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Millimeter-Wave Microstrip Antenna Arrays with Waveguide Feed Network

Millimeterwellen-Mikrostreifenleitungsantennen mit Hohlleiterspeisenetzwerk

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Abstract
A major restriction of high gain microstrip antenna arrays is found in their high losses, mainly due to the feeding network. In this contribution, design and results of three different microstrip array antennas with a low-loss waveguide feed network are presented. Interconnects between planar structures and waveguide network are done by slot coupling. The waveguide network for these test antennas was machined from aluminum, but in a later phase, it might be fabricated using plastic injection molding and electroplating to realize low-loss, low-cost planar mm-wave antennas.

Übersicht
Hohe Verluste, insbesondere durch planare Speisenetzwerke, bilden eine wesentliche Einschränkung für den Entwurf von planaren Antennengruppen mit hohem Gewinn. In diesem Beitrag werden Entwurf und Ergebnisse für drei verschiedene planare Antennen mit Hohlleiterspeisenetzwerk vorgestellt. Die Verbindung zwischen Speisehohlleiter und planaren Antennenelementen erfolgt mittels Schlitzkopplung. Für die hier vorgestellten Testantennen wurde das Speisenetzwerk aus Aluminium gefräst; später einmal könnte Kunststoffspritzgußtechnik und Metallisierung der Hohlleiterteile zu einer kostengünstigen Herstellung solcher Antennen beitragen.

Für die Dokumentation
Planare Antennen / Speisenetzwerke / Antennenverluste / Millimeterwellentechnik

1. Introduction

For communication and sensor applications, antennas with low profile, low loss and low production cost are required. While planar antennas are optimal with respect to antenna depth and cost, they suffer from high losses, especially for narrow beamwidth [1]. Slotted arrays [2] or arrays of horn antennas with a waveguide feed network [3] are lower in loss, but partly complicated in their design or restricted with respect to bandwidth, and they do not readily lend themselves to low cost fabrication. Recently, some work has been reported on the fabrication of waveguide networks and antennas using plastic injection molding and electroplating [4].

A detailed analysis of the loss mechanisms of microstrip array shows that losses mainly are produced by the feed network. If bandwidth – which is another limiting factor for many planar antennas – has to be maintained, a parallel type or corporate feed network has to be chosen. The length of such a tree type network, and consequently its losses, increases strongly with the overall size of the antenna array (**Fig. 1**). If an element spacing of half a free space wavelength and a microstrip transmission line loss of 0.15 dB per guide wavelengths are assumed, maximum gain of a microstrip array is in the range of 30 ... 35 dB. With increasing antenna size, beamwidth still decreases, but gain decreases, too. Losses can be reduced to some extent using a combination of parallel and series type feed network, but at the cost of reduced bandwidth only, especially for large arrays. Consequently, some attempts have already been made to replace the planar feed network by a metal waveguide network [5–8].

This paper describes the design and results for three different approaches of waveguide fed microstrip antenna arrays at 10 GHz, 24 GHz, and 38 GHz. In all three examples, a corporate feed network is chosen to maintain the bandwidth of the microstrip antenna elements. Consequently, due to space requirements both for the feed network topology as well as for the lateral waveguide dimensions, two by two element microstrip subarrays with a planar feed structure are selected. These then are coupled electromagnetically to the underlying waveguide structure through a slot in the ground plane of the planar substrate [9]. The basic idea of this concept is depicted in **Fig. 2a**. An open waveguide feed network is fabricated in a carrier structure, and it is closed by

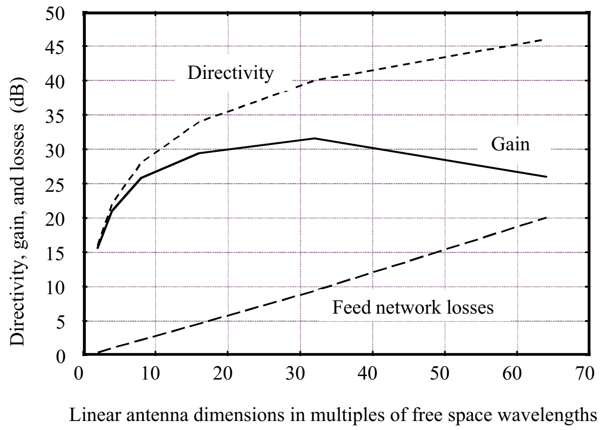

Fig. 1: Feed network losses, directivity and gain of a microstrip array with corporate microstrip feed network

