A Large Planar 39-GHz Antenna Array of Waveguide-Fed Horns

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***Abstract*—A planar antenna in which box horns are used as radiating elements is described. The feed network is built by connecting rectangular waveguides with T-junctions. The matching of the T-junctions is improved by using rounded splitters and matching pins in the junctions. The radiating element has been designed to cancel out the grating lobe. The grating lobe is due to an element spacing larger than one wavelength. The highest sidelobes are at least 31 dB below the main beam in the H-plane and 16 dB in the E-plane. A gain of 37 dBi has been achieved at 39.2 GHz. These results demonstrate the feasibility of this antenna for applications requiring high gain at millimeter wavelengths.**

***Index Terms*— Antenna arrays, horn antennas, millimeter wave, planar antenna.**

I. Introduction

PARABOLIC reflector antennas are currently used as high-directivity antennas in the millimeter-wave region. A drawback of reflector antennas is the thickness of the antenna. It would be easier to hide the antenna if it were a lot thinner than the parabolic reflector antennas, which are about 20 cm thick at 38 GHz (gain 38 dBi).

There are several concepts of building planar high-directive antennas [1]–[5]. Two major aspects limit the use of these antennas: one is the required bandwidth and the other the efficiency of the antenna (or the feed network). The losses in the feed network can be reduced by selecting a low-loss transmission line, but problems arise since the width of these transmission lines exceed half a wavelength and it is therefore not geometrically possible to feed each radiating element in parallel with a network in one plane without enlarging the element spacing beyond a wavelength. Parallel feed is needed to get a wide enough bandwidth and a one-plane concept is needed to keep the construction of the antenna simple.

According to the principle of pattern multiplication, the radiation pattern of an array of identical elements can be described as the product of the pattern of the element and the array factor [6]. The effect of mutual coupling is not included in order to simplify the design procedure. An element spacing larger than one wavelength causes grating lobes in the radiation pattern [6]. One way to remove the grating lobes is to find a radiating element, with zeros in the radiation pattern at the same angle as the grating lobes. In this way, the sidelobes in the radiation pattern of the antenna are eliminated.

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In this study, effort has been made to design a planar high-gain antenna that is considerably thinner than 20 cm. Parabolic reflector antennas have a high return loss and in order to replace them, the return loss must be high enough for this kind of antenna. The target reflection coefficient is set to -15 dB to ensure proper function of components connected to the antenna.

II. Radiating Element

Due to the size of the feeding waveguide, the element spacing is larger than one wavelength. The grating lobes are to be eliminated by the zeros in the radiation pattern of the element. The radiating element should be simple, but still have the radiation pattern desired to eliminate the grating lobes.

The easiest way to increase the directivity of an open waveguide end is to enlarge the opening. This is done by attaching a horn antenna to the waveguide opening. By placing the elements in rows and columns next to each other, a 16×16 element array antenna can be constructed.

A. E-Plane Horn

A large aperture with a constant amplitude and phase distribution has no large sidelobes further away from boresight [6]. Such an aperture can be built of E-plane horns in the E-plane since the amplitude distribution in the aperture of the horn is equally distributed in that plane. This is due to the TE_{10}-mode in the horn.

The enlarging of the horn increases the aperture phase error but the effect of this error is negligible if it stays smaller than 45° [6]. A smaller opening angle requires a longer horn to get the same aperture size. To keep the thickness of the whole antenna small, it is essential to keep the horn short, which leads to a compromise between phase error and size. The horn has been designed to have an aperture phase error of 45°. Since the aperture distribution in the aperture differs from a constant one due to the phase error, sidelobes will result in the E-plane due to the element spacing.

B. Box Horn

The box horn is described in [7], and the version used here is only a slightly modified one. The element spacing in the H-plane is about 1.8λ, which means that a grating lobe is located approximately in the direction 35° from the main beam. The element must therefore have a zero in its radiation pattern at the same angle 35°.

