INVITED PAPER

Antenna Concepts for Millimeter-Wave Automotive Radar Sensors

General sensor concepts for automotive collision-avoidance radars operated at about 77 GHz are discussed in this paper; several types of automotive antennas are also discussed.

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ABSTRACT | Automotive radars are on the market since 1999, both in the frequency range around 24 GHz as well as 76.5 GHz, with a new frequency band ranging from 77 to 81 GHz intended for medium and short-range sensors. The choice and design of the respective sensor antennas are determined by the requirement for high gain and low loss combined with small size and depth for vehicle integration, the challenges by the millimeter-wave frequency range, and a great cost pressure for this commercial application. Consequently, planar antennas are dominating in the lower frequency range, while lens and reflector antennas had been the first choice at 76.5 GHz, partly in folded configurations. With increasing requirements towards a much more detailed observation of the scenery in front or around the vehicle, multibeam antennas or scanning antennas have been designed, and solutions based on (digital) beamforming with a number of integrated antennas are in use or under development. General antenna concepts, partly including some system aspects, as well as three realized antenna configurations will be described in detail in this contribution.

KEYWORDS | Automotive applications; leaky-weave antennas; lens antennas; microstrip antennas; millimeter-wave radar; radar antennas; reflector antennas

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I. INTRODUCTION

In an early stage automotive sensors integrated into a car were used solely in comfort functions supporting an automatic speed control by keeping a safe distance to the preceding vehicle. The aim for further developments during the last years has been to make radar available for safety functions like adaptive cruise control (ACC), forward collision alert, rear traffic crossing alert, or blind spot detection.

Thus, sensors have to look into all directions around the vehicle with differently defined scanning and distance relations. Rear traffic crossing alert and blind spot detection operate in the near range and simply give information whether one or more targets in a certain area are present, whereas ACC and forward collision alert have to scan the entire traffic scheme not only in the near range but also—dependent on the maximum speed of the object—in the mid and far range. There is no unique definition of near, far, and midrange, however, ball park numbers for the limits are 40 and 100 m, respectively.

As a consequence, a much wider field of view compared to ACC is required, resulting in some kind of "imaging" of the scenery in front of the sensor. Thus, much more effort has been put to the design of novel antenna concepts, partly in combination with modified overall sensor arrangements, including multibeam antennas, scanning antennas, switched antenna concepts, and beam forming approaches with multiple transmit and receive antennas.

After penetration into the market of premium level cars the sensors shall nowadays become available for lower cost vehicles, and thus cost reduction is the major driving factor. This has the consequence that the cost of the complex RF components including the antennas has to be strongly reduced whereas the effort for digital signal processing can be increased. This will lead to a change from the scanning or multibeam antenna principle to digital beamforming.

When designing automotive antennas the engineer faces the task that all components must be suitable for mass production, operate in a temperature range from −40 °C to 85 °C . . . 105 °C, be shock proof, and the entire arrangement has to be compact in size. The implications of all this on the choice of materials and even the performance should not be underestimated.

Frequencies allocated for short range are in the 24.05–24.25-GHz frequency range (ISM band), some wider bands in the 24-GHz frequency range, but with different allocations and restrictions in different countries, and the 76–77-GHz range for the far range (ITU-R M1452, ITU Footnote 5.150). Recently, in Europe the band from 77–81 GHz has been allocated for short and mid range, similar efforts are going on in other parts of the world as well. In the near future almost all long or mid range antennas will operate in the 76–81-GHz range.

In this paper, we briefly describe general sensor concepts followed by the explanation of different types of automotive antennas, including reflector, lens, and array antennas. Examples from different providers of such antennas are presented.

II. GENERAL SENSOR CONCEPTS

Automotive radar sensors provide information about other vehicles and the road surroundings with respect to distance (range), speed, and, depending on the specific configuration, angle (cross range). Range is determined by measurement of the flight time of the electromagnetic wave from the radar to a target and back while relative speed is determined evaluating the Doppler frequency shift. Automotive sensors typically use either a pulse modulation [1] or frequency modulated constant wave (FMCW) signals with saw tooth or triangular frequency modulation [2]. Most of the automotive pulse sensors operate in a sampling mode with some similarity to a sampling oscilloscope (Fig. 1). The received pulses are down converted with a pulse delayed by a time τ; an intermediate frequency (IF) signal occurs only if the time of flight of the pulse is identical to the delay. Together with a low-pass filter (LPF) for the IF signal, bandwidth at the receiver output can be considerable reduced, and a further digital processing with moderate speed is possible. For the FMCW sensor, a signal with a linear frequency ramp is transmitted and then received with a delay time (see Fig. 2). Down conversion with the transmitter signal then results in an IF signal the frequency of which is proportional to the target distance. A typical further processing is done via analog–digital converter (ADC) and fast Fourier transform (FFT).

