Proceedings of ISAP2016, Okinawa, Japan

A Phased Array Antenna with Horn Elements for 300 GHz Communications

Sebastian Rey[1], Thomas Merkle[2], Axel Tessmann[2] and Thomas Kürner[1]
[1]Institut für Nachrichtentechnik, Technische Universität Braunschweig, Schleinitzstraße 22, 38106 Braunschweig, Germany
[2]Fraunhofer Institut für Angewandte Festkörperphysik IAF, Tullastraße 72, 79108 Freiburg, Germany

Abstract – **For THz communication systems, highly directive antennas are required to overcome the high free space path losses. For this reason, electrical beam steering is one of the key challenges for future applications. In this paper, a design for a first electrically steerable antenna operating at around 300 GHz is presented. The design is based on a phased array which consists of four horn antenna elements. A simulated total gain of 20.7 dBi was achieved.**

Index Terms — **submillimeter-wave antenna, 300 GHz, phased array, THz communications.**

1. Introduction

THz communications are one of the possibilities to meet the demand for ever increasing data rates. In recent years, several publications have presented RF front-ends and transmission experiments in the frequency range around 300 GHz with target data rates of 100 Gbit/s [1]. At 300 GHz, the free space path loss already causes an attenuation of 101.9 dB for a distance of 10 m. Directive antennas need to be applied to enable communications at all. In our previous work in [1], e.g., two antennas with a gain of 24.2 dBi were used at the transmitter and the receiver.

Within the IEEE 802 project in the Working Group 15, a first standard for communications at 300 GHz is currently under development [2]. The targeted applications, e.g. wireless fronthaul/backhaul for cellular mobile radio networks, have in common that they apply point-to-point links in rather static scenarios because of the need for directive antennas. If beam steering capabilities are necessary, a mechanical implementation may be sufficient in these scenarios. For a future deployment of THz links in dynamic scenarios, electronic beam steering is a key factor.

In section 2, the design of a phased array for a demonstration of electronic beam steering at 300 GHz is introduced. Due to the mutual influences between the elements and the array, the description is straight forward. An alternative design is briefly discussed in section 3. Finally, section 4 concludes the paper with an outlook on future work.

2. Design of the antenna

In order to successfully demonstrate the beam steering at 300 GHz, several challenges have to be mastered: The transmitter, and the receiver and the antenna have to be realized. Furthermore, the phase shifting has to be implemented. Phase shifters operating at 300 GHz introduce additional losses and increase the integration complexity drastically. For this reason, a demonstration with either phase shifting the local oscillator or the IQ-data is targeted here. Nevertheless, four transmitters/receivers, like the ones presented in [1], are required and this approach has led to two design decisions and some constraints:

- The four elements are arranged in one dimension, enabling beam steering in the horizontal direction.
- For flexibility and practical reasons, the antenna module is fed by four WR-3 wave guides.
- The operational frequency range is 275 to 325 GHz.
- A total gain of at least 20 dBi is required to enable communications, c.f. [1].

(1) Phased array introduction and simulation setup

The theory of a phased array is well known and understood (e.g. [3]). With four identical elements in one line, the gain of the array can be 6 dB higher than the gain of a single element. Thus, for each element a gain of at least 14 dBi is necessary (see next subsection). Grating lobes can completely be avoided if the spacing between the elements is less than half of a wave length. Nevertheless, the wave length is only approx. 0.922 mm for 325 GHz.

The antenna elements and the array were simulated with a time-domain solver using CST Microwave studio. Only results from the final array design are presented here.

(2) Design of the antenna elements

The 7.6 dBi antenna gain of an open ended WR-3 wave guide is not sufficient. In Fig. 1, the dimensions of the wave guide and an attached pyramidal horn are introduced. The dimensions of the aperture and the flare were optimized to achieve at least a gain of 14 dBi and an S11 of -20 dB or better in simulations. A higher gain could be obtained with a larger aperture but in order to mitigate grating lobes the small side C should remain small. The final dimensions are summarized in table 1.

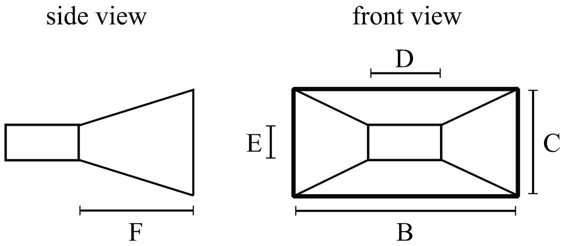

Fig. 1. Wave guide and horn dimensions.

TABLE I
Antenna Parameters derived by simulations

Letter	Dimension	Value
B	Horn aperture width	3.0 mm
C	Horn aperture height	1.0 mm
D	WR3 wave guide width	0.8640 mm
E	WR3 wave guide height	0.4320 mm
F	Horn flare length	3.577 mm
r_x	Horizontal spacing (array)	1.25 mm (= C + 0.25 mm)

(3) Design of the antenna array module

The complete antenna module is depicted in Fig. 2. The horn antennas were rotated by 90° to achieve a smaller element spacing r_x and to reduce the impact of grating lobes. The path length of the four WR-3 wave guides to the horn antennas at the front was matched. In contrast to CW radar, the path lengths have to be identical and it is not sufficient to only match them to multiples of the wave length. With a bandwidth of 50 GHz, the length of one symbol is approx. 5 mm. Thus, a difference of one wave length would cause severe inter-symbol interference.

