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Microstrip ring antennas operating at higher order modes for mobile communications

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Indexing terms: Microstrip antennas, Mobile antennas, Higher order mode antennas

Abstract- An experimental study of microstrip ring antennas suitable for use in mobile communication systems is presented. Conical radiated beams are generated by the TM_{21} and TM_{41} modes. Dual mode concentric rings have been designed which switch the beams in elevation as the vehicle traverses up and down hills or changes latitude within a continent, while maintaining omnidirectional azimuth coverage to optimise signal reception. The authors have successfully designed and tested a stacked array which gives beam coverage in elevation from 20° to 60° with a gain > 6 dBi. Mode switched antennas are a cheap and viable alternative to an expensive phased array antenna with continuous beam steering. Various feeding techniques have been investigated for exciting these modes. Bandwidths of 5% or more were attained for each mode. Coaxial probes gave good coupling efficiency and, with the addition of impedance compensating cylinders, bandwidths of 11% and 5% for the TM_{21} and TM_{41} modes, respectively, were obtained. Electromagnetic coupling provided a less mechanically complex feed system and control over the input impedance via the length of the feed overlap under the patch. Bandwidths of 7% were obtained for both modes and the resonant frequency was tunable by about 6% by varying the feed overlap length.

Introduction: Many new satellite based services for road vehicles are planned to come into service in the late 1990s. For example, cars and trucks will have access to satellite telecommunications and global positioning systems. Compact antennas, mounted inconspicuously on the vehicle, will be required to receive these services together with roadside traffic information data. Not only are these services likely to be operated at different frequencies but the radiation pattern requirements from the antennas will also be different. For example, telecommunications may be provided via a geostationary satellite system requiring antenna beams pointing at elevation angles between 20° and 60° at European latitudes, i.e. 30° - 70° from zenith. Alternatively, continuously orbiting satellites, as proposed in the Motorola Iridium system, may provide a similar service network. One difficulty is that the antenna beam is required to track the satellite while the vehicle turns or travels up and down hills. Antenna gains of 3 dB or more are specified for the telecommunications systems addressed here, depending on the application and in all cases the antennas are to be circularly polarised. Three solutions to the antenna problem can be envisaged. The first is to use an omnidirectional antenna, but this can be discounted at present due to low gain. Secondly, the satellite may be tracked using a phased array; however, this is an expensive option and as such can be ruled out for standard consumer terminals. The third solution, which is reported here, is to generate a conical beam, which can be switched in elevation to optimise the gain. This beam configuration gives omnidirectional coverage in azimuth allowing a vehicle to turn without problems and

addresses the antenna problem for geostationary orbit satellite systems. For continuously orbiting systems a fundamental TM_{11} mode patch can be added to the antenna array to cover up to 30° from the zenith. Patches operating in this mode have been widely discussed elsewhere [1].

In this paper a study of concentric annular ring arrays [2, 3] is reported in which the rings were excited in various modes, resulting in conical beams pointing at different elevation angles [4]. The concentric ring element geometry is shown in Fig. 1. The rings resonated near 6 GHz and most were printed on a very low dielectric constant honeycomb substrate ($\epsilon_r = 1.05$, thickness = 3 mm). Exciting higher-order modes is often difficult, as the radiation patterns exhibit asymmetry and high crosspolarisation levels. The patches reported here were circularly polarised. As part of our work we have used a near field test range to study the mode excitation, measuring a full three-dimensional image of the beam shape. Later, in Section 2, it is shown that switching between modes provides a degree of beam steering in elevation while maintaining omnidirectional azimuth coverage. Measurements of the gain are also presented here. The location of the antenna on a vehicle will determine the size of the ground plane allowed for the patch.