the planar antenna substrate. The carrier structure finally may be fabricated using plastic injection molding and electroplating as it has been demonstrated before for a 58 GHz waveguide antenna [4] or 28 GHz mm-wave filters and diplexers [10]. The planar structure then simply is glued or soldered to the carrier structures, and the antenna subarrays are automatically coupled to the feed network without the need for any other fabrication steps. As the necessary technologies for precise glueing were not available for these investigations, a modified set-up is used to allow an easy fabrication of the waveguide structure from aluminum and a control of the contact between carrier structure and planar substrate around the coupling slots (**Fig. 2b**). The waveguide structure is milled into the carrier block from the backside including short channels to the top. Attaching the planar substrate to the carrier block, a good contact is required only around the channels which can be inspected from below. Finally, a cover plate is screwed to the bottom of the block .

On this basis, three different approaches were investigated. The 10 GHz antenna has 8 × 8 microstrip elements and a feed network using reduced height waveguide, the 24 GHz array was designed with 8 × 8 elements, too, and a ridge waveguide network, and the 38 GHz antenna with 2 × 16 elements and an E-plane feeding network. In all three cases, the planar antenna elements were designed using a method of moments [11]. Slot coupling and the interaction of slot coupling and antenna elements were com-

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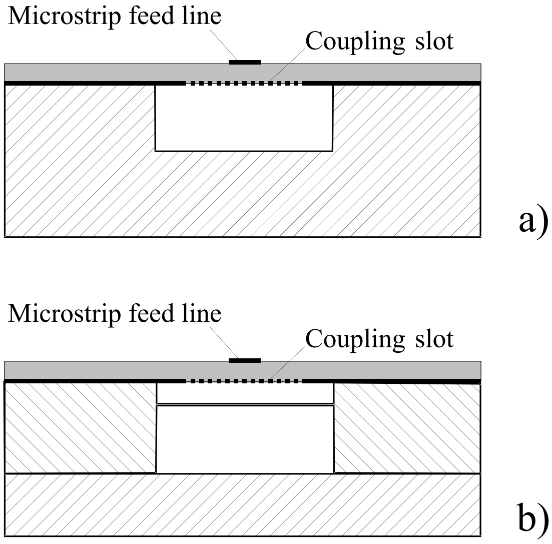

Fig. 2: Cross section of slot coupling between waveguide feed network and Microstrip line.
(a: possible final version, b: arrangement used for the first experimental antennas)

puted with an in house FDTD code [12], and the waveguide network with a mode matching method or FDTD, too.

2. 10-GHz Antenna

A first test of this type of antenna was made at a frequency of 10 GHz with 4 × 4 microstrip subarrays (2 × 2 elements each) and reduced height waveguide for the feed network. The layout of the subarray and the basic configuration of the feed arrangement are shown in **Fig. 3**. The four microstrip patch elements are matched to the connecting lines using an inset feed arrangement and are connected to the central feeding line with a small planar network. As the slot coupling inherently provides a 180° phase shift, a very simple and symmetrical structure results. In a first step, a single patch was designed, followed by an analysis including mutual coupling between the patches and the effect of slot coupling to waveguide. Special care was taken to optimize this coupling – together with impedance matching of the complete subarray – for minimum radiation of the slot.

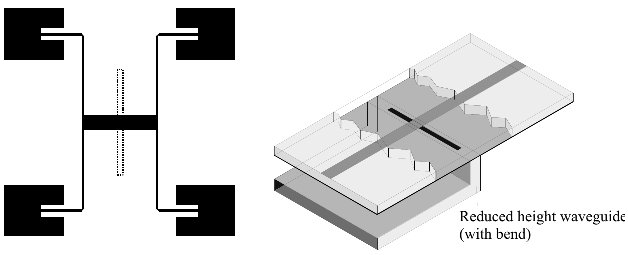

Fig. 3: Layout (left) and coupling section of 2 × 2 microstrip subarray

The subarrays are fed with equal amplitude and phase through the coupling slots using the waveguide network as shown in the photograph of **Fig. 4**. As can be seen from its topology, the distance between the subarrays must be at least twice the waveguide width plus some space for waveguide walls and screws to fix the bottom cover. Selecting an equal spacing of the microstrip patches, distances of well above half a wavelength result, in this case 0.8 wavelengths or 24 mm. The waveguide T-junctions contain metal ridges for matching purposes. While this was sufficient for the first three junctions, the close combination of the T-junctions