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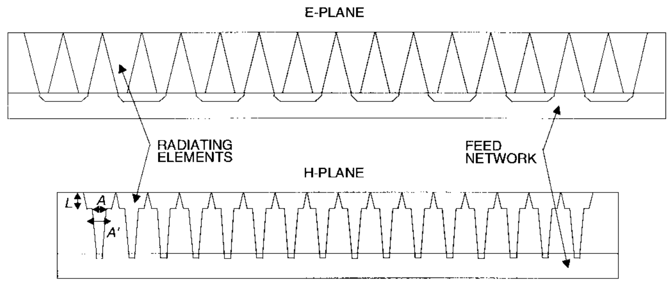

Fig. 1. E- and H-plane cuts.

At the sharp transition in height from A' to A, a higher order mode TE_{30} is excited in addition to the fundamental mode TE_{10} (see Fig. 1). The E-field in the aperture of the box horn can be approximated as the sum of the fields of the modes [7]. The ratio of the amplitudes of the two wavemodes is dependent on the ratio A/A' [7]. In addition to the relative amplitudes of the modes, their phase difference has to be considered. In order to get the wanted amplitude distribution, the wavemodes TE_{10} and TE_{30} have to be in opposite phase at the horn aperture. Different modes have different propagation coefficients and the required phase difference of 180° determines the length L of the box [7]. The total length of the radiating element is determined by the phase error allowed in the E-plane. By choosing the relative amplitude of the TE_{30}-mode excited in the box horn, it is possible to adjust the zero in the radiation pattern of the box horn. The dimensions of the box horn have been selected so that the zero in the radiation pattern occurs at the same angle 35° as the grating lobe.

III. Feed Network

The purpose of the feed network is to divide the input signal in such a way that every element is fed by a waveguide of equal electrical length (parallel feed). In this way the feed network is made as insensitive to frequency changes as possible and does not limit the bandwidth. One key factor is a low-profile feed network that is simple to manufacture and consists of as few parts as possible.

The distance between the feeding point and an element at the aperture edge is evidently large since a high gain requires a large aperture. It follows that every element must be fed by a long transmission line, which underlines the importance of a low-loss transmission line. Low-loss transmission lines at millimeter-wavelengths are the rectangular and circular waveguides.

A. Waveguide

The antenna is to be fed from a standard WR-28 waveguide (rectangular waveguide with dimensions $a = 7.11$ and $b = 3.56$ mm) and it is, therefore, natural to choose a rectangular waveguide as the waveguide used in the feed network. The width of the waveguide basically sets the distance between the radiating elements in both directions. It is, therefore, important to choose the width of the waveguide as small as possible. In the frequency range 37.0–39.5 GHz, the width may be chosen as small as 5 mm without significant loss increase. The height of the waveguide is not that important and is set to 3.56 mm.

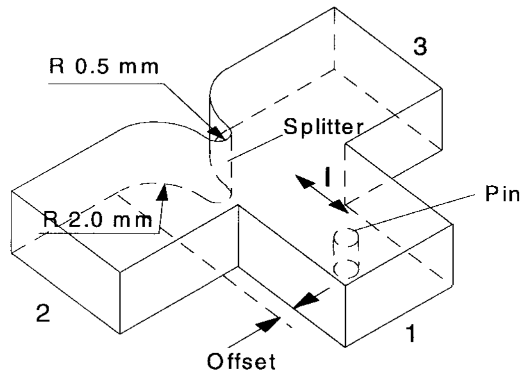

Fig. 2. Improved waveguide T-junction.

The transition from the standard waveguide to the 5-mm-wide waveguide is made in a fashion that is very similar to an H-plane horn. This transition functions very well and does not require much space.

B. Power Divider

The aim is to realize the feed network in a single metal block. Waveguide feed networks have been designed for satellite applications [8], [9], but in this case a very low-profile feed network is needed to decrease the antenna thickness. A T-junction can easily be realized in one metal piece by milling, and the radiating elements make the lid of the waveguide. Unfortunately, the reflection coefficient of a normal T-junction of rectangular waveguides is very high. In order to reach the matching goal of -15 dB for the antenna, it is necessary to improve the matching of a single T-junction.