In many cases the antennas are likely to be printed over small ground planes, possibly attached to a sun roof as these are easily integrated into the structure. Consequently, an experimental study was carried out to investigate the variation in gain as the size of ground plane was varied. Increased gain can be obtained by using a stacked array of two elements [5], again with switched mode beams giving omnidirectional azimuth coverage. Finally, typical bandwidths required for communications systems vary from 5% to 10% whereas those for patch antennas are often only a few percent. We have addressed this problem in Section 3 by experimentally investigating three feed techniques for exciting these modes: coaxial probes, electromagnetic coupling and aperture coupling. No significant differences were measured between the radiation patterns for each feed method.

2 Higher order mode beams

2.1 Radiated beams

Software based on the cavity model was written to compute the radiation pattern beam shapes for higher order modes which in turn were verified experimentally. The modes which turned out to be of most interest for mobile communications to a vehicle were the TM_{21} and TM_{41} modes [4]. These modes have conical beams which are useful for systems operating with geostationary satellites where the satellite appears at low elevation angles, such as European and North American latitudes, typically 25° to 70° from boresight. Such a beam shape allows continuous coverage in azimuth as the vehicle turns while providing a directional beam in elevation. The inner and outer radii of the rings tested were 9.3 and 21.3 mm, and 24.0 and 38.0 mm respectively. The TM_{21} mode pattern peaked at an angle of 35° from boresight/zenith (an elevation angle of 55°) as shown in the three-dimensional plot in Fig. 2a, the pattern being acceptably symmetrical in all planes with a ripple of about +/- 1 dB. The axial ratio for the antenna in this mode was 3 dB at worst across the bandwidth. Fig. 2b shows a contour map for the TM_{21} mode where the radiation peaked at 55°. This mode was far more difficult to excite symmetrically than the TM_{41} mode. The patterns were essentially conical although some asymmetry between the planes is apparent. A ripple of 5 dB was measured between planes, shown clearly by the difference between the

vertical and horizontal planes-in Fig. 2b, and the axial ratio was 4dB over the bandwidth. We have achieved better results using a combination of commercial hybrid couplers and direct coaxial feeding but the patterns presented are typical for a fully integrated patch and feed network. However, there is room for improvement for this mode. A cut through the beam for these two modes, measured at 6 GHz, is shown in Fig. 3. The beam axial ratios were about 2 dB, measured using a rotating linearly polarised source. This result gives a much more favourable impression of the radiation patterns than the full three dimensional plots in Fig. 2. The figures quoted above were for the honeycomb substrate 3 mm thick with $\epsilon_r = 1.05$. Increasing ϵ_r to three increased the beam angle by 8° . This gives a degree of design flexibility for the elevation coverage.

2.2 Gain

The gain of these modes was measured with the patches printed over a large ground plane. The results, given in Fig. 4, showed that the mean gain was about 7 dB for the TM_{21} mode and 6 dB for the TM_{41} mode. A further investigation of the gain was carried out as the size of the ground plane was reduced. On truncating the ground plane the gain varied about the mean value by about ± 0.5 dB (see Fig. 4) until the ground plane was barely larger than the patch itself, about 20%, where after it fell significantly. This indicated that these antennas could be mounted on very small ground planes without a significant degradation in the performance. No major changes were noted in the radiation patterns for small ground planes.

2.3 Mode/beam switching array

The dual concentric ring antenna shown in Fig. 1a consisted of two concentric rings, each ring being excited at a different mode as indicated. The radiation pattern coverage in elevation for these two modes together is shown in Fig. 3, giving a gain > 3 dBi from 22° to 70° in elevation, sufficient for low gain requirements at European latitudes. The peak measured gain was 6 dBi for the TM_{21} mode and 7 dBi for the TM_{41} mode. However, by switching between the modes, the gain can be continuously optimised for a given vehicle position/orientation. This has significant benefits and is a simple, low cost method of achieving beam tracking in elevation while maintaining omnidirectional azimuth coverage. Mode switching can be either continuous or driven by a comparator as for cellular networks. For applications where increased gain is required an array of stacked elements may be used, this is detailed in Reference 5. The stacked array, where elements were mounted one above the other spaced about 1 wavelength apart, maintains the omnidirectional azimuth coverage while giving about 3 dB more gain. The gain was measured at 9 dBi for the TM_{21} mode and 10 dBi for the TM_{41} mode. For 6 dBi or more gain an elevation angle coverage from 18° - 58° was obtained. This may be changed by about 6° by printing the antennas on a higher permittivity substrate, $\epsilon_r = 3$.