In general, signal bandwidth, either via pulse width or FMCW frequency deviation, determines the range resolution ΔR (*separation* between two targets):

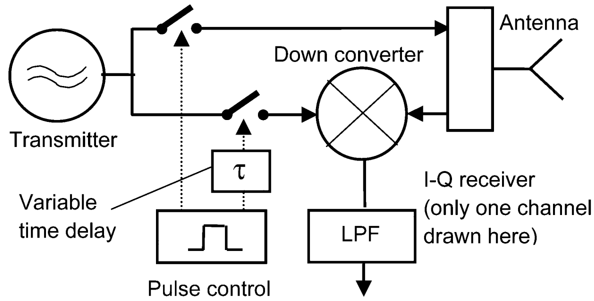

Fig. 1. ***Basic block diagram of an automotive pulse radar.***

$$\Delta R \geq \frac{c_0}{2\Delta f} \quad (1)$$

with c_0 as speed of light and Δf the modulation bandwidth. Typical values of ΔR range from about 1 m for early systems to some cm for newer short-range broadband systems (up to 5-GHz bandwidth).

A number of years ago, the RF circuits of the frontends were built based on discrete devices like Gunn elements and Schottky diodes; today monolithic microwave integrated circuits (MMIC) based on GaAs [3] and silicon-germanium (SiGe) are available, even with one and more RF frontends on a single chip [4].

The angular or cross range observation depends on the sensor application and is determined by its antenna arrangement. In an early stage, when automotive sensors were used solely in comfort functions supporting the

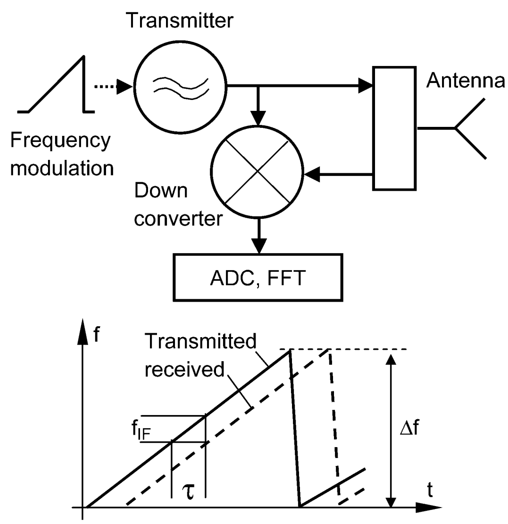

Fig. 2. ***Basic block diagram and time-frequency diagram of an FMCW radar.***

automatic speed control by keeping a safe distance to the preceding vehicle, a few (switched) narrow antenna beams were sufficient to monitor the own and adjacent lanes on a highway. Today, automotive sensors increasingly are employed for safety purposes both for highway ("long range") as well as for dense urban ("short range") traffic scenarios, leading to the necessity of much more sophisticated antenna and overall system concepts.

III. GENERAL TYPES OF AUTOMOTIVE ANTENNAS

The cross sectional dimensions of the sensor are determined by the antenna; an estimation of the achievable 3 dB antenna beamwidth (in degrees) of a standard antenna or antenna array is given by

$$\Delta\Phi = 60^\circ \frac{\lambda}{D} \quad (2)$$

where λ is the free space wavelength and D the overall antenna dimension in the respective plane. For far range applications like ACC in the 77-GHz frequency range, typical antenna beamwidths are in the range of $3^\circ \ldots 4^\circ$, resulting in antenna diameters from 60 to 100 mm and in gain values of around 30 dB; at 24 GHz, antenna size and beamwidth typically are larger. Mid and near range systems have wider beamwidths and lower gain, but require a wider angle of view by scanning, multiple beams, or beamforming.

A. Reflector and Lens Antennas

First antennas were realized as lens antennas [5] or parabolic reflector antennas. As the sensor depth is of great concern due to the limited space for integration into the vehicle surface, folded configurations of such antennas have been developed [6], [7] as sketched in Fig. 3(a) and (b). In these antennas, a feed initially radiates against a polarizing grid, the wave is reflected towards a planar structure where the wave is reflected again, but with a polarization twisted by 90°. Such polarization twisting can be achieved by structures where the reflection phase angle differs by 180° for the two principle polarization directions. Thus, a wave incident with a polarization tilted by 45° with respect to the principle axes of the structure is reflected in the orthogonal polarization as indicated in Fig. 3(e). Such structures, for example, can be realized by a (printed) grid placed a quarter wavelength in front of a metal plane Fig. 3(c) or by printed patches with appropriate geometry Fig. 3(d).

In [8], the complex lens or curved reflector has been replaced by a planar printed structure (reflectarray) which, at the same time, can perform focusing of an incident spherical wave and twist the polarization (see Fig. 4 top).