By using a splitter in the T-junction (see Fig. 2), it is possible to reach a simulated reflection coefficient of about -15 dB for one T-junction. This is unfortunately not low enough for this kind of application, since many junctions are to be connected resulting in even poorer matching for the whole feed network. Another method of matching a circuit is to excite a second wave, which cancels out the wave reflected from the T-junction. This can be done by placing an obstacle in the waveguide. The shape of the obstacle may be chosen freely, but from a manufacturing point of view a cylindrical shape is suitable and simple. Cylindrical objects in a rectangular waveguide are analyzed in [10]. The matching of the T-junctions is accomplished with a cylindrical pin in the input port of the junction. By choosing the dimensions and the position of the pin carefully, one can according to simulated results achieve reflection coefficients of less than -19 dB for a single T-junction over the frequency range 37.0–39.5 GHz as shown in Fig. 3.

The reason for using two different methods of matching the junction is that by using a splitter alone a reflection coefficient low enough cannot be reached and the splitter is needed to get an unequal power division between the output ports. The unequal power division is needed to taper the amplitude distribution over the antenna aperture.

The realization of unequal power division has been described in [11] and the same method has been used here. The T-junction was optimized using the software High Frequency

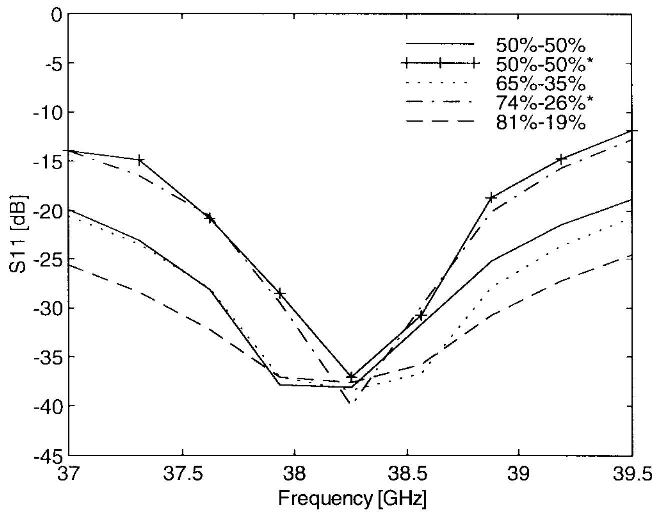

Fig. 3. Simulated reflection coefficients of the T-junctions. (* indicates reflection coefficient of the last two stages together.)

Structure Simulator® from Hewlett-Packard and the simulated S_{11}-parameters of the different power dividers are shown in Fig. 3. The amplitude ratio of the output ports for each power divider is indicated in Fig. 3. In the last power division stage there is not enough space for the matching pins. Therefore, the second last stage also takes care of the matching of the last stage. The combination of the last two power divisions makes a 5-port, which is indicated in Fig. 3 with a star (*).

A tapered distribution is applied in the H-plane to get lower sidelobes in the radiation pattern. The tapered amplitude distribution is obtained with asymmetrical T-junctions in the feed network.

C. Bend

The waveguide has to be bend in order to feed the radiating elements from behind. It is also convenient to feed the whole antenna from the rear side, and since the feed network is to be build in one plane this requires design of a 90° E-plane bend.

Usually, when one needs to bend a rectangular waveguide, it is done by simply bending the waveguide using a fairly large radius [12]. This method requires much space which in this case is an unwanted property. There is another space saving possibility to construct a wideband 90° angle [13]. It has been found to work very well in the frequency range in question, with a simulated reflection coefficient of less than −30 dB.

D. Element Spacing

The feed network has been constructed by connecting the designed T-junctions with rectangular waveguides. Due to geometrical restrictions, it is not possible to achieve element spacings smaller than one wavelength with this type of concept in neither the E- nor the H-plane. The directivity and therefore the gain reaches local maxima approximately every 0.9λ [14]. The number of grating lobes is proportional to the element spacing in wavelengths [6]. It is therefore possible to increase the element spacing in the H-plane to 1.8λ from the smallest possible of about 1.3λ in order to maximize the gain. This can be done without additional grating lobes in the radiation pattern.