3 Feed networks

Excitation of the patches at higher order modes required multiple feed points both for mode suppression and symmetrical excitation. The feed positions were different for each mode. For circular polarisation two pairs of feeds were used, positioned diametrically opposite each other. The feed points in each pair were spaced 45° apart around the ring for the TM_{21} mode and 22.5° apart for the TM_{41} mode, one being fed 90° out of phase with the other [6]. Stripline networks consisting of power splitters and hybrid couplers were designed to give the required excitation. A variety of

coupling methods from the feed to the patch have been investigated experimentally. The coupling methods were:

- (i) direct using a coaxial probe from the stripline to the patch
- (ii) electromagnetic coupling where the feed line was run directly beneath the patch
- (iii) a variation of the latter where a slot in a microstrip ground plane was placed between the feed line and the patch. These are shown in Fig. 5.

The best result obtained for each method is summarised in Table 1. Bandwidths were measured for a return loss of - 10 dB. The patches were printed onto a honeycomb substrate 3 mm thick with $\epsilon_r = 1.05$. For the noncontact coupling, the transmission feed lines were printed on RT Duroid with $\epsilon_r = 2.33$. The bandwidth was improved by increasing the substrate height but often at the expense of the efficiency and the generation of surface modes in the dielectric.

Table 1: Bandwidth of ring patches for different feed methods

Feed method to patch	Bandwidth %	
	TM ₂₁ mode	TM ₄₁ mode
Coaxial probe 0.7 mm diameter	4	2
0.7 mm coaxial probe plus compensating cylinder	11	5
Electromagnetic coupling (no slot)	7	7
Electromagnetic coupling through slot	8	4

3.1.1 Direct probe feeding: is commonly used where the patch substrate is easily machined. It provides efficient coupling of the signal to the patch and is shown in Fig. 5a. For a standard probe of 0.7 mm diameter, bandwidths of 4% and 2% were measured for the TM₂₁ mode and TM₄₁ modes, respectively, see Table 1. The bandwidth can be increased by using a compensated probe as shown in Fig. 5a, where a metal cylinder was placed symmetrically around the 0.7 mm feed probe. Fig. 6a shows the change in input impedance measured for the TM₂₁ mode which in this case resonated near 7GHz. The introduction of a cylinder 2 mm long and 4 mm in diameter reduced the input resistance from about 100 Ω to 50 Ω while the reactance curve became more inductive and changed far less rapidly through the resonance. This resulted in a bandwidth improvement from 4% to 11%. A similar but more dramatic improvement was measured for the TM₂₁ mode resonating near 6.3 GHz, Fig. 6b. The real part of the input impedance was reduced from 270 Ω to 50 Ω with a significant reduction in the magnitude and rate of change in the imaginary component too. In this case the cylinder was 2 mm long and 3 mm in diameter and the bandwidth increased from 2% to 5%. Other modes resonating within the measurement range were similarly improved indicating that this method of probe compensation gives a significant improvement in the bandwidth.

