic radiated power (EIRP), the antenna efficiency should be as high as possible. The complete sensor is mounted at the front part of a car and, therefore, should have a profile as low as possible. In addition, multibeam sensors are required to improve the surveillance capabilities within a reasonable area in front of the vehicle.

Different types of antennas have already been investigated; the preferred choice of a planar antenna, however, suffers from its high losses [4]. Antennas based on slotted arrays [11] or dielectric structures [5] mostly exhibit a rather complicated structure and do not easily lend themselves to low-cost mass production. In addition, the need for at least three antenna beams makes the situation even more difficult.

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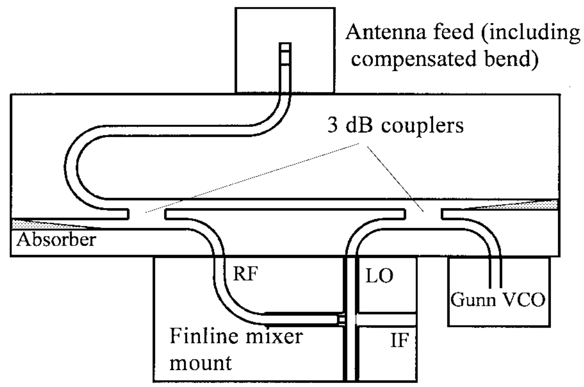

Fig. 1. Basic block diagram of the radar front-end.

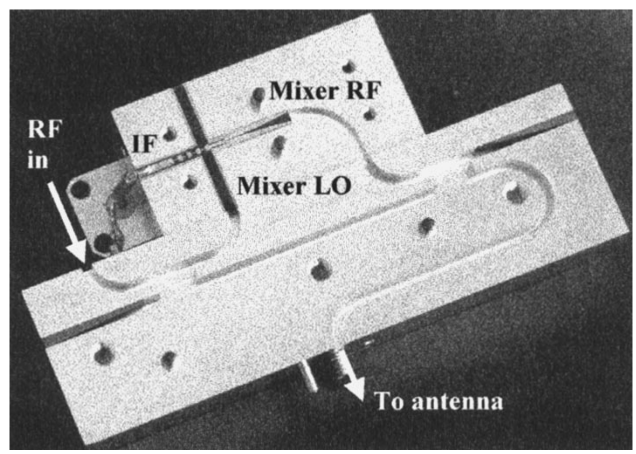

Fig. 2. Photograph of opened split block mounts of the front-end with couplers and finline mixer.

This work describes the design and realization of a 77-GHz FM/CW radar sensor based on a standard transmitter/receiver configuration, with a novel low-loss printed antenna configuration, which can avoid many of the problems listed above.

II. Millimeter-Wave Front-End

As this sensor was, in a first step, intended to test a novel arrangement of a front-end and printed antenna, a rather simple metal waveguide and finline circuitry was chosen, consisting of a Gunn voltage-controlled oscillator (VCO), two E-plane waveguide couplers, and a finline balanced mixer [12]. The basic setup of this front-end is shown in Fig. 1. The balanced finline mixer (see Fig. 2) includes a thin Duroid substrate with

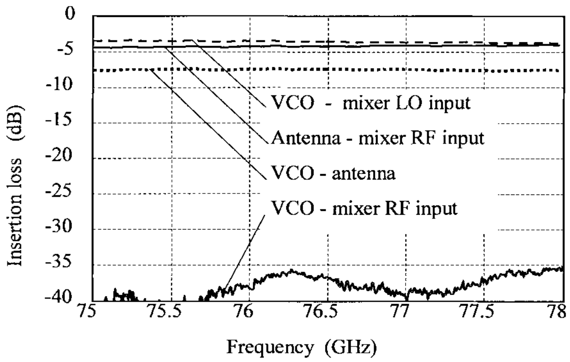

Fig. 3. Insertion loss and isolation of coupler network.

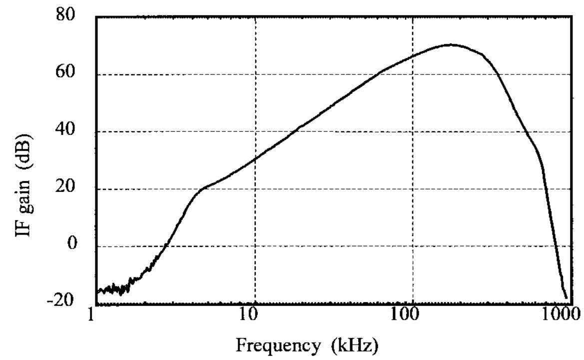

Fig. 5. Gain characteristics of the IF amplifier.