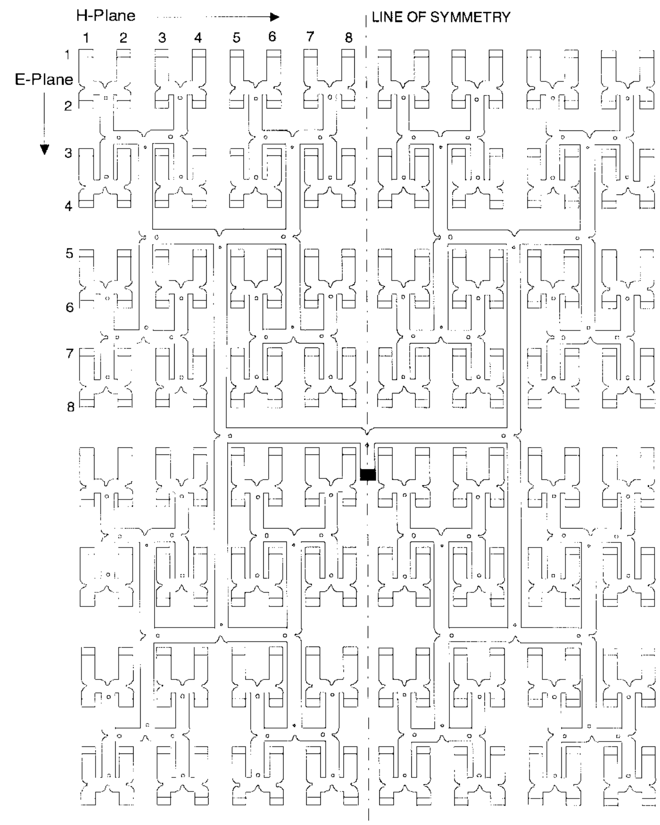

Fig. 4. The feed network.

The spacing in the E-plane is determined by the required phase corrector of half a wavelength and the width of the waveguide. In addition the T-junction and the phase corrector, the E-plane bends need some space. Therefore, the element spacing in the E-plane is set to approximately 2.4λ. A schematic picture of the feed network is presented in Fig. 4.

IV. Experimental Results

A. Model Antenna

A 256-element antenna array has been manufactured according to the design procedure presented in the previous chapters. Aluminum has been chosen as the basic material from which the parts have been milled. The prototype antenna consists of 18 parts which are kept tightly together with screws. The feed network has been milled from a single plate, but the radiating elements have been built of 17 pieces to avoid rounded edges in the element. The overall dimensions of the antenna array are 32.1 cm × 24.8 cm × 4.0 cm ($L \times W \times H$). The E- and H-plane cuts of the antenna are shown in Fig. 1.

B. Radiation Patterns

The measured radiation patterns for the E- and H-plane at 39.2 GHz are shown in Figs. 5 and 6 together with the calculated patterns. The measurements were performed outdoors at

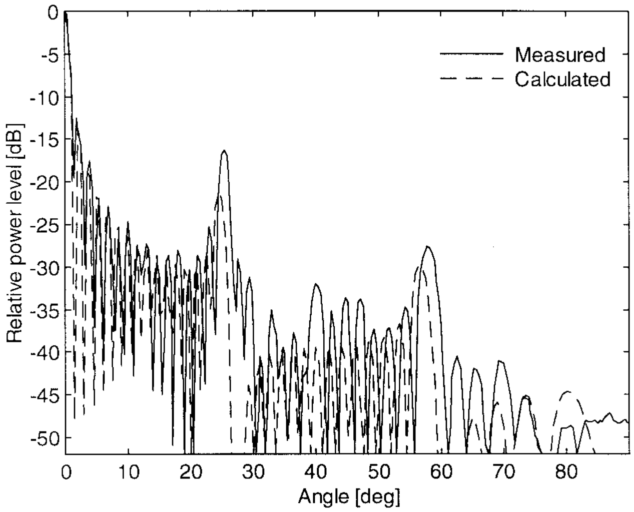

Fig. 5. E-plane radiation pattern.