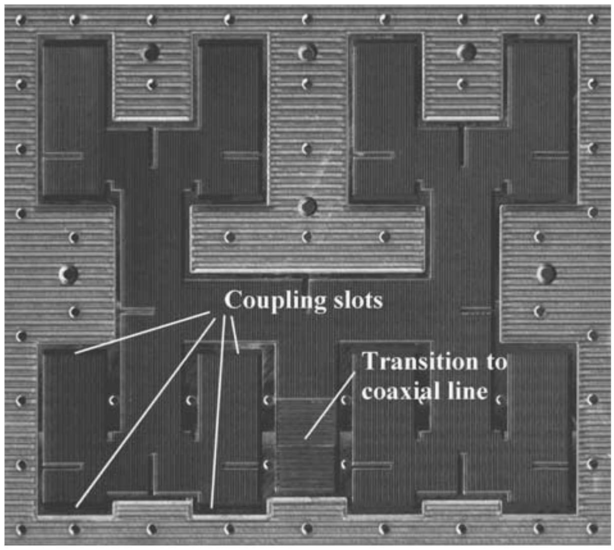

Fig. 4: Photograph of the waveguide feed network of the 10 GHz antenna

towards the coupling slots required a combined analysis and optimization of three junctions each including higher order mode coupling. As a result, additional matching elements had to be introduced to maintain a low return loss and a good amplitude balance. For proper phase excitation, half wavelength section were introduced in the paths for the upper subarrays. Furthermore, the network includes an integrated probe transition to a coaxial connector.

The overall planar array was fabricated on a substrate with a thickness of 1.52 mm and a dielectric constant of 2.5 (**Fig. 5**). It was glued to the waveguide block using conductive epoxy; the contact around the coupling slots was inspected from the bottom before the cover plate was mounted.

Fig. 6 shows the radiation diagrams of the antenna in the two planes. Beamwidths are around 9° in both planes. According to the equal amplitude excitation, a side lobe level of 13 dB was expected. It is slightly higher in the H-plane, and lower in E-plane close to the main beam, but additional lobes rise up to –13.5 dB around 40°. These lobes are due to residual slot radiation; a more detailed analysis of this effect and a remedy will be presented at the example of the 38 GHz antenna described in section IV. Furthermore, the substrate was slightly too thick resulting in some surface wave excitation [13, 14] which affects the radiation dia-