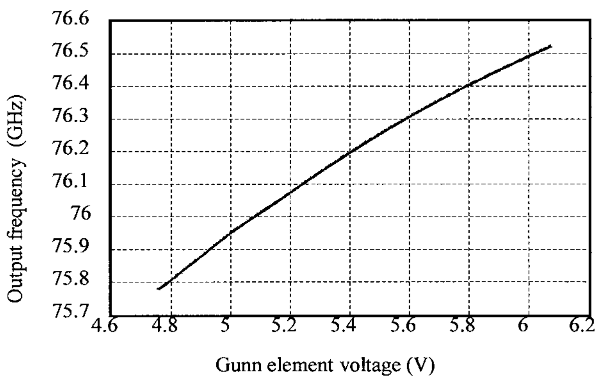

Fig. 4. Voltage-frequency characteristics of the Gunn VCO.

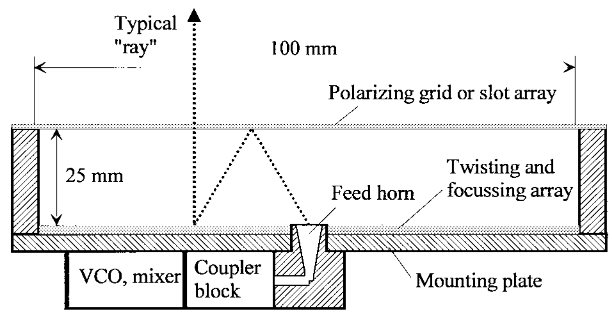

Fig. 6. Basic setup of radar sensor and basic principle of the printed folded reflector antenna.

two GaAs Schottky diodes; as an alternative, silicon diodes are considered as well because these typically result in lower $1/f$-noise, which is relevant to the low IF frequency-range sensitivity of the FM/CW system.

The Gunn oscillator provides an output power of +17 dBm; nearly half of this is used to drive the mixer. The transmitted power at the antenna feed point is about +10 dBm. Due to the arrangement with two couplers, 3 dB of power is lost both for transmit and receive; however, no complicated and expensive circulator is required, and a good isolation between transmitter output and receiver input can be achieved (better than 35 dB between 75–78 GHz [see Fig. 3]), resulting in a significantly reduced leakage of the VCO power with its noise sidebands to the receiver output.

The voltage-frequency characteristics of the VCO is plotted in Fig. 4. An improved linearity is achieve by an additional voltage control via an EPROM to compensated the non-linearities of the VCO characteristics. No efforts, however, were made up to now to compensate for the temperature dependencies of the oscillator frequency. The bias signal of the oscillator is modulated with a triangular signal with a period of 2 ms (ramp duration: 1 ms). The frequency deviation is adjustable up to 200 MHz, resulting in a maximum IF frequency of 200 kHz at a maximum range of 150 m. The minimum range resolution, therefore, is 0.75 m.

To compensate the $1/R^4$ dependence of the received signal, the IF path includes a high-pass filter providing a transmission coefficient increase of approximately 12 dB per octave. In addition, some additional high-pass performance is included to reject frequencies below 5 kHz to avoid problems with low-frequency signals due to frequency-dependent diode asymmetries (Fig. 5). The complete front-end is directly mounted to the back plate of the antenna (Fig. 6).

III. Printed Antenna

A key component of this sensor is the folded reflector antenna arrangement [13] solely employing printed structures. Based on the concept of planar reflector antennas consisting of an array of printed patches or dipoles acting as fixed reflection phase shifters [14], [15], such a focussing array was modified to include a polarization twisting of the electromagnetic field.

The principal function of this antenna is illustrated in Fig. 6. The radiation of the feed is reflected by a printed grid or slot array at the front of the antenna. Following this, the wave is incident on a special array of rectangular metal patches printed on a standard microwave substrate with full backside metallization. The cell size of the array is typically a half-wavelength. The patch axes are tilted by 45° with respect to the incident electric field. The field can be decomposed into components parallel to the two axes of the dipoles. The dimensions of the patches are designed in such a way that, on the one hand, a phase difference of 180° occurs between the two components of the reflected wave—giving the twisting performance. On the other hand, an overall phase shift is adjusted according to the focussing (phase shifting) requirements. The outgoing plane wave can then pass the grid or slot array.