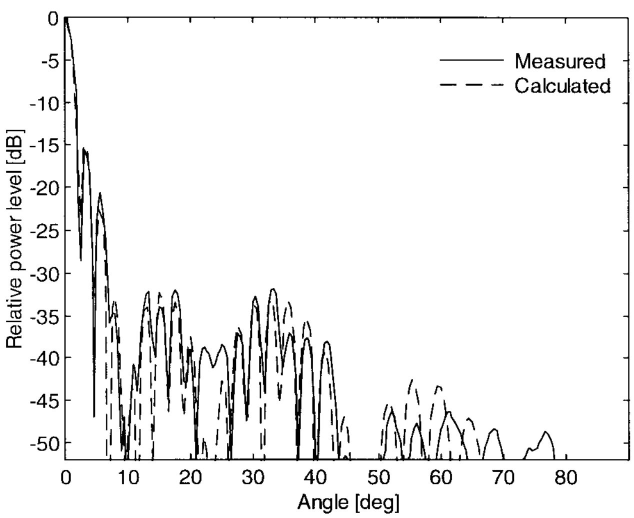

Fig. 6. H-plane radiation pattern.

a distance of 25 m since a sufficiently large anechoic chamber was not available.

In the E-plane radiation pattern, two sidelobes can be clearly detected. These sidelobes are not completely cancelled out due to the phase error in the E-plane aperture distribution of the radiating element. These sidelobes are 16 and 27 dB below the main beam. In the H-plane radiation pattern, the highest sidelobe is 31 dB below the main beam at an angle of about 34° from the main lobe.

C. Matching

The matching of the antenna was measured with a vector network analyzer and the results are presented in Fig. 7. The return loss of the antenna was measured to be larger than 14 dB over the frequency range 36.6–39.3 GHz.

D. Gain and Efficiency

The gain of the antenna was measured by the gain comparison method. A 20-dBi pyramidal horn antenna was used as a reference. The measured gain of the 256-element antenna

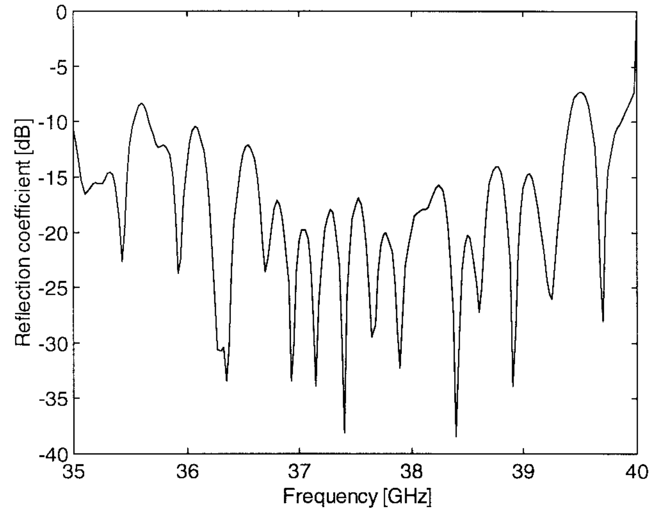

Fig. 7. Measured reflection coefficient as a function of frequency.

at 39.2 GHz was 37 dBi, which corresponds to an aperture efficiency of 37%. At a close frequency of 35 GHz a gain of 32.0 dBi has been achieved with a 1024-element microstrip array (aperture efficiency approximately 20%) [3]. A single radiating element has an aperture efficiency of about 50%, which indicates feed network losses of about 1.3 dB in the prototype antenna.

V. Conclusions

The goal was to design a planar high-gain antenna for millimeter wavelengths. The designed sidelobe level was -33 dB in the H-plane and the estimated gain was 38 dBi. A sidelobe level of -31 dB in the H-plane and a gain of 37 dBi at 39.2 GHz was measured for a prototype antenna. The return loss was designed to be larger than 15 dB over a 6.5% bandwidth and the measured return loss of the antenna was higher than 14 dB over the range 36.6–39.3 GHz, which corresponds to a 7.1% bandwidth. The results have been achieved with an very thin antenna with a simple construction. This type of antenna has proven its usefulness as a high-gain planar antenna suitable for microwave and millimeter-wave frequencies.

Acknowledgment

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