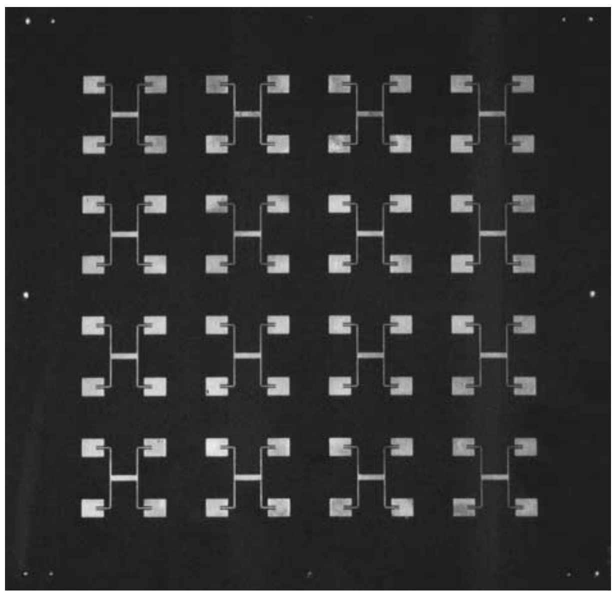

Fig. 5: Photograph of the planar antenna array of the 10 GHz antenna

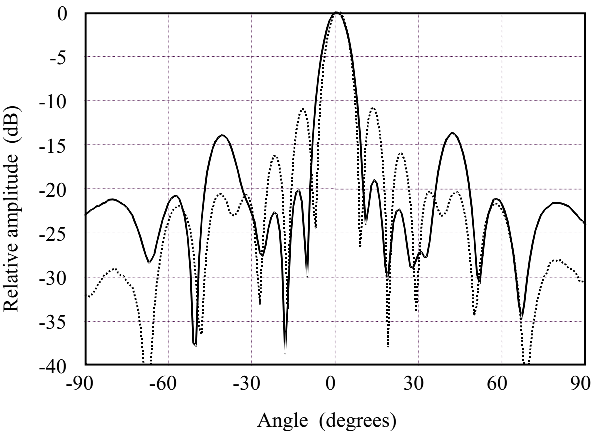

Fig. 6: E-plane (——) and H-plane (⋯⋯) radiation diagrams of the 10 GHz antenna

grams, too. Antenna bandwidth at –10 dB return loss is 450 MHz, although the return loss is deteriorated by some problems with the contact between the waveguide network and the cover plate. Gain was measured to 25 dB at 10 GHz and is better than 22 dB over a 900 MHz bandwidth.

3. 24-GHz Antenna

In a next step, a ridge waveguide feed network was selected for the antenna to allow a closer spacing of the radiating elements. Frequency was increased to 24 GHz for possible applications in the ISM band. Substrate thickness was chosen to 0.5 mm; related to wavelength, this is smaller than for the 10-GHz antenna, resulting in reduced surface wave excitation.

The design of the planar radiating elements and the slot coupling was done in the same way as before; the layout is quite similar to that of the 10-GHz antenna (Fig. 5). Some complication was introduced by the choice of ridge waveguide; thus the design had to be done using FDTD computations for the T-junctions and the matching elements (**Fig. 7**). For the transition to a standard waveguide input, a stepped taper from ridge waveguide to rectangular waveguide was chosen, including a matched E-plane bend. Once again, equal amplitude and phase excitation for all radiating elements was adjusted.

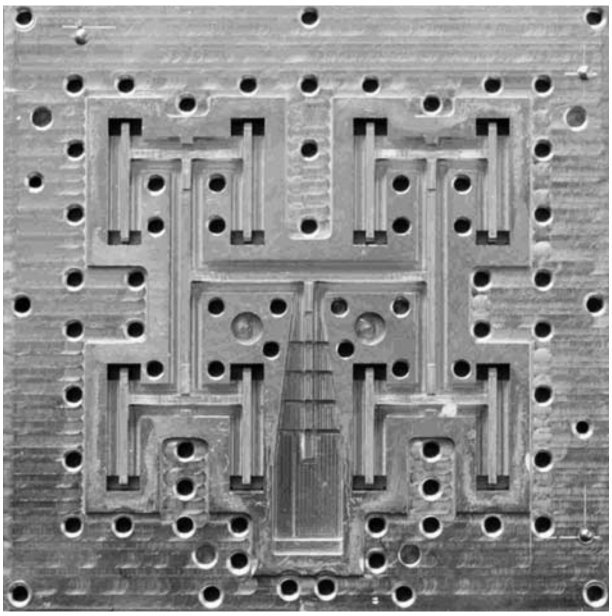

Fig. 7: Photograph of the waveguide feed network of the 24 GHz antenna

The radiation diagrams of this antenna are plotted in **Fig. 8.** Beamwidths are 8.5°, and the sidelobe level in both planes is quite close to that expected for an antenna array with equal element excitation. As with the 10-GHz antenna, however, some lobes appear in the E-plane diagram due to radiation from the slot coupling between waveguide and microstrip. Return loss shows a strong ripple, again due to contact problems in the waveguide assembly.

