A Flexible Dielectric Leaky-Wave Antenna at 160 GHz

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***Abstract*—Flexible antennas provide the opportunity to place them on bent or moving surfaces. For leaky-wave antennas the mechanical flexibility offers a second possibility to modify the beam direction besides the frequency scanning property. This paper presents a leaky-wave antenna with a tapered metalized grating on flexible high density polyethylene in the frequency range from 140 GHz to 175 GHz. The high efficiency antenna was investigated with numerical calculations and a full wave simulation. The fabricated antenna has a scanning range of 20° and the measured gain is between 16.5 dBi and 17.5 dBi. A bend in the antenna structure affects its properties and increases the sidelobe level and the angular width.**

I. Introduction

Frequencies above 100 GHz have attracted strong interest in the last years for radar applications [1] as well as for high-speed data communication [2]. For these frequencies antenna design becomes a challenging topic. Known concepts from lower frequencies, like patch antennas on PCB, are ineffective because of high losses in the substrate and at the MMIC to PCB transition. Rectangular waveguide horn antennas are feasible above 100 GHz, but they are expensive and complex to produce. Nowadays on-chip antennas are mainly used [1]–[3] in combination with lenses above the chip to increase the gain.

For measurement setups in the millimeter and submillimeter wave range dielectric waveguides are used also [4]. The low attenuation, low fabrication costs, and high flexibility of dielectric waveguides offer new prospects.

Dielectric rod antennas are used as end-fire antennas above 100 GHz by tapering the end of the waveguide [5]. A different type of dielectric antenna is the leaky-wave antenna, which additionally provides a frequency scanning characteristic [6]. Leaky-wave antennas are known as rigid blocks made of Teflon [7] or silicon, which can be used up to the millimeter wave range [8]. By introducing special perturbations on the waveguide the disadvantageous stopband at broadside can be avoided.

Instead of an additional complexity at such small wavelengths and dimensions, a flexible dielectric leaky-wave antenna can be applied. A change of the beam direction can be achieved by the frequency scanning property up to broadside and by an additional mechanical antenna movement in the E-plane and in the H-plane. Furthermore, flexible antennas can be used in systems with fixed transceiver positions where only the antenna can be moved.

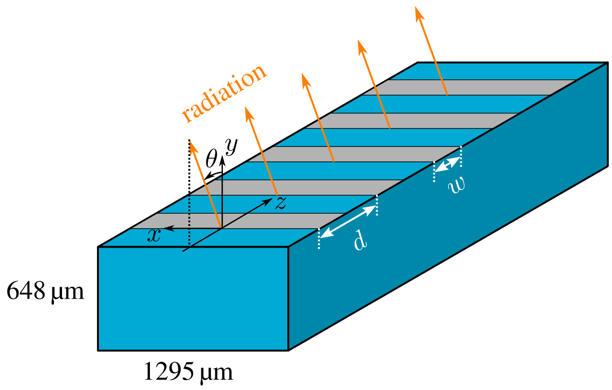

Fig. 1. View on a dielectric leaky-wave antenna with rectangular cross-section and metalized grating.

In this paper, such a flexible leaky-wave antenna is presented. The dielectric waveguide is made of high density polyethylene (HDPE) ($\varepsilon_r = 2.25, \tan\delta = 3.1 \cdot 10^{-4}$) and the antenna is metalized on the waveguide instead of using a second metalized substrate. First, the principle concept of a leaky-wave antenna is explained, afterwards, the detailed design and fabrication process is described and the measurement results are shown.

II. Antenna Fundamentals

On a leaky-wave antenna, as depicted in Fig. 1, a slow wave compared to a free space wave travels along an unperturbed guiding structure in z-direction. This means, that the wavenumber of the guiding structure β_g is larger than the free space wavenumber k_0 [9]. Through the placement of periodic perturbations with distance d on the structure, an infinite number of leaky modes with wavenumber $\beta_n < k_0$ is excited. The radiated beam is fan-shaped and directive in the $y{-}z$ plane. The beam direction θ is given by

$$\theta = \sin^{-1}\left(\frac{\beta_n}{k_0}\right) = \sin^{-1}\left(\frac{\beta_\mathrm{g} + 2n\pi/d}{k_0}\right), \qquad (1)$$

where n is the number of the leaky mode, also called space harmonic, with $n = 0, \pm1, \pm2, \ldots$ According to (1), the beam direction is frequency dependent and can be changed with the periodicity d of the perturbations. With increasing frequency, the beam moves from backward direction to forward direction. At broadside, the leaky-wave antenna has a stopband where