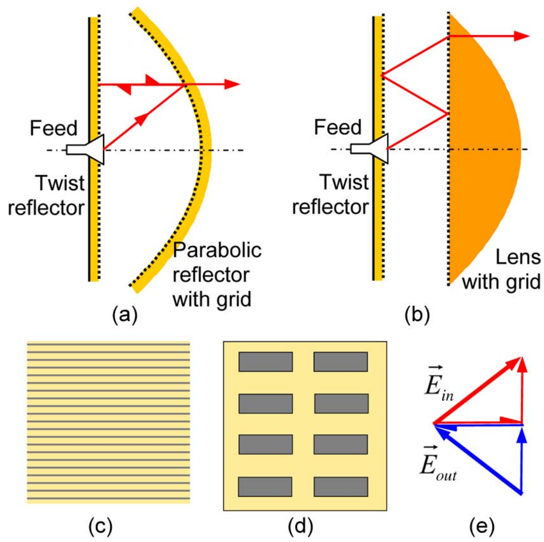

Fig. 3. ***(a) Folded reflector and (b) lens antennas, (c) and (d) basic structures, and (e) principle for polarization twisting.***

Typical reflecting elements of such a reflectarray are rectangular patches. An antenna of this type with three beams (generated by three different feed locations) has been implemented into the second generation of Mercedes radars (Fig. 4, bottom), and this principle is also used in the third generation sensor (see Section IV-C).

Lens and reflector antennas typically exhibit very low loss, advantageous in combination with millimeter-wave semiconductor elements for power generation of quite

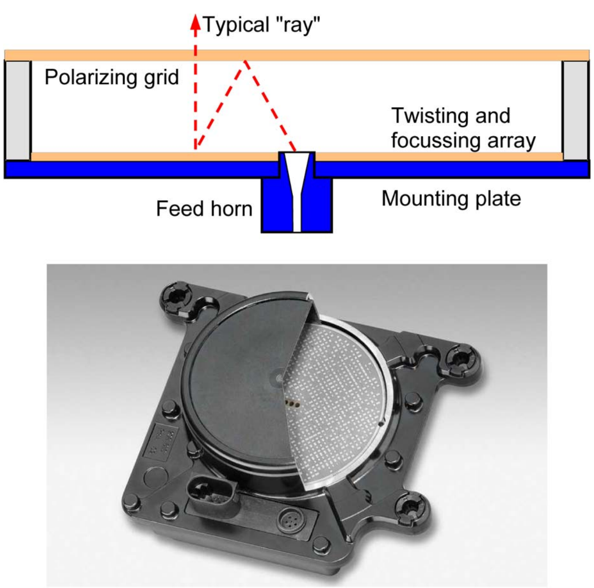

Fig. 4. ***Cross section and photograph (courtesy of Conti ADC) of a folded reflectarray antenna (frequency 76.5 GHz, antenna diameter 90 mm, depth 23 mm).***

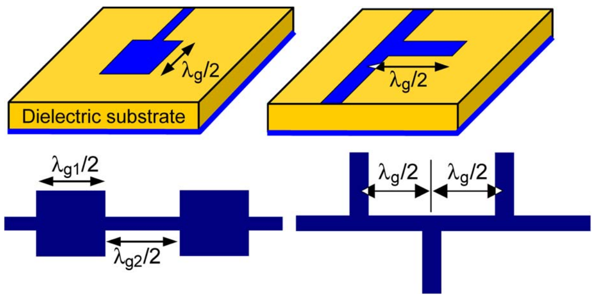

Fig. 5. ***Microstrip patch antenna (top left) and open stub(s) as radiator (top right) and series arrangement of elements for broadside radiation (bottom).*** $\lambda_g, \lambda_{g1}, \lambda_{g2}$***: wavelengths of the respective transmission line.***

moderate level, but they require a non negligible depth of a few centimeters, thus purely planar antennas are gaining more and more interest.

B. Planar Antennas

The most common type of planar antennas is based on microstrip [9], [10]. Single antenna elements can be half-wavelength resonators or dipoles (patch antennas) or the open end of a microstrip stub (see Fig. 5). These elements can be combined in series and/or parallel arrangements to form antenna arrays with the required overall antenna diagram. Typically, microstrip antennas exhibit bandwidths in the range of a few percent, increasing with lower dielectric constant of the substrate and substrate thickness. The latter, however, leads to an increased radiation also of the feeding network and to the excitation of surface waves. A way out of this may be feeding the patch from the backside via a slot in the ground plane.

Single-patch antennas can be used as feeding elements for a lens antenna ([5], see also Section IV-B), or arrays of microstrip patches can be used directly as automotive antennas [1], [4], [11], [12]. For larger antenna arrays, feed network losses may pose a limit for antenna size.