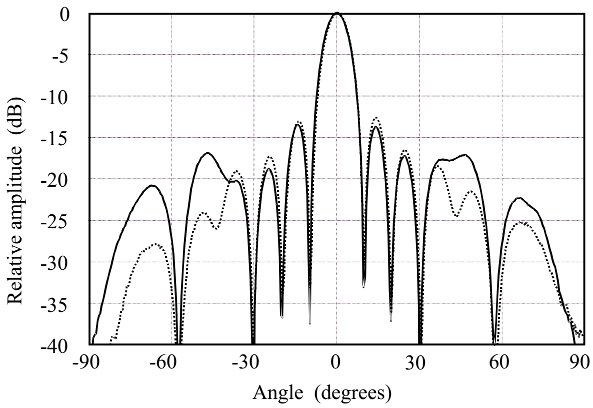

Fig. 8: E-plane (——) and H-plane (⋯⋯) radiation diagrams of the 24 GHz antenna

4. 38-GHz Antenna

As a last antenna, a 2 × 16 element antenna array is described for the communication band around 38 GHz. Compared to the antennas presented above, some further improvements were made:

- For the waveguide feed network, an E-plane configuration was selected. This, on the one hand, allows an even closer spacing of the microstrip elements, and on the other hand, as the waveguide is cut in the center, contact problems are considerably reduced.
- A taper was introduced in the element excitation to reduce sidelobe level.
- A detailed investigation was done to reduce the effect of the feed radiation on the E-plane radiation diagram.
- In one plane, the relative size of the array is increased by a factor of two to achieve a narrower beamwidth. To simplify the antenna design, however, only one row of planar subarrays was included in the other dimension.

The basic setup of the 38-GHz antenna is shown in **Fig. 9**. The planar array consists of eight 2 × 2 subarrays on a substrate with a thickness of 0.26 mm and a dielectric constant of 2.5. This planar feed network then is coupled to the E-plane waveguide network (WR22) via slots in the ground plane of the planar substrate (Fig. 9). Planar elements, coupling to waveguide, and the waveguide network were designed in an analogue way as described before for the other antennas. To reduce the sidelobe level, an amplitude taper was included in the design of the feed network using unsymmetrical T-junctions (**Fig. 10**). Originally, a Dolph-Chebishev distribution for –20 dB sidelobe level was selected; the far-off sidelobes then are further reduced by the subarray characteristics.

With the other antennas as described above, problems occurred due to residual radiation from the slot coupling; this could not be suppressed here, too. A detailed analysis revealed a radiation intensity by each slot of approximately 12 dB below each subarray's radiation. Phase difference between the two radiation sources was about 110° for the subarray feed arrangement as used before (**Fig. 11a**). As a first measure, efforts were made to reduce this influence by modifying the subarray layout and adjusting an

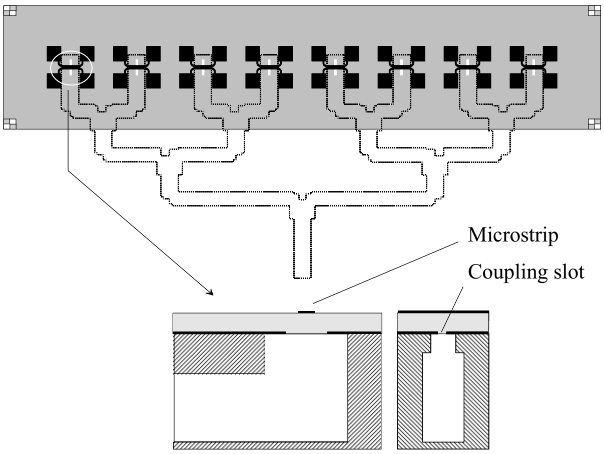

Fig. 9: Basic structure and principle of the waveguide fed microstrip array antenna