3.1 2 Electromagnetic coupling: shown in Fig. 5b, provides a noncontact connection to the patch. A microstrip line runs directly under the antenna, separated by a dielectric honeycomb substrate, and the degree of overlap L between the two provides control over the input impedance. This technique is preferred where either drilling the substrate is difficult, e.g. glass or ferrite, or where large numbers of connections are

needed such as in phased arrays. However, one disadvantage of this method is that the microstrip lines are unshielded and may radiate, directly interfering with and distorting the patch radiation. There are no reported results using this method of feeding for higher order modes. This coupling method not only allows the patch to be matched but also provides a convenient method for finely tuning the resonant frequency by adjusting the overlap. As an example, changing the overlap from -1 to +4 mm tunes the frequency by 300 MHz, from 5.05 GHz to 5.35 GHz. Fig. 7 shows the corresponding change in input impedance for the TM_{21} mode, an overlap of 2 mm giving a 50Ω input impedance and 7% bandwidth. The bandwidth also varied as the feed overlap changed and ranged from 5% to 7%. The bandwidth obtained for the TM_{41} mode was also 7%, again the feed overlap affecting the input impedance. A frequency tuning range similar to that of the TM_{21} mode was also achieved for this mode.

3.1.3. Aperture coupling: A variant of the last method is to use a stripline feed with a slot aperture etched into the ground plane and place the patch, supported on honeycomb, over the slot, as shown in Fig. 5c [7]. This eliminates feed line radiation and maintains a noncontact connection although radiation from the slot aperture can become a problem. The aperture for feeding the ring patches may be a complete annular slot or a restricted arc. In this study, slots of varying length were examined. Fig. 8 shows the variation in input impedance for the TM_{21} mode for two different arc lengths, 48° and 100° , and a full annular slot, all 1 mm wide. This mode was matched at 5.8, 6.0 and 6.3 GHz, respectively, for the three slot lengths. For the shorter arc length of 48° the impedance components varied far less near 6 GHz than for the longer arcs, resulting in bandwidths of 7% and 5%, respectively, for the two modes. For a complete ring slot the bandwidth was limited to 2%. Clearly, the slot length gives some control over the input impedance and resonant frequency. However, although good empirically based results were achieved here, aperture fed patches are generally difficult to design and the coupling efficiency from the feed line to patch is often very poor. Further work is to be directed at this problem.

4 Conclusion

Conical radiated beams have been generated and measured for annular ring patches. Initial impressions from single plane radiation patterns were that the performance for both modes was similar. However, three-dimensional radiation patterns revealed that the performance of the TM_{21} mode was superior to that of the TM_{41} mode which proved to be far more difficult to excite. It is expected that the $TM_{,,}$ mode antenna performance can be improved with fine tuning of the feed network exciting it. These antennas are suitable for mounting on vehicles for use in mobile communication systems employing geostationary satellites. The patches can also be adapted to systems using continuously orbiting satellites, such as the Iridium system, with the addition of a ring or disc operating at the fundamental TM_{11} mode radiating a conventional boresight beam. Gains of 6-7 dBi were obtained for the TM_{21} and TM_{41} modes. Dual mode concentric rings have been designed which switch the beams in elevation as the vehicle traverses up and down hills or changes latitude within a continent, while maintaining omnidirectional azimuth coverage to optimise signal reception. We have successfully designed and tested a stacked array which gives beam coverage in elevation from 20° to 60° with a gain > 6 dBi. Mode switched antennas are a viable alternative to an expensive phased array antenna and far cheaper to implement. Bandwidths of 5% or more were attained for each mode using a variety

of feeding methods, and in some cases 10% was achieved. Coaxial probes provide a straightforward feed to the patches giving good coupling efficiency and, with the addition of impedance compensating cylinders, bandwidths of 11% and 5% for the TM_{21} and TM_{41} modes, respectively. Electromagnetic coupling provides a less mechanically complex feed system and control over the input impedance via the length of the feed overlap under the patch. Bandwidths of 7% were obtained for both modes and the resonant frequency was tunable by about 6% by varying the feed overlap length. However, for some applications direct radiation from the feed lines may cause unacceptable radiation pattern interference. Finally aperture slot coupling provides acceptable bandwidths of up to 8%. However, the slot itself tends to radiate causing significant lobes in some planes and the coupling efficiency to the patch antenna is generally low, reducing the gain by 2 to 3 dB. In addition, further work needs to be carried out on the modelling of all the coupling methods to optimise the designs. In conclusion, a conformal patch array has been presented which provides a viable alternative to the phased array as a vehicle based antenna operating with satellite communication systems.