An alternative approach to planar antennas is based on dielectric guides, exhibiting lower loss compared to microstrip. To form an antenna, a dielectric guide typically is loaded with periodic perturbations [see Fig. 6(a)] where part of the guided power is radiated, and the fields

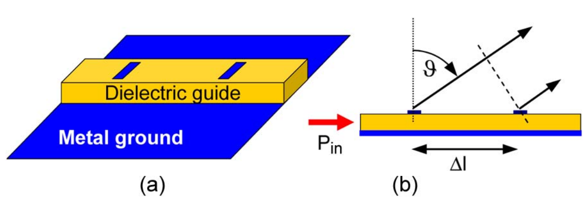

Fig. 6. ***Antenna based on a dielectric guide with periodic perturbations (a) and sketch for phase angle calculation (b).***

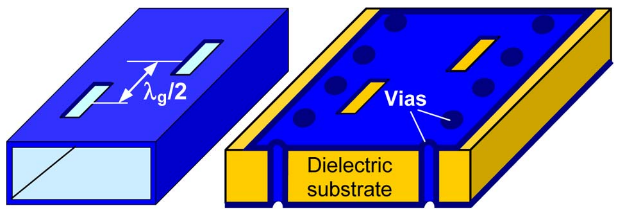

Fig. 7. ***Slotted waveguide and slotted synthetic waveguide array.***

superpose to form the overall far field radiation diagram. For a given direction of radiation, the partial radiated fields must superimpose in phase. According to Fig. 6(b), the following relation must hold

$$k_0 \cdot \Delta l \cdot \sin(\vartheta) + 2\pi = k_d \cdot \Delta l \tag{3}$$

where k_0 and k_d are the phase constants of free space and the dielectric guide, respectively.

A final antenna realization to be mentioned in this section is the waveguide slotted array (Fig. 7). It consists of a metal waveguide with longitudinal or transversal slots, e.g., [13]. Once again, radiation contributions from a number of slots superimpose in phase to form the desired radiation pattern. For an easy and low-cost fabrication of such arrays, a synthetic integrated waveguide (SIW) can be realized within a dielectric substrate where the side walls are formed by rows of vias [14], [15].

C. Digital Beamforming

Antenna arrays as partly mentioned in the previous subsection are connected by transmission lines and provide fixed beams. Antenna elements or subarrays can also be connected to phase shifters (and attenuators) providing possibilities for electronic beam scanning (see Fig. 8, left side); this can get relatively complex, lossy, and costly at millimeter-wave (mm-wave) frequencies. An alternative is to use several antenna elements or subarrays and either switch these successively to a receiver or transmitter, or connect them to multiple transmit–receive circuits, easily

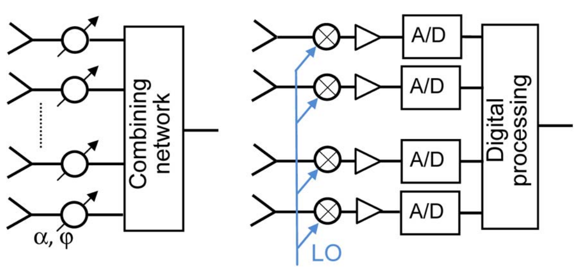

Fig. 8. ***Concepts of a phased array antenna (left side) and digital beamforming receiver (right side).***

done with modern MMICs like in [4]. Fig. 8, right side, shows the example of a receiver with digital beamforming. The scene of interest is illuminated by a separate transmit antenna. A number of receiver channels down convert and amplify the respective signals. The IF signals are sampled and converted to a sequence of digital numbers which can be processed further. After range processing for each channel—typically using an FFT, amplitude and phase angle are available for each range cell and receive channel. Multiplication with a complex number is equivalent to adjust amplitude and phase angle for the analog signal. As a consequence, with appropriate processing (typically another Fourier transform in cross range), different radiation diagrams and beam shapes can be adjusted simultaneously, thus being able to measure the scenery in front of a car with high precision [1], [16], [17]. Comparable to *analog* beamforming with a phased array, this approach typically is referred to as *digital* beamforming.

The subarray beamwidth in such an approach must be sufficient to cover the angle range of interest for the respective application. The subarrays can be arranged at relatively large, but different distances between each other, so a high lateral resolution can be achieved, while the different distances can be optimized to remove ambiguities (grating lobes). Some more details are explained at the example as given in the next section. In addition, with a suitable lateral arrangement of the subarrays for transmit and receive, even an effective aperture width larger than the physical one can be achieved [18].