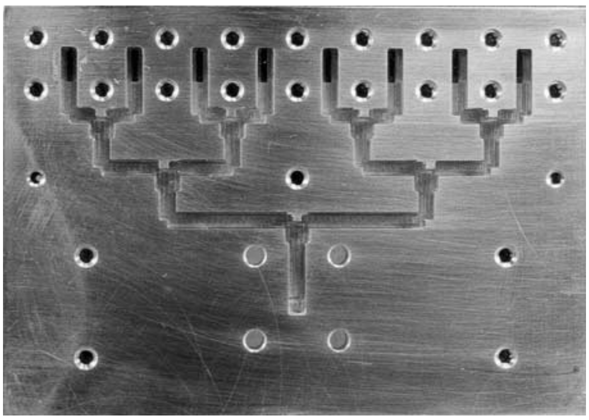

Fig. 10: Photograph of opened waveguide feeding network with coupling slots

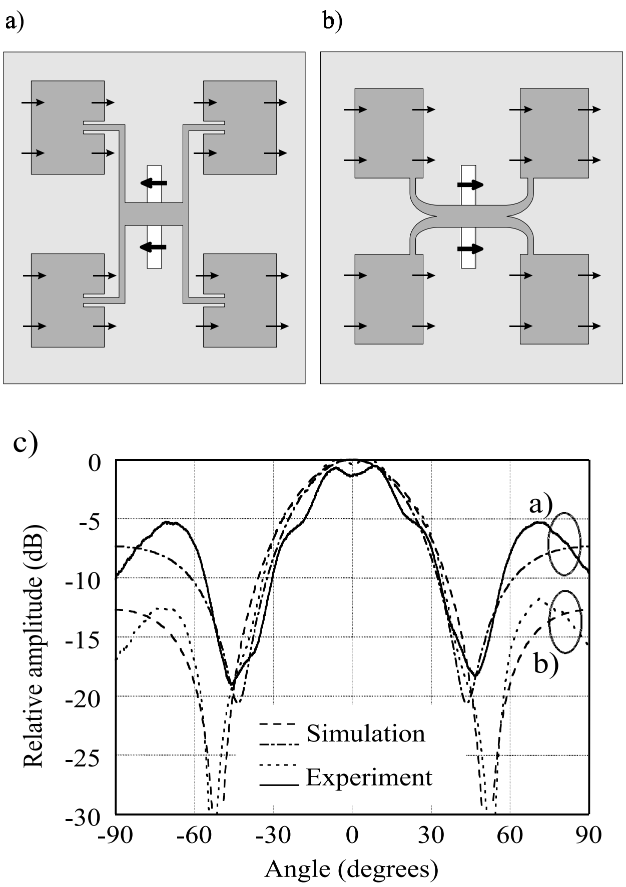

Fig. 11: Previous (a) and modified (b) subarray layout (top) and 2 × 2 subarray E-plane radiation diagrams of these two arrangements (c)

in-phase radiation of slots and patches. To this end, the patches are fed at the nonradiating edges (**Fig. 11b**). Impedance match is adjusted by the feed position. Furthermore, the whole subarray structure was optimized for equal phase of the electric fields in the slot and at the radiating patch edges. In **Fig. 11c**, theoretical and experimental E-plane radiation diagrams are plotted, showing a considerable improvement in the subarray radiation characteristics of the modified structure.

Based on this modification, a 2 × 16 element antenna was designed, fabricated, and tested. **Fig. 12** shows the measured E-plane radiation diagrams of both a single 2 × 2 subarray (including slot coupling to a waveguide port) and of the complete. A sidelobe level of –20 dB for the complete antenna could be achieved as intended, but again, some kind of grating lobes can be detected at around ±45°. At around ±53°, a common null can be seen for the subarray and the complete antenna. A detailed analysis revealed that the array factor of the 8 subarrays provides grating lobes at about ±45°. Without slot radiation, however, these grating lobes are cancelled by the nulls of the subarrays. The slot radiation, however, leads to some shift of these nulls such that the grating lobes are no longer suppressed. Consequently, the distance between the subarrays had to modified to shift the grating lobes of the array factor to the nulls of the subarrays (including the effect of slot radiation), maintaining, however, the element distance in the subarrays.