The original design of this antenna is done on the basis of *periodic* structures, e.g., [16], and ray tracing. For varying

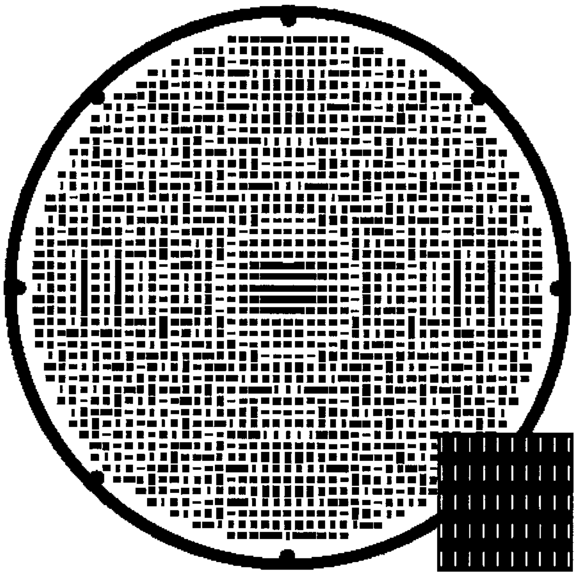

Fig. 7. Layout of twisting reflector and polarizing slot array (not to scale). Mounted in the antenna, the twisting reflector is rotated by 45°.

patch dimensions, the reflection phase angles are calculated for both principal polarizations. The optimum combination of phases is then selected from this set of data according to both twisting and focusing requirements. An optimization of the complete antenna is intended based on a full-wave spectral-domain method [17], [18]. At the moment, however, the size of the antenna (25 wavelengths in diameter) still leads to problems with respect to computer memory and computation time.

If the polarizing grid or slot array is replaced by a novel type of circular polarizer [19], even circular polarization can be achieved with this type of antenna.

The antenna designed for this sensor has a diameter of 100 mm and a thickness of 25 mm. As polarization filter, a slot array was chosen as an optimal transmission performance at the desired frequency could be achieved with a commercially available substrate material (TMM4 material of 1.02-mm thickness and $\varepsilon_r = 4.5$). A printed grid would give a slightly better performance with respect to losses and bandwidth, but then an application-specific substrate thickness would be necessary (which is not a problem in a mass production). The focusing and twisting reflector is fabricated on a Duroid material of 0.254-mm thickness ($\varepsilon_r = 2.22$). The layout of this reflector is shown in Fig. 7, together with a small section of the slot array. Different from other planar antennas, the feeding of the radiating structure is done quasi-optically; this results in considerably reduced feed losses compared, for example, to a microstrip type of antenna. Furthermore, most of the reflecting patches are not in resonance, thus, the element losses are low. With a low profile of only 25 mm, and the fabrication of only two printed substrates, this antenna provides an interesting alternative for sensor and communication applications.

The E- and H-plane radiation diagrams of the complete antenna are plotted in Fig. 8. Beamwidth is 2.7°, and the sidelobe level in both planes amounts to about -24 dB. Significant deterioration of the antenna diagrams have not been

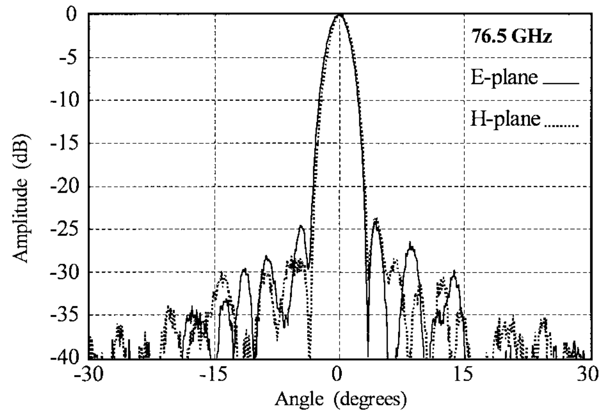

Fig. 8. Radiation diagram of the folded reflector antenna.