D. Fabrication, Packaging, and Mounting Considerations

As already mentioned in the introduction, automotive radars have to operate in a temperature range from −40 °C up to 85 °C or even higher, they have to withstand shock and vibrations, and they have to operate under conditions of rain, snow, or ice. Selections of materials, fabrication processes, packaging as well as mounting of the sensor have to be selected carefully.

Substrate materials need to be suitable for the high frequency, their physical and electrical properties should be reasonably constant over the temperature range, and they should not absorb moisture. On the other hand standard microwave substrates may be too expensive, so a compromise has to be made in this respect. Etching of the planar structures should, as far as possible, be done using standard PCB processes, but may require accuracies down to 20 μm for the 77-GHz frequency range—this also poses a great challenge towards tolerance-optimized antenna design. Metal surfaces, in addition, need be protected against corrosion by suitable plating.

The antenna and the radar sensor as a whole, finally, have to be protected by a suitable package. This typically is done by an overall housing, as can be seen also at the examples given in the following section. The cover in front of the antenna (radome) must be transparent to the electromagnetic wave in the respective frequency range, leading to an optimized thickness for the used plastic materials in the order of multiples of half a guide wavelength within the material. This optimized thickness only is perfect for one angle of radiation. For all other angles there is a performance degradation due to reflection. Major effort is necessary to keep the influence of such a reflection below a given threshold. If the cover is close to the antenna, even a codesign of antenna and cover has to be done.

Mounting of the radar sensor at the car requires a position from which the radar can cover the relevant angle of view, but space limitations and overall car design concepts require some compromise; so typical mounting positions are behinds the radiator grille or the bumper. Today, the bumper often is painted, and efforts have to be done to ensure a sufficient transparency of the bumper, even with paintings containing metallic particles. This can be done by optimizing the thickness of the bumper material or by adding some matching layer in front of the radar [19].

Furthermore, during operation, the radome must not be covered by layers of water, ice or snow; this would severely deteriorate its performance. To avoid this, a protected mounting position, e.g., behind the bumper, a water repellent radome surface, or a suitable form or orientation of the radome to blow away water or snow just by the natural airstream of the car can be selected.

IV. EXAMPLES OF REALIZED SENSOR ANTENNAS

Today, automotive radars are offered by quite a number of companies including Autoliv, Bosch, Continental ADC, Delphi, Fujitsu Ten, Hella, Hitachi, InnoSent, Mitsubishi, TRW Autocruise, or Valeo. As examples for different antenna approaches, three sensor antennas will be described in more detail, including a microstrip array configuration for beamforming, a lens antenna with microstrip feed elements, and a more complex scanning antenna comprising different principles as mentioned in the last section.

A. Microstrip Array Antenna (Toyota Laboratories)

Fig. 9 shows a photograph of a sensor/antenna study performed by Toyota Laboratories. The antenna consists of six subarrays, three each for transmit and receive. In a first version, antenna selection has been done by switching, but also some study was performed with parallel receivers. Each antenna subarray consists of two series-fed arrays in parallel (in later realizations, the arrays are center-fed to avoid frequency scanning). The radiation structures are half-wavelengths dipoles fed at one edge and oriented at an angle of 45° resulting in the same direction of antenna polarization. This serves as a first measure to reduce interference from oncoming cars also equipped with radar having the same concept of polarization. All subarrays provide relatively wide beams in azimuth; the respective angular resolution is achieved by beamforming, i.e., by

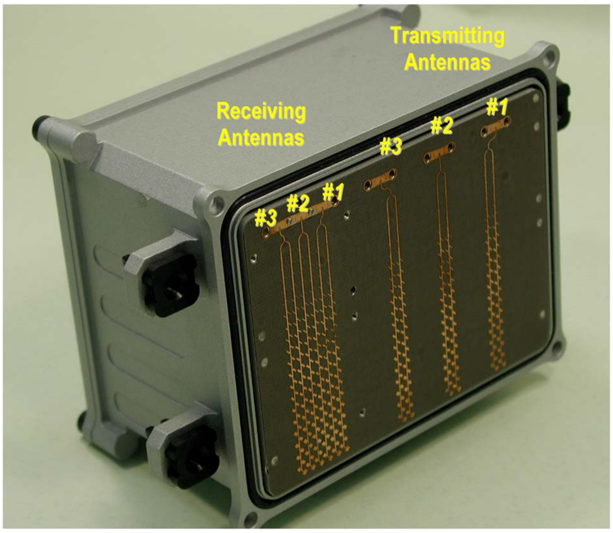

Fig. 9. *Automotive sensor with three transmit and three receive antenna arrays in microstrip technology (courtesy of Toyota Laboratories), antenna radome removed.*