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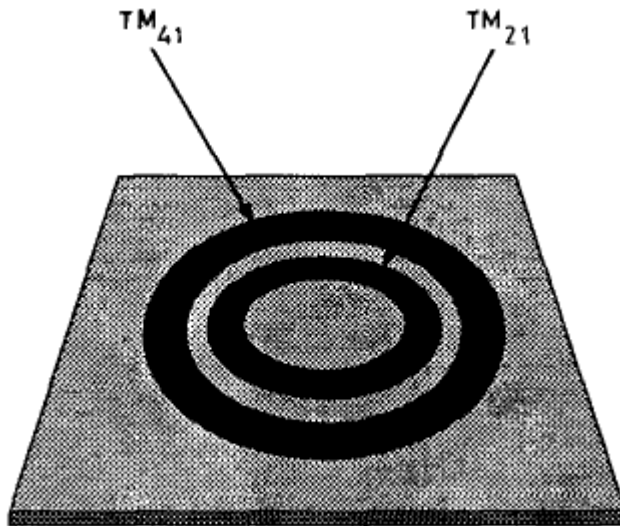


Fig. 1 Concentric annular ring microstrip antennas operating at two modes; TM_{21} and TM_{41}

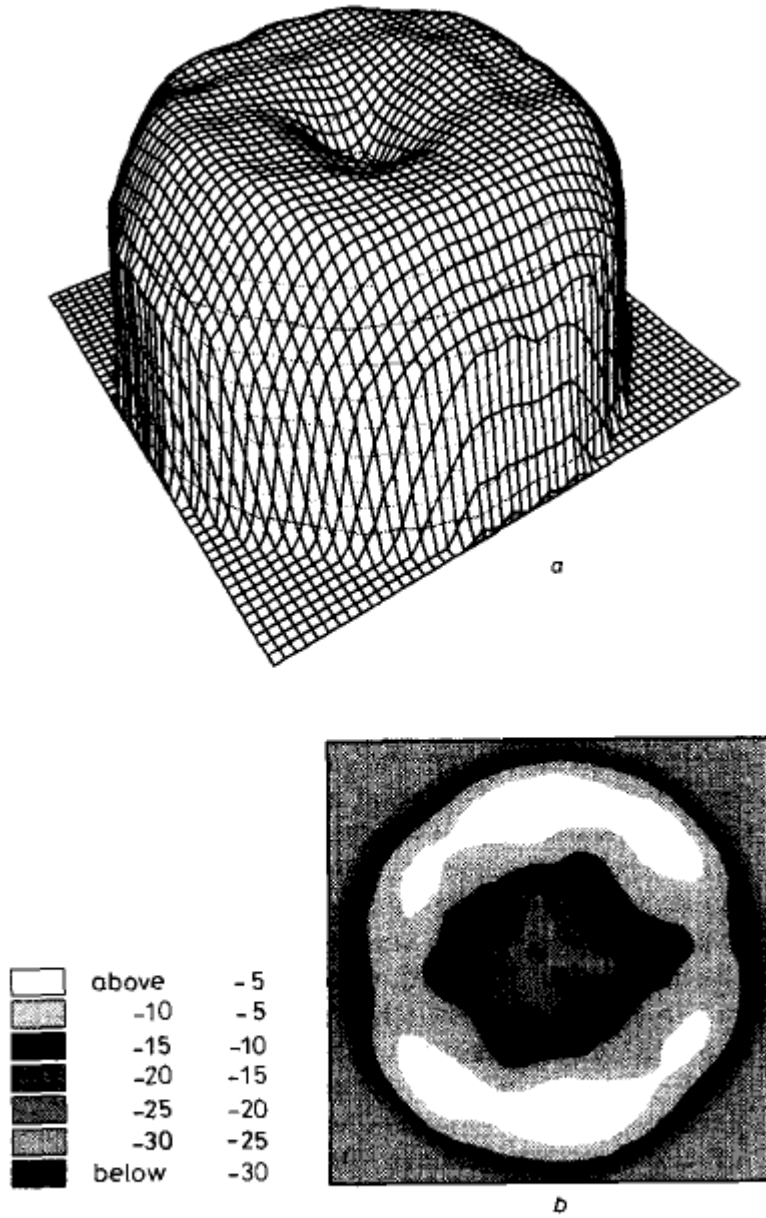


Fig. 2 Three-dimensional radiation patterns of annular ring patches measured on a planar near-field test range

a TM_{21} mode

b TM_{41} mode

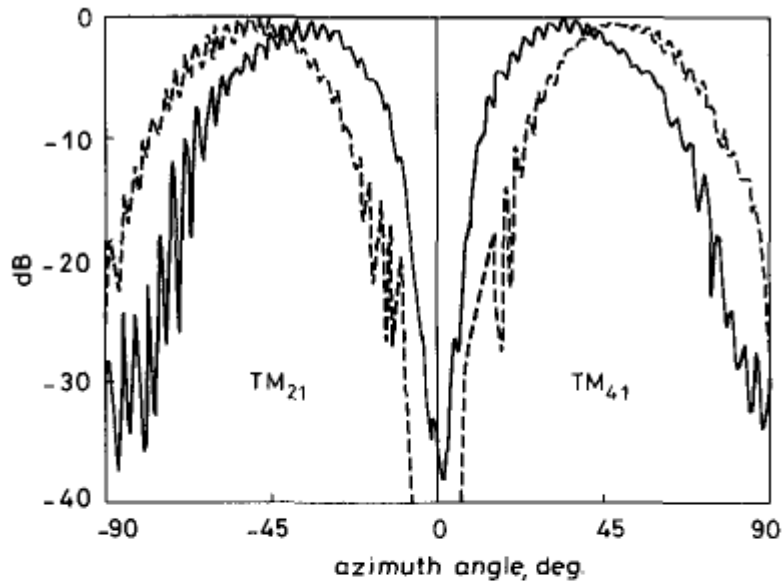


Fig. 3 *H-plane circularly polarised radiation patterns for annular rings at 5.7 GHz measured using a rotating linear probe source*

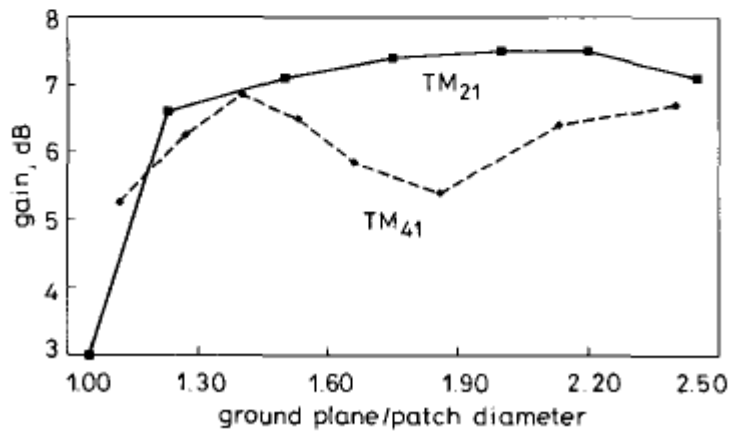


Fig. 4 *Gain of annular rings measured as a function of ground plane/patch diameter*

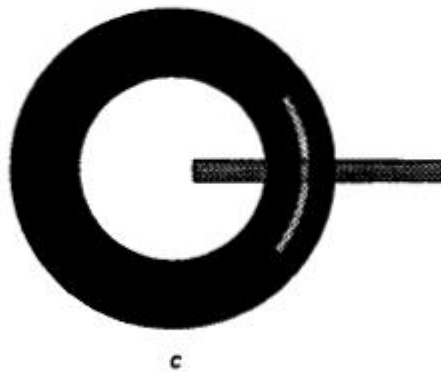
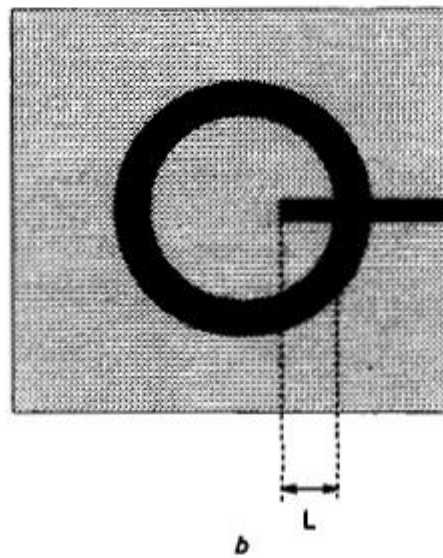
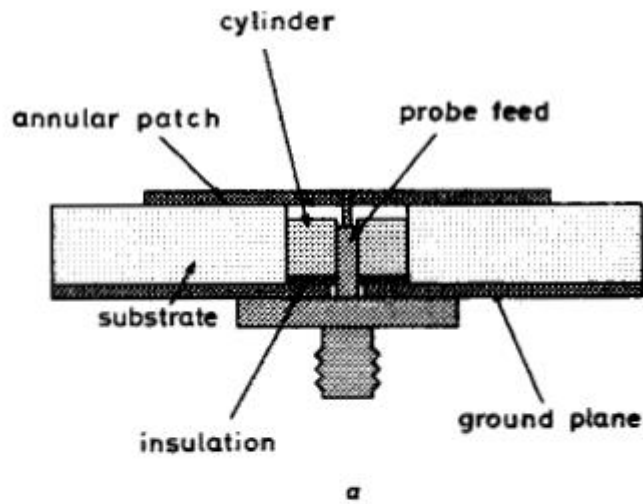


Fig. 5 Feeding methods for annular ring patches

a coaxial probe feed (with compensating cylinder)

b electromagnetic coupling using a $50\ \Omega$ microstrip line running under the patch separated by a honeycomb substrate

c electromagnetic coupling to the patch via an annular slot 1 mm wide in the ground plane of a $50\ \Omega$ stripline patch supported on honeycomb above slot

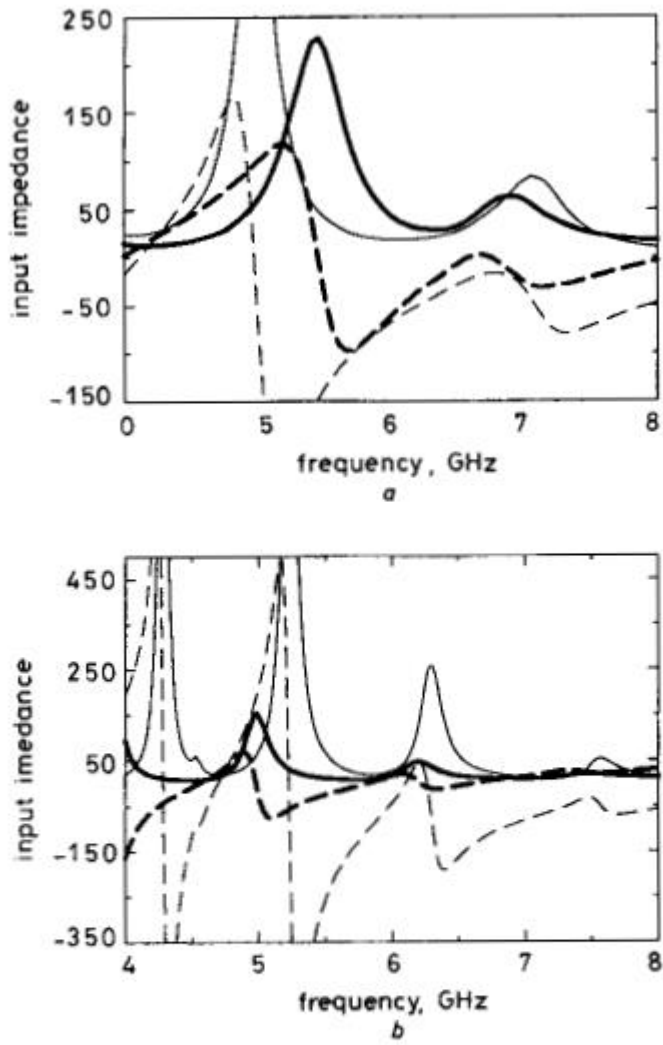


Fig. 6 Input impedance of annular ring patches using coaxial probe feeds (see Fig. 5a)

a TM_{21} mode

— 0.7 mm diameter probe

— 3 mm long, 4 mm diameter cylinder on probe

b TM_{41} mode

— 0.7 mm diameter probe

— 2 mm long, 3 mm diameter cylinder on probe

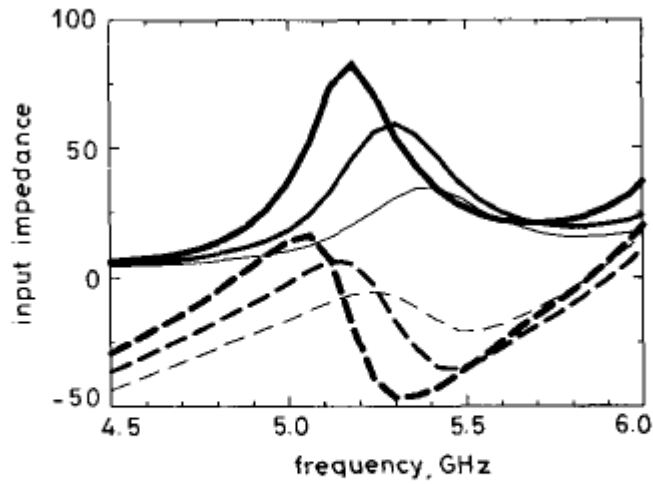


Fig. 7 Electromagnetic coupling using microstrip line (see Fig. 5b) for TM_{21} mode: variation of input impedance with line overlap L

- $L = -2$ mm
- $L = 2$ mm
- $L = 5$ mm

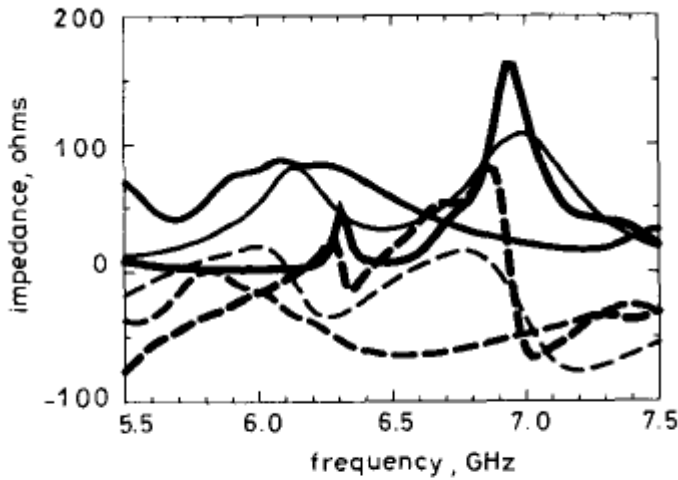


Fig. 8 Input impedance for electromagnetic coupling via a slot in ground-plane under antenna (see Fig. 5c) as a function of slot length

- 360° annular slot
- 110° slot length
- 48° slot length