Hidden antennas for vehicles

by R. J. Langley and J. C. Batchelor

The introduction of new telematics and broadcast systems into vehicles has led to a requirement for multiple antennas that can be hidden from view. This paper commences by presenting the results of simulations to identify the components of a car's structure that influence the radiation pattern of a printed VHF antenna on the rear windscreen. Two dual-band antenna designs are then presented for operation in the 900 and 1800 MHz telephone bands. The first is a planar inverted-F antenna that can be concealed in the bumpers, the second a hybrid structure based on the top-loaded monopole principle and mounted beneath the vehicle's roof.

1 Introduction

Radio reception in cars has a long history, beginning in the 1930s when car radios were introduced commercially under the brand name 'Motorola'. The use of radios in cars became so popular that, in 1947, the name of the manufacturing company was changed to reflect the brand name.

The introduction of new telematics and broadcast systems into vehicles has led to a requirement for more antennas. Whereas once it was necessary to have only one antenna—for AM/FM radio reception—now antennas for analogue and digital radio, television, telephone and navigation systems may be required.

There is a need to hide all these antennas while improving antenna performance using diversity or adaptive systems. The plastic and glass areas of the car are obvious targets for mounting antennas where they are completely out of sight and hence secure, leaving the aerodynamics and styling of the vehicle unimpaired. This presents considerable challenges for the antennas community and this paper summarises some of the work on novel hidden antennas currently being carried out at the University of Kent.

Two categories of antenna designs are discussed:

(*a*) conformal printed antennas for analogue VHF-frequency-range broadcast radio
(*b*) antennas for mobile cellular communications operating at 900/1800 MHz—top-loaded monopoles and planar inverted-F antennas (PIFAs).

The paper concentrates on the effects of a car body on antenna radiation patterns.

2 VHF vehicle antennas

Although new higher frequency and digital systems are currently being deployed, consumer take-up is expected to be relatively slow due to high equipment costs and concerns over the untried service provision. It is important therefore that the facility to receive analogue VHF and MF transmissions remains for the foreseeable future.

Wing/roof-mounted monopoles

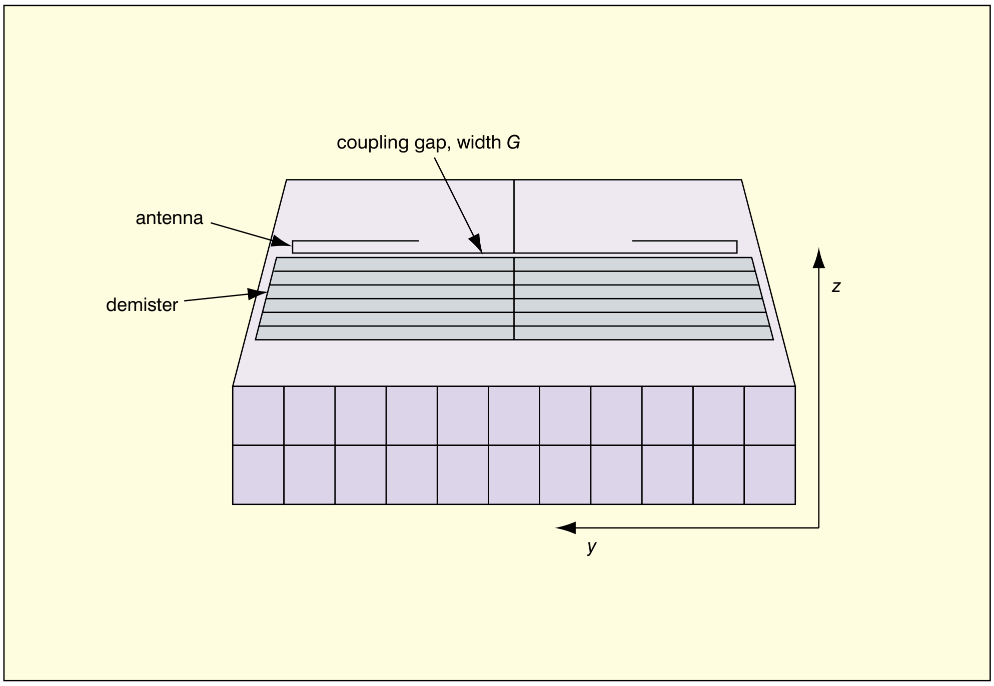
Tolerable reception of MF and VHF signals has been provided by long (subresonant) monopole antennas that are usually mounted on the wing or the roof of the car body. Although AM and FM stations can be received via a single monopole, fading due to the shadowing and multipath effects of mobile environments causes a definite degradation of the signal-to-noise ratio (SNR). Additionally, at FM-band wavelengths (3 m at the centre of the band) the car body behaves as a resonant cavity causing deep nulls to appear in the antenna's radiation pattern and this loss of omnidirectionality produces further fading in the mobile channel.

Conformal printed screen antennas

FM stations broadcast in the band between 87·5 and 108 MHz. At these frequencies it is possible to produce a halfwave resonant structure by convoluting the antenna conductors. The favoured method for fabricating the convoluted structure is to print it on the front or rear windscreen. It is more common to use the rear windscreen, though this means that a reduced screen area is available for the antenna due to the presence of the rear demister wires. An example of a rear-windscreen printed analogue radio antenna is shown in Fig.1, where the wire convolution is visible together with its position above the demister.

Successful antennas designs have been realised by using the demister as a ground plane grid and exciting the slot between the antenna element and the ground. Although the folded antenna allows the slot to be

Fig. 1 Mesh of rear view of car showing printed antenna configuration



resonant, there is an effect on the polarisation purity of the radiated fields and this must be investigated as part of the design process. Fortunately, in Britain FM is broadcast on both vertical and horizontal polarisations, which makes a dual-polarised antenna necessary in any case. Feeding printed antennas can be problematic as it is often not possible to connect to a local ground. The resulting floating ground can make input matching difficult.

Finally, multipath fading can be significantly reduced by the use of spatial diversity in the receiving antenna. For the diversity to be effective, it is necessary to arrange for the separate receiving antenna patterns to be sufficiently uncorrelated for spatial fading points to be received independently. The size of VHF antennas makes it impossible to implement more than one on the average automobile body and it is therefore of interest to introduce some controlled asymmetry in the antenna shape. This can be done by switching in shunts to ground at various points along the antenna structure.

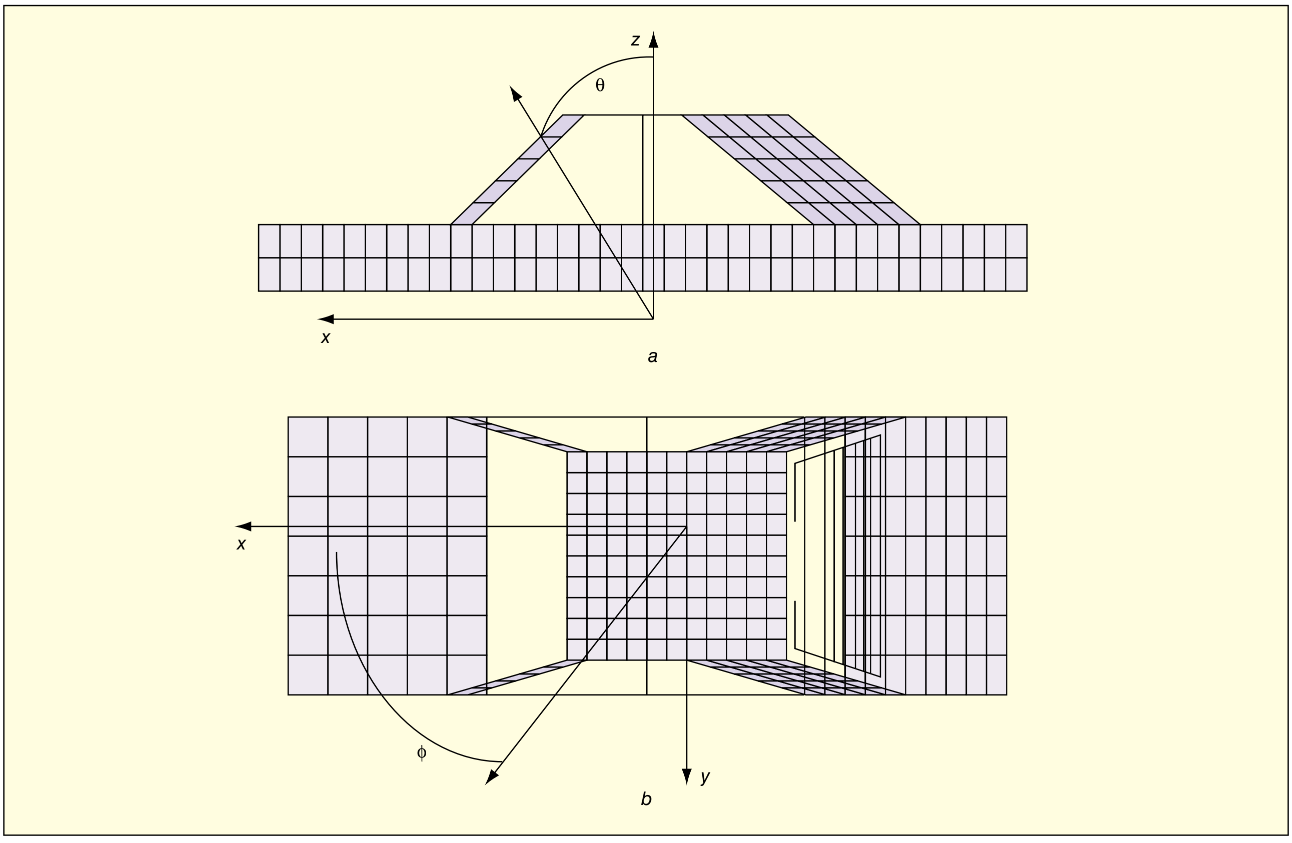


Fig. 2 Mesh of car body: (*a*) side elevation; (*b*) top plan with bottom wires removed for clarity

Modelling vehicle–antenna interaction at VHF

In the past the automotive industry has not required accurate modelling of the performance of wing-mounted monopole antennas. These simple antenna structures operate with a tolerable efficiency and any attempt at implementing a diversity system would be unpopular with consumers as the increased number of antennas would be unsightly. However, the advent of printed screen antennas has made detailed electromagnetic modelling and design more desirable[1,2]. The conformal nature of printed screen antennas means that they interact strongly with the structures of the vehicle body and research has been carried out at the University of Kent[3] to identify the electromagnetically significant parameters of a car body.

The simulations presented below were made using the NEC-2 freeware developed in the USA. This software uses thin current elements to model wire mesh representations of structures and has the advantages of simplicity and high simulation speed. A disadvantage of the code is its inability to model dielectric structures. This meant that the glass screens could not be included in the model. Omitting the glass screens resulted in poor input impedance modelling, however the radiation patterns were simulated with great accuracy. The presence of the glass was only of secondary importance as its electrical thickness was about one thousandth of a wavelength near the FM band centre.

Although much more powerful electromagnetic simulators are available which are capable of meshing automobile manufacturer's CAD (Computer Aided Design) files, the meshing process is often very laborious and much unnecessary detail is included in the structure. This increases the design time and development costs in an industry with very tight profit margins. Our study therefore sought to identify how a vehicle body could be simplified for modelling at VHF frequencies and also show how particular structures on a car body are likely to affect radiation patterns from printed antennas.

A simplified wire mesh model of a Nissan Gloria saloon car available in Japan is shown in Fig. 2. The rectilinear nature of the mesh obviously deviates from the actual surface contours of the vehicle, though it was found that if the width-to-length aspect ratio was chosen according to the height above ground these simplifications were not important. The structure parameters that have an important influence on the shape of the radiation pattern are identified below. As the antennas investigated in our work are for use in terrestrial broadcast systems, only radiation at low elevation angles (2°) is considered.

Firstly, the *presence of a ground plane* below the car was

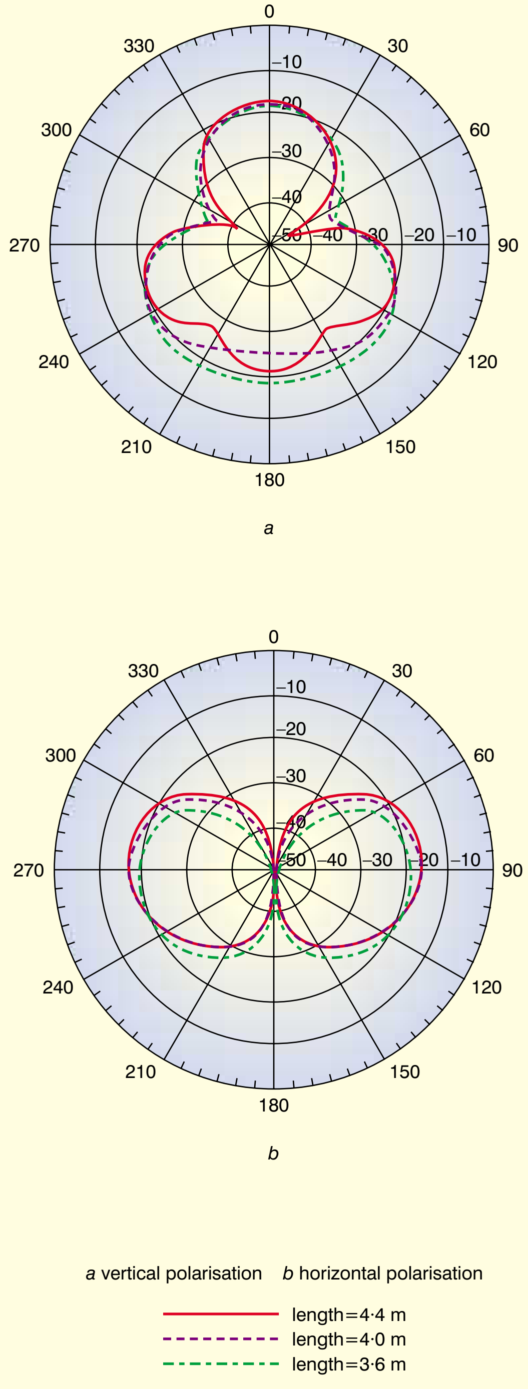