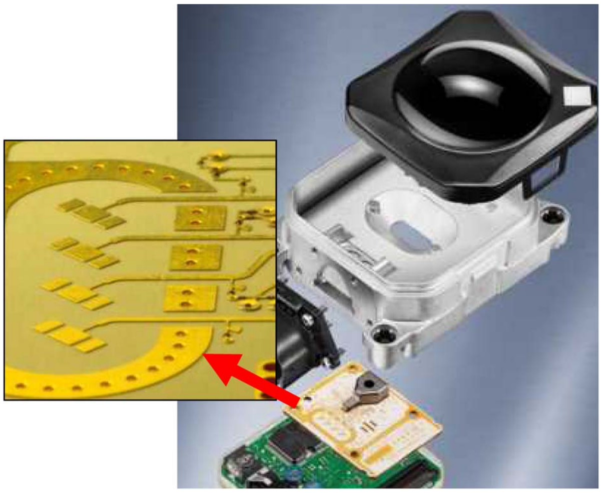

Fig. 11. *Exploded view on the Bosch LRR3 sensor and details of the planar antenna elements feeding the lens. (Sensor photograph provided by Bosch.)*

digitally superimposing results from nine measurements (three receive and three transmit positions).

According to antenna theory, the angular distribution of the radiated fields (radiation diagram) of an antenna is proportional to the Fourier transform of its excitation distribution in the respective plane. On the other hand, the signal transmitted from one subarray and received by another one is proportional to the multiplication of the radiation diagrams of these two arrays. Consequently, this product can also be derived from an excitation distribution formed by the convolution of the two individual excitations. Superposition of the measurements from three transmits and three receive subarrays then results in the convolution of the respective excitation distributions. Assuming, for simplicity, Dirac pulse shaped excitation distributions for the subarrays, leads to the configuration as indicated in Fig. 10. (Basically, this assumption is correct for the *array factor* of the radiation diagram; the final radiation diagram then is achieved by multiplication with the *subarray* radiation diagram). As a result, the configuration as given in the example in Fig. 9 results in a synthetic antenna array with densely arranged subarrays (see Fig. 10). Recently, such concepts also have been called MIMO radar, although in general, the different transmit channels are operated sequentially. Weighting the nine individual measurements with complex numbers (representing phase and amplitude adjustments), different beam direction or modifications of the radiation diagram can be adjusted and evaluated simultaneously.

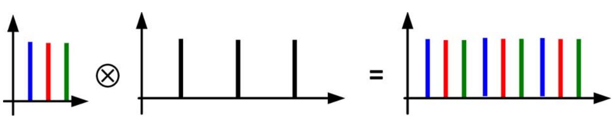

Fig. 10. *Ideal antenna excitation distribution and convolution of transmit and receive antenna excitation resulting in a densely populated synthetic array.*

B. Bosch Sensor LRR3

The LRR3 automotive radar sensor of Bosch came onto the market in 2009. It is based on the FMCW principle, and the mm-wave transmit and receive circuits are integrated on a four-channel SiGe monolithic chip [4] connected to four single microstrip patch antennas combined with parasitic elements to adjust bandwidth and beamwidth. The antenna elements are tilted by 45° to reduce interference from oncoming cars. The antenna elements serve as feeds for a lens antenna [5] resulting in four narrow beams. An exploded view on the complete sensor and the planar antenna section is shown in Fig. 11. With overlapping radiation diagrams of the beams (see Fig. 12) the angular detection of targets is done by monopulse principles, resulting in an angular accuracy considerably better than the beamwidth, provided that only one target is in the respective range cell.

C. Continental Sensor ARS300

Also in 2009, Continental ADC introduced the third generation of their automotive radar with completely new features and a novel approach for the radar antenna. The antenna of the ARS300 scans with a narrow beam over a given azimuth range, it performs auto-alignment, and is compact in size.

As can be seen in Fig. 13 the entire arrangement consists of a dielectric waveguide in the vicinity of a grooved