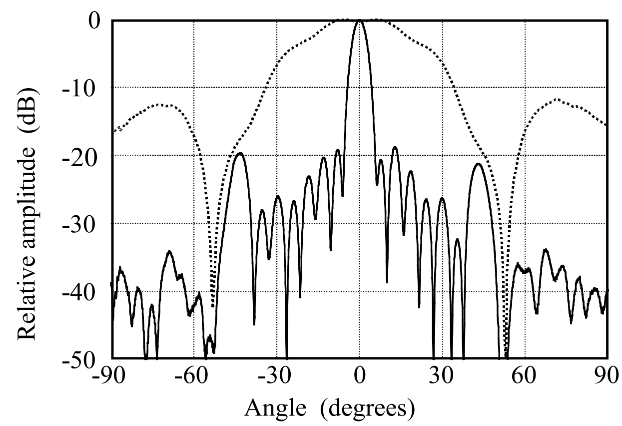

Fig. 12: Experimental E-plane radiation diagrams of a 2 × 2 subarray (⋯⋯) and the first design of the complete 38 GHz antenna (——)

Based on these results, a second antenna was built up. A photograph of this antenna is shown in **Fig. 13**. **Fig. 14** shows the experimental radiation diagrams of this antenna. Obviously, the level of the sidelobes produced by the grating lobes of the slot radiation is decreased by 4dB compared to the first design. However, it seems that the subarray nulls have shifted slightly, and that their depth is decreased. As the distance between the subarrays has been reduced, this effect is likely due to increased coupling between the patch elements. In the E-plane, a 3 dB beamwidth of 5.1° results; the H-plane beam, due to the small antenna dimensions in that plane, is 35° wide. E-plane sidelobe level is nearly –20 dB (as designed). The overall return loss of the antenna array (**Fig. 15**) is better than –10 dB over a bandwidth of 2.3 GHz (6 %).

5. Conclusion

Design and results of three different planar antennas for 10 GHz, 24 GHz, and 38 GHz have been demonstrated. All three antennas are based on a waveguide feeding network with slot coupling to a number of 2 × 2 planar microstrip antenna arrays. Based on an E-plane waveguide feeding network, a suitable choice of substrate thickness, and a proper subarray spacing, surface wave

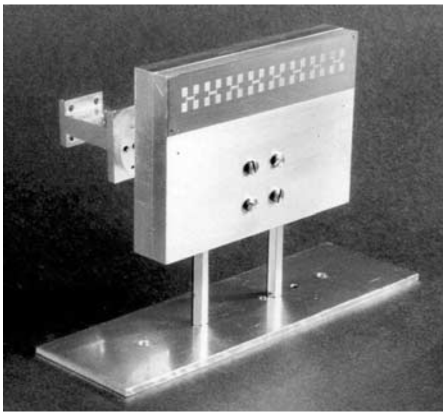

Fig. 13: Photograph of complete antenna assembly

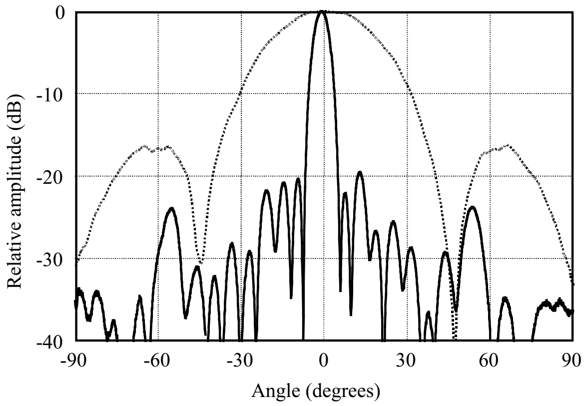

Fig. 14: Experimental E-plane (——) and H-plane (······) radiation diagram of the complete antenna with slightly reduced distances of the subarrays

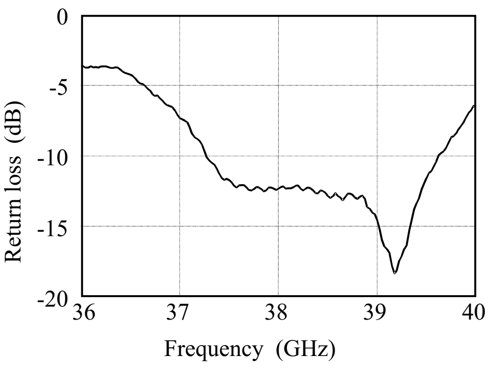

Fig. 15: Measured return loss of the complete array

problems and the effect of coupling slot radiation could be controlled. Best results were achieved with the 2 × 16 element antenna at 38 GHz. This array gives the basis for a 16 × 16 element array with low feed line losses. In a final version, the waveguide network might be fabricated using plastic injection molding reducing fabrication cost.

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