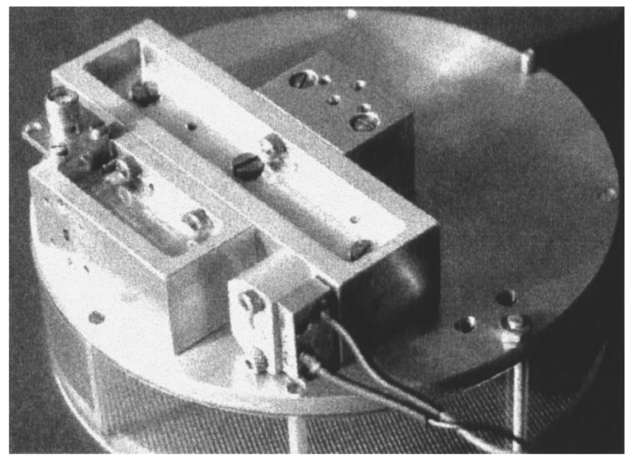

Fig. 9. Photograph of the 77-GHz radar front-end.

found in the frequency range from 75.5 to 77.5 GHz. Gain was measured to 35 dB compared to a value of 35.7 dB calculated from the beamwidths. A photograph of the antenna with the radar front-end is shown in Fig. 9.

IV. Radar Tests

A test evaluation of the radar data is performed via an interface card and a personal computer (laptop). The IF signal is AD converted, stored, and then transferred (at a lower speed) to the PC, where a fast Fourier transform is done. According to this procedure, only part of the FM/CW ramps are accessible. Rising and falling slopes of the triangular ramp, however, are separately recorded and evaluated. In this way, it is possible to evaluate both distance and speed of a target—although with some slight restrictions (for short distances, the maximum speed is limited).

Fig. 10 shows the spectrum of a relatively complex stationary test arrangement. 1 kHz corresponds to 0.75-m distance (at 200-MHz frequency deviation). Fig. 11 is the result of a test with a car moving toward the stationary radar. Evaluating both the rising and falling ramp, two different peaks occur in the spectrum, separated by twice the Doppler frequency. From this, a target distance of approximately 50 m and a speed of about 28 km/h (including the direction of the movement) can be derived. Fig. 12 displays the spectra of a car at a 20-m

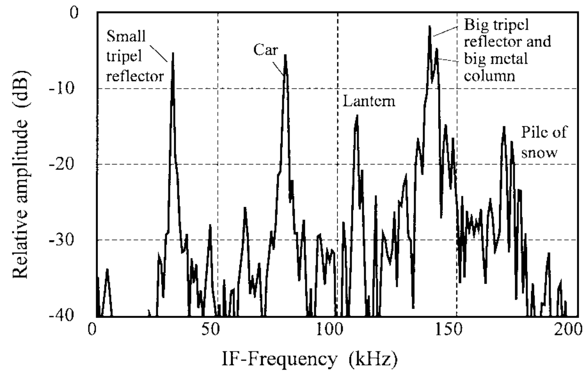

Fig. 10. IF spectrum of the radar for a complex stationary test scene.

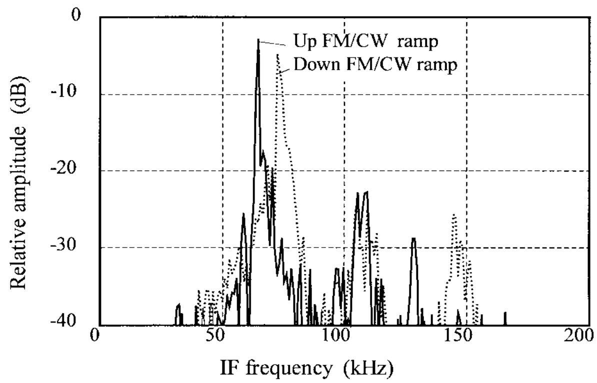

Fig. 11. IF spectrum at both an up and down FM/CW ramp for a car moving toward the radar (distance approximately 50 m, speed 28 km/h).