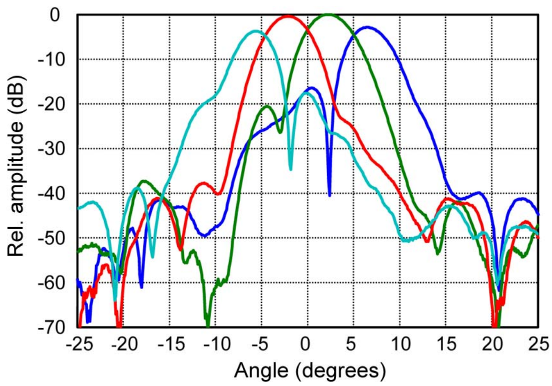

Fig. 12. ***Azimuth radiation diagrams of the Bosch LRR3 sensor.***

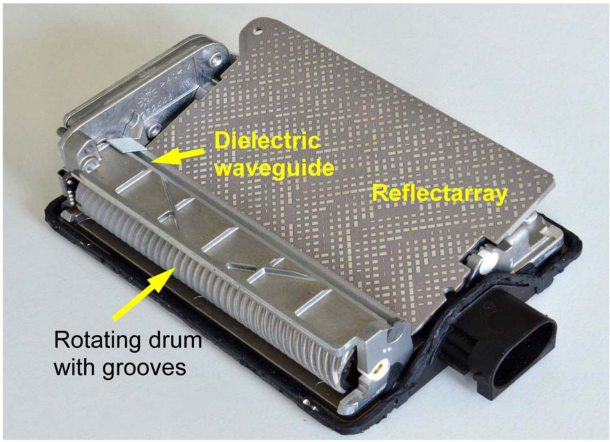

Fig. 14. ***Photograph of the ARS300 antenna (cover with transreflector removed).***

rotating drum and a folded space consisting of a polarizer or transreflector, also serving as mechanical protection and radome, and a focusing reflectarray.

An electromagnetic wave travels along the dielectric guide with a propagation constant k_d. The drum is placed close to the dielectric waveguide, and the metal ridges between the grooves of the drum form periodic perturbations similar to those indicated in the form of metal patches in Fig. 6. This results in coupling of power from the waveguide mode into the radiating mode according to (3). To scan the radiated beam over a given angle, the period of the grooves has to be modified—the groove period depends on the rotational angle, and the actual groove period in the direct vicinity of the guide determines the direction of the radiated beam. Rotating the drum then leads to a scanning of the beam [20]. A great effort has been spent designing the drum in a way to find the optimum shape and size of the grooves such that at each azimuth angle a beam of a given angle of divergence with sidelobes below a given threshold is obtained. A unique feature of this waveguide drum unit is that both the direction of radiation and the beamwidth can be altered such that different sensor modes from short to long range (up to 200 m) can be covered by a single setup.

Additionally, the beam shape has to be adjusted in elevation as well. This is done by a folded reflectarray configuration as described earlier in Section III-A. The required polarizer is attached to the cover of the sensor such that the beam radiated from the dielectric waveguide/drum unit is reflected towards a reflectarray consisting of a dielectric layer glued on a conducting plate. Phase angles are adjusted such that a narrow beam results in elevation, together with the necessary polarization twisting. A photograph of the antenna with removed transreflector/cover can be seen in Fig. 14. Measurement of the radiation diagrams has been done using the complete radar resulting in two-way diagrams. Some of these far-field radiation diagrams for different drum positions can be seen in Fig. 15. Two-way beamwidths are in the range of 2.5°.

In addition, this antenna exhibits another unique feature. Whereas the headlights of a car can be adjusted in elevation by any skilled person, this is different for a radar

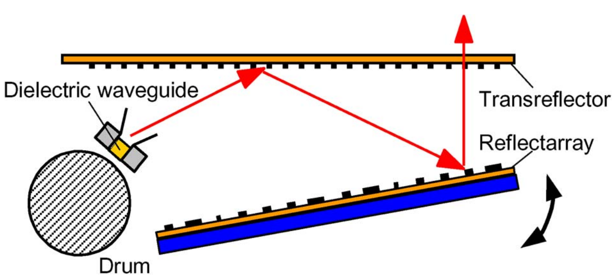

Fig. 13. ***Cross section of the ARS300 antenna.***

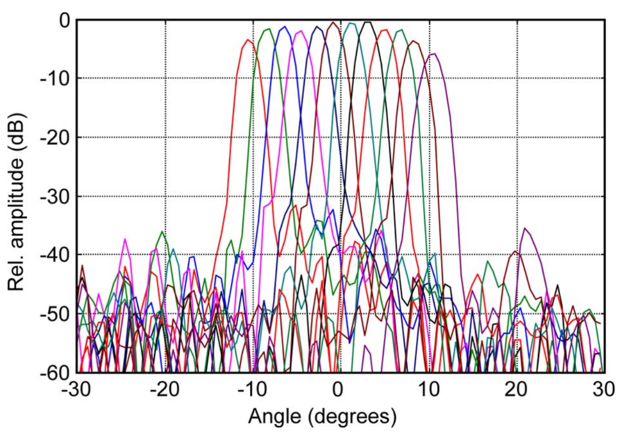

Fig. 15. ***Two-way azimuth radiation diagrams of the ARS300 antenna for different drum positions.***

sensor with its nonvisible radiation. With this antenna, the reflectarray can be tilted to some extent by a motor unit and performs an auto-alignment in elevation. ■

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REFERENCES

[1] I. Gresham, A. Jenkins, R. Egri, C. Eswarappa, N. Kinayman, N. Jain, R. Anderson, F. Kolak, R. Wohlert, S. P. Bawell, J. Bennett, and J.-P. Lanteri, "Ultra-wideband radar sensors for short-range vehicular applications," *IEEE Trans. Microw. Theory Tech.*, vol. 52, no. 9, pp. 2105–2120, 2004.