Finally, in Fig. 3 (left) the vertical and the horizontal antenna patterns of the inner elements are shown. The depicted gain is 14.8 dBi with a horizontal (along C) half-power beam-width (HPBW) of 50° and a vertical one (along B) of 26.6°. The outer elements have a 2.2° wider horizontal HPBW and the gain is 0.2 dBi less. Therefore, no “dummy” horns without feed were realized on the outside. S11 has a mean value of -25.7 dB with a maximum at -22.7 dB.

The maximum difference of the normalized vert. pattern of the array for all values above -25 dB, in comparison to the one of the elements, is less than 0.1 dB. Therefore, only the hor. pattern is depicted in Fig. 3 (right) for a target angle α of 0° and -20°, respectively. The corresponding phase increment δ is calculated according to (1) with the wave length λ.

$$\delta = -2\pi/\lambda \cdot r_x \cdot \sin(\alpha) \tag{1}$$

In total, a gain of 20.7 dBi has been realized with a hor. HPBW of 10.3° and a vert. one of 23.6°. As expected, the simulated gain increased from 19.9 dBi at 275 GHz to 20.7 dBi at 300 GHz and to 21.4 dBi at 325 GHz with a hor. HPBW of 11.3°, 10.3°, 9.5° and a vert. one of 24.9°, 23.6° and 22.3°, respectively. For a target angle of -20°, the gain of the main lobe drops by 1.7 dB whereas the one of the grating lobe increases from 9.5 dBi to 17.4 dBi. The main beam and the grating lobe are separated by an angle of 47°. Therefore, beam steering will be possible in the range of -20° to +20°.

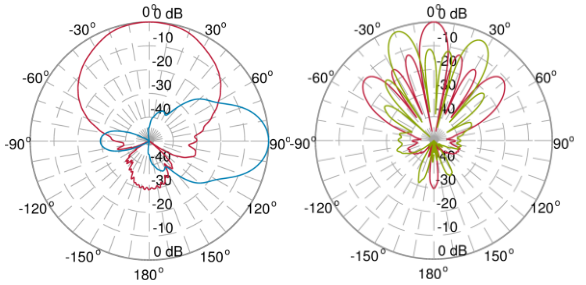

Fig. 3. Normalized hor. (red) and vert. (blue) antenna pattern of a single element (left). Hor. pattern of the array (right) for a target angle of 0° (red) and -20° (green).

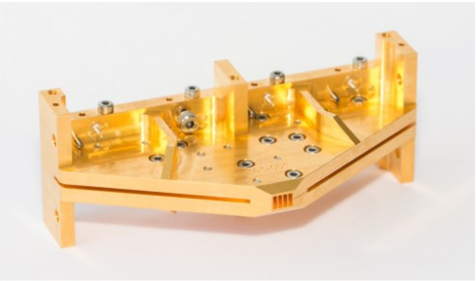

Fig. 2. Antenna module; the WR-3 wave guide flanges are located on the back side.

3. Discussion of an alternative design

With a customized wave guide ($E = 0.23$ mm) and an H-plane sectoral horn ($C = E$), an antenna spacing of half of the wave length would be possible to avoid grating lobes completely. Usually, wave guide dimensions are chosen as $D = 2E$ and the cut-off frequency is $f_c = c/(2D)$, c.f. [4]. In this case, the cutoff is at 325 GHz. Therefore, D has to be increased to at least 0.55 mm for a cutoff at 275 GHz. In order to maintain the element gain of ~14 dBi, the horn width B increases by a factor of approx. 4.3 to 13 mm since the size of the aperture is proportional to the gain. The vertical HPBW reduces to ~6°. This alternative design has no safety margin. It is still not suitable for manufacturing since a minimum separation of 0.25 mm between the horn elements is required for typical milling processes. This way, it is not possible to completely avoid grating lobes for practical reasons.

Taking into account that the antenna was bound to several constraints, it is promising and measurements of the antenna patterns are currently in progress.

4. Conclusion

The design of a phased array antenna with horn elements was presented for a first demonstration of electronic beam steering at 300 GHz. The antenna has recently been manufactured at the Fraunhofer IAF. The next steps will be the measurement of the antenna patterns (elements and array) and the demonstration of the beam steering approach.

Acknowledgment

The authors thank Martin Zink for drawing the final CAD based on the functional design of the antenna. This work has been performed within the TERAPAN project which is funded by the German Federal Ministry of Research and Education (BMBF) under grant number 03V0411.

References

[1] I. Kallfass et al, “Towards MMIC-Based 300GHz Indoor Wireless Communication Systems,” *IEICE Trans. Electron*, vol. E98.C, no. 12, pp. 1081–1090, 2015.
[2] IEEE 802.15.3d Website: http://www.ieee802.org/15/pub/index_TG3d.html
[3] C. A. Balanis, Antenna theory, 3rd ed. Hoboken: Wiley, 2005.
[4] R. F. Harrington, “Time-harmonic electromagnetic fields,” New York: IEEE Press, 2001.