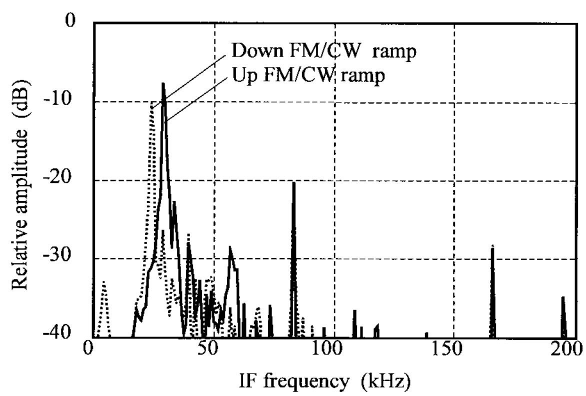

Fig. 12. IF spectrum at both an up and down FM/CW ramp for a car moving away from the radar, including some stationary targets (distance approximately 20 m, speed 17 km/h).

distance moving away from the radar at 17 km/h, together with some stationary targets.

V. Beam Scanning

Most automotive radars presently under development provide at least three beams to enable a supervision of adjacent lanes or to "see" into bends of the street. For future applications, such as anticollision radar, even more beams are considered necessary to do some kind of imaging of the scene in front of the vehicle. Switching between several antennas or feeds [2], mechanical scanning [5], [6], or frequency scanning

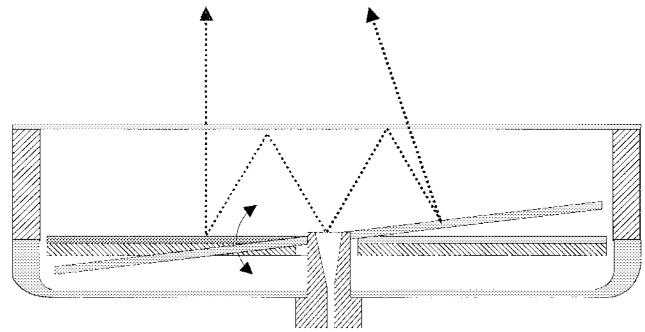

Fig. 13. Principle of beam scanning of folded reflector antenna.

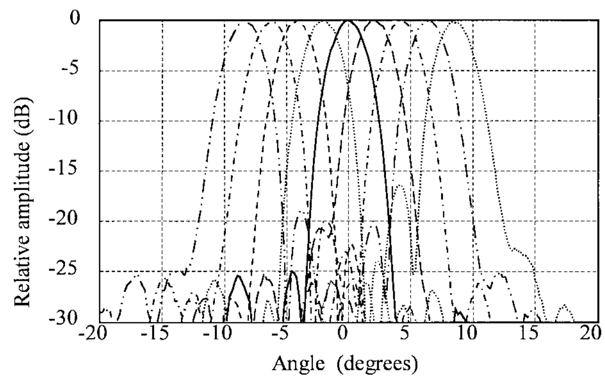

Fig. 14. H-plane radiation diagrams of mechanically scanned antenna (scanning in H-plane, $f = 76.5$ GHz).

[8] have been considered or, as an alternative, monopulse antennas are employed [2], [7]. To implement a scanning option into the antenna reported here, a modified concept similar to [6] was tested (Fig. 13). By tilting the focusing and twisting plate—without moving the millimeter-wave front-end—the beam is scanned at twice the tilting angle of the plate. In the test antenna, the tilted mirror simply was made adjustable by a screw and a spring. In an actual application, a small motor or a simple magnetic mechanism can take this task. If the carrier plate for the reflector substrate is made light enough, no high mass is involved, and a fast scanning, as required for practical applications, is possible [6].

In a first experiment, the antenna with vertical polarization was scanned in azimuth (H-plane) up to an angle of $\pm 10°$. A number of radiation diagrams are plotted in Fig. 14. A slight asymmetry was found due to some inaccuracy in the mechanical setup. Up to a scanning angle of $\pm 6°$, a sidelobe level of better than -20 dB is maintained. This has to be compared to the scanning properties of standard reflector antennas with an f/D-ratio of 0.5, as it is used here. The amplitudes of the main beams vary only slightly within the scanning range investigated here. Very similar results are achieved scanning the antenna in the E-plane.

VI. Conclusion

A 77-GHz radar sensor has been described. It is based on conventional E-plane circuits for the front-end, but on a novel low-loss low-profile printed antenna. At the moment, this sensor provides a single antenna beam only, but with a separate antenna, a good scanning performance of two or more beamwidths to both sides has been demonstrated. The low-profile antenna arrangement, as presented in this paper, can be an interesting solution for automotive applications. Due to the planar nature of the antenna, a low-cost production should be possible.

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