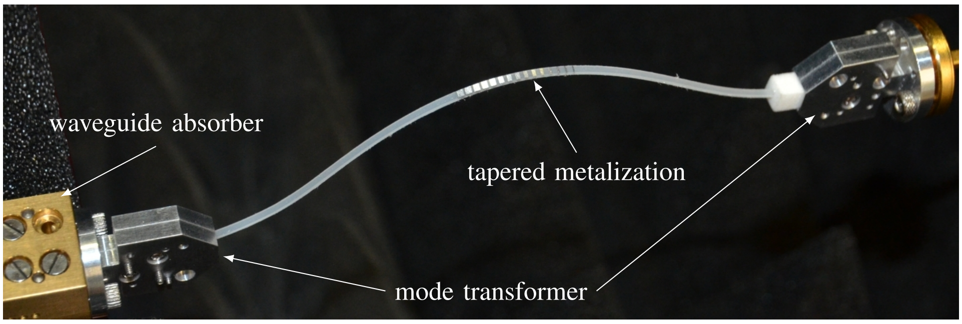

Fig. 2. Bent dielectric leaky-wave antenna in the measurement setup for radiation pattern measurement.

the traveling wave turns into a standing wave and the antenna gain and efficiency decreases.

Previous studies have shown, that a dielectric waveguide can be selected as a guiding structure. In this case $\beta_g = \beta_0$ and for a single beam operation only the first leaky mode $(n = -1)$ is excited. For the condition $\beta_0/k_0 > 3$ it is possible to scan from backward end-fire to forward end-fire with a single beam. Otherwise, the second leaky mode $(n = -2)$ is excited from a certain frequency on and a second beam would appear. As perturbations a grating of dielectric [6] or metallic strips [10] is proposed.

III. Design of the Antenna

In the design procedure, the dielectric waveguide is numerically investigated [11] to determine the wavenumber in the waveguide and consequentially the beam direction of the antenna. Since a low loss and flexible waveguide is needed, further research on the dimensions and the material is required.

The smaller the waveguide dimensions are, the less the wave is attenuated by dielectric losses and the more flexible is the waveguide. The dimension determines also the radiation efficiency at the grating structure and in bends. With decreasing cross-section of the waveguide, the radiated energy at the grating as well as the undesired radiation in bends increases.

Furthermore, the dielectric waveguide feeding has an influence on the dimension. In this case, a mode transformer from rectangular to dielectric waveguide is used as described in [12]. Therefore, the chosen dielectric waveguide dimension (648 µm × 1295 µm) is a compromise between small dielectric losses, high flexibility, high radiation efficiency, and simple fabrication. The measured loss of a fabricated dielectric waveguide made of HDPE is 4.5 dB/m.

For the perturbation grating itself, the radiation from dielectric and metallic strips are investigated with a full wave simulator. The height of dielectric strips made of the same material as the waveguide has to be in the range of the waveguide height to achieve an efficient radiation. This size leads to an irregular beam pattern in the H-plane due to different scattering centers.

In addition to a regular beam pattern, metallic strips have a higher radiation efficiency, which can be controlled by the strip width w. For small widths the radiated energy per strip is very small, and for a high efficiency the antenna aperture has to be large. On the other hand, if the strip width is too large $(w > 0.5\lambda_g)$, most of the radiated energy is produced by the first few strips. Consequently, the aperture size is small and due to the strong decreasing distribution of the radiated energy, the sidelobes are very high.

In [13] a linear tapering of the strip width is suggested to reduce the sidelobe level. The width w_m of strip m is empirically determined in simulations and is

$$w_m = (0.15 + 0.045(m-1))\lambda_g. \quad (2)$$

The realized antenna has $m = 15$ metal strips and a periodicity of $d = 1.4$ mm. The simulated scan range is from −22° to 6° with a single beam in the frequency range from 140 GHz to 190 GHz with a stopband at 177 GHz. Compared to the antenna proposed in [14], this dielectric leaky-wave antenna has a smaller scan range and a stopband, but this can be compensated by bending the flexible antenna in order to get the desired characteristics. Furthermore, the fabrication is considerably simpler.

IV. Measurement Results

For the realization of the leaky-wave antenna, a common dielectric waveguide is metalized. At first, a 3 mm thick HDPE plate is thinned to the dielectric waveguide's width before its shape in the E-plane with a taper at the transition to the rectangular waveguide is milled with a CNC machine. Afterwards, the dielectric waveguide is metalized at the grating positions with a 5 nm thick titanium adhesion layer and a 100 nm thick aluminum layer. During the metalization, the dielectric waveguide is covered with a 100 µm thick mask with notches at the grating positions. Due to fabrication tolerances, the strip width of the fabricated antenna is approximately 50 µm larger. A bent dielectric leaky-wave antenna in the measurement setup is shown in Fig. 2.

A. Matching and Transmission

The measured and simulated reflection coefficient of the leaky-wave antenna are illustrated in Fig. 3. The mentioned stopband is visible from 173 GHz to 182 GHz, where the reflection coefficient is larger than −10 dB. At frequencies below this stopband, the measured $|S_{11}|$ is almost completely below −20 dB. Compared to the simulation, additional ripples are visible in the measurement results. These ripples are reflections

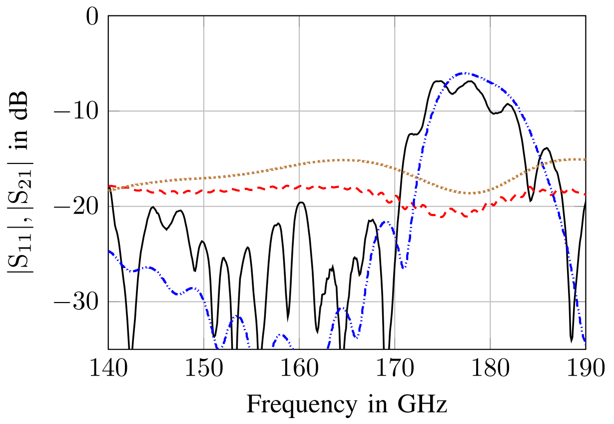

Fig. 3. S-parameter measurement (S_{11} (——), S_{21} (- - - -)) and simulation (S_{11} (-·-·-), S_{21} (·········)) for the leaky-wave antenna.

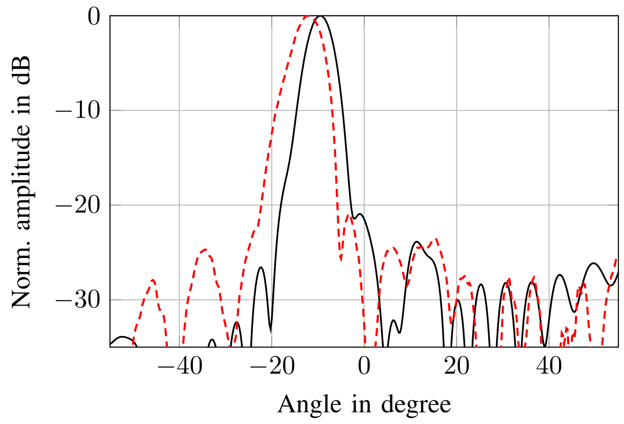

Fig. 4. Radiation pattern in the E-plane at 160 GHz, measurement (- - - -) and simulation (——).

in the mode transformer, which s-parameters were measured in an extra back-to-back measurement. In the simulation model, only the antenna itself without mode transformer and losses is considered because of the large electrical size.

To reach a high efficiency in leaky-wave antennas, as little power as possible should be guided on the waveguide behind the antenna. Therefore, the insertion loss of the antenna in addition to the reflection coefficient is shown in Fig. 3. The measured $|S_{21}|$ is below −18 dB outside the stopband and implies a high efficiency for the leaky-wave antenna of more than 95 %. Inside the stopband, the transmission decreases to less than −20 dB. The simulated values are up to 3 dB higher which can be explained with the previously mentioned problematic simulation and additional losses due to tolerances in the grating structure. The efficiency in the stopband is below 80 %.

B. Radiation Pattern

For the radiation pattern measurements, the open end of the antenna is matched with a mode transformer to rectangular waveguide and a waveguide absorber. The measured and simulated radiation pattern in the E-plane of the antenna at 160 GHz is shown in Fig. 4. The measured 3 dB angular width is 6.3° and the maximum sidelobe level is −20.9 dB. The measured results agree well with the simulated ones except for the main beam direction, which is shifted by 3°. This is caused by the difficult alignment of the flexible antenna and flat cambers in the material.

In the H-plane the measured angular width is 56.8°. This broad angular width is well visible in the measured 3-D radiation pattern for elevation angles $-37° < \theta < 37°$ in Fig. 5.

Between 140 GHz and 180 GHz, the antenna scans from −23.8° to 0.3°. In this frequency range, the angular width and the maximum sidelobe level remain almost constant. For higher frequencies, the second leaky mode is excited and a second beam appears.

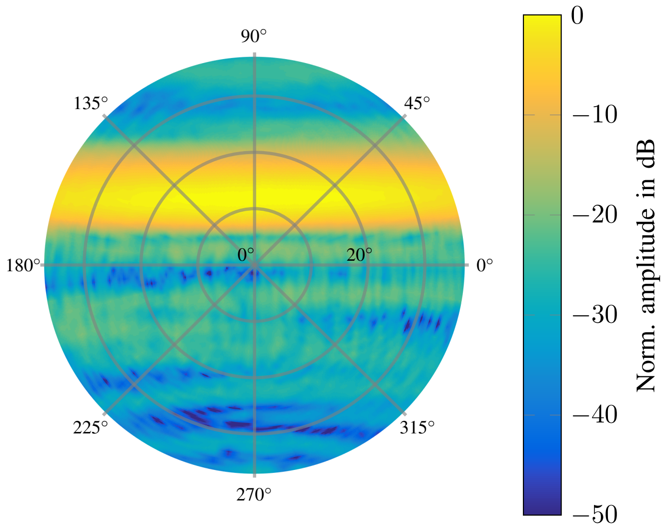

Fig. 5. Measured 3-D radiation pattern at 160 GHz with the H-plane orientation horizontally and the E-plane vertically.

C. Gain

The gain measurement is depicted in Fig. 6. To determine the gain, the losses from the mode transition and the dielectric losses in the feeding waveguide are de-embedded. In the stopband from 175 GHz to 180 GHz, the gain decreases to 14 dBi. Also the radiation efficiency decreases, as the stopband range agrees with the reflection coefficient and the transmission measurement. From 140 GHz to 170 GHz the measured gain is between 16.5 dBi and 17.5 dBi. Above the stopband, gain decreases from 16 dBi on, since the second leaky-mode is excited.

D. Influence of Flexibility

The flexibility of the antenna influences the radiation characteristics. Therefore, the dielectric waveguide and the antenna were investigated on the behavior with bends in the E-plane.

The dielectric waveguide itself has a frequency and dimension dependent radiation in bends. The realized waveguide has

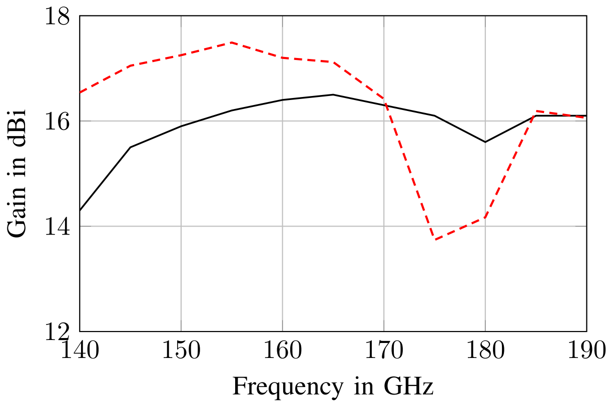

Fig. 6. Measured (- - - -) and simulated (——) gain over frequency.

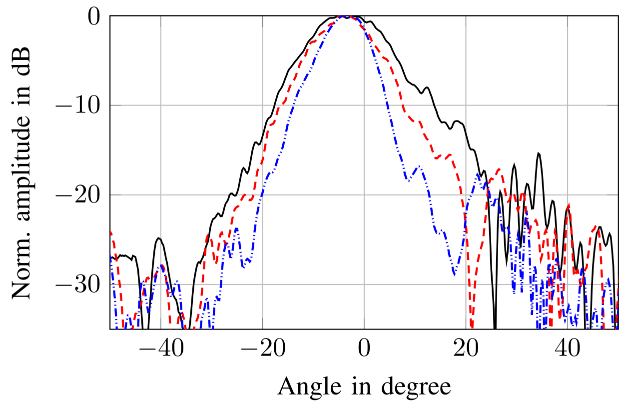

Fig. 7. Measured radiation pattern in the E-plane at 160 GHz for bend radii $r = 4\,\text{cm}$ (——), $r = 6\,\text{cm}$ (- - - -) and $r = 8\,\text{cm}$ (-·-·-).

radiation losses of over 2 dB for a 180° bend for radii smaller than 2 cm at 160 GHz. For lower frequencies, the radiated power increases.

As only the antenna should radiate, curve radii below 4 cm should be avoided. Above these radii, the radiation from the waveguide itself can be neglected, but the bending still effects the radiation characteristics of the antenna. The influence of the bend radii on the radiation pattern is shown in Fig. 7. With increasing radius, the 3 dB angular width decreases and approaches the angular width of the straight antenna. Furthermore, the sidelobe level increases up to −15.4 dB with more ripples on the measured pattern for smaller radii.

This behavior can be explained with the radiation from the strips. Each grating strip in the bend radiates in a slightly different direction and consequently, the beam becomes wider and the sidelobe level increases. The influence on the transmission and the reflection coefficient of the antenna is negligible.

V. Conclusion

In this paper, a flexible dielectric leaky-wave antenna in the frequency range from 140 GHz to 175 GHz is presented. The antenna's flexibility enables applications, in which a fixed position is not desired and despite the stopband of the antenna a frequency scanning property over a large angular width was achieved.

A low loss dielectric waveguide made of HDPE was metalized with an aluminum grating structure using a mask on the waveguide. With a tapered strip width, a sidelobe level of the antenna below −20.9 dB was realized. The measured gain in the radiation band is 17.5 dBi with a high efficiency of 95 %. By bending the antenna up to a radius of 8 cm, the 3 dB angular width and the sidelobe level is almost constant compared to the straight antenna.

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