[2] A. J. Hymans and J. Lait, "Analysis of a frequency-modulated continuous-wave ranging system," *Proc. IEE—Part B: Electron. Commun. Eng.*, vol. 107, no. 34, pp. 365–372, 1960.

[3] M. Camiade, D. Domnesque, Z. Ouarch, and A. Sion, "Fully MMIC-based front end for FMCW automotive radar at 77 GHz," in *Proc. 30th Europ. Microw. Conf.*, 2000, pp. 1–4.

[4] V. Winkler, R. Feger, and L. Maurer, "79 GHz automotive short range radar sensor based on single-chip SiGe-transceivers," in *Proc. 38th Europ. Microw. Conf.*, 2008, pp. 1616–1619.

[5] T. Binzer, M. Klar, and V. Groß, "Development of 77 GHz radar lens antennas for automotive applications based on given requirements," in *2nd Int. ITG Conf. Antennas (INICA'07)*, 2007, pp. 205–209.

[6] I. Gresham, N. Jain, T. Budka, A. Alexanian, N. Kinayman, B. Ziegner, S. Brown, and P. Staecker, "A compact manufacturable 76–77-GHz radar module for commercial ACC applications," *IEEE Trans. Microw. Theory Tech.*, vol. 49, pp. 44–58, 2001.

[7] Millitech Corporation, "Crash avoidance FLR sensors," *Microw. J.*, vol. 37, no. 12, pp. 122–126, 1994.

[8] W. Menzel, D. Pilz, and M. Al-Tikriti, "MM-wave folded reflector antennas with high gain, low loss, and low profile," *IEEE Antennas Propag. Mag.*, pp. 24–29, Jun. 2002.

[9] J. R. James, P. S. Hall, and C. Wood, *Microstrip Antenna Theory and Design*. London, U.K.: Peregrinus, 1981.

[10] K.-F. Lee and K.-F. Tong, "Microstrip patch antennas—Basic characteristics and some recent advances," *Proc. IEEE*, 2002, DOI: 10.1109/JPROC.2012.2183829.

[11] M. E. Russell, A. Crain, A. Curran, R. A. Campbell, C. A. Drubin, and W. F. Miccioli, "Millimeter-wave radar sensor for automotive intelligent cruise control (ICC)," *IEEE Trans. Microw. Theory Tech.*, vol. 45, pp. 2444–2453, 1997.

[12] S. Tokoro, K. Kuroda, and A. Kawakubo, "Electronically scanned millimeter-wave radar for pre-crash safety and adaptive cruise control system," in *Proc. IEEE Intell. Veh. Symp.*, 2003, pp. 304–309.

[13] K. Sakakibara, A. Mizutani, N. Kikuma, and H. Hirayama, "Design of narrow-wall slotted hollow waveguide array for arbitrarily linear polarization in the millimeter-wave band," in *Proc. IEEE Int. Symp. Antennas Propag.*, 2006, pp. 3141–3144.

[14] J. Hirokawa and M. Ando, "76 GHz post-wall waveguide fed parallel plate slot arrays for car-radar applications," in *Proc. IEEE Int. Symp. Antennas Propag.*, 2000, vol. 1, pp. 98–101.

[15] J. F. Xu, W. Hong, P. Chen, and K. Wu, "Design and implementation of low sidelobe substrate integrated waveguide longitudinal slot array antennas," *IET Microw. Antennas Propag.*, pp. 790–797, 2009.

[16] Y. Asano, S. Ohshima, T. Harada, M. Ogawa, and K. Nishikawa, "Proposal of millimeter-wave holographic radar with antenna switching," in *Proc. IEEE Inter. Microw. Symp.*, 2001, pp. 1111–1114.

[17] A. Stelzer, R. Feger, and M. Jahn, "Highly-integrated multi-channel radar sensors in SiGe technology for automotive frequencies and beyond," in *Proc. ICECom Conf.*, 2010, pp. 1–11.

[18] N. Kees, E. Schmidhammer, and J. Detlefsen, "Improvement of angular resolution of a millimeterwave imaging system by transmitter location multiplexing," in *Proc. IEEE Int. Microw. Symp.*, 1995, pp. 969–972.

[19] F. Fitzek, R. H. Rasshofer, and E. M. Biebl, "Metamaterial matching of high-permittivity coatings for 79 GHz radar sensors," in *Proc. European Microw. Conf.*, 2010, pp. 1401–1404.

[20] V. Manasson, L. Sadovnik, and R. Mino, "MMW scanning antenna," *IEEE AES Syst. Mag.*, pp. 29–33, Oct. 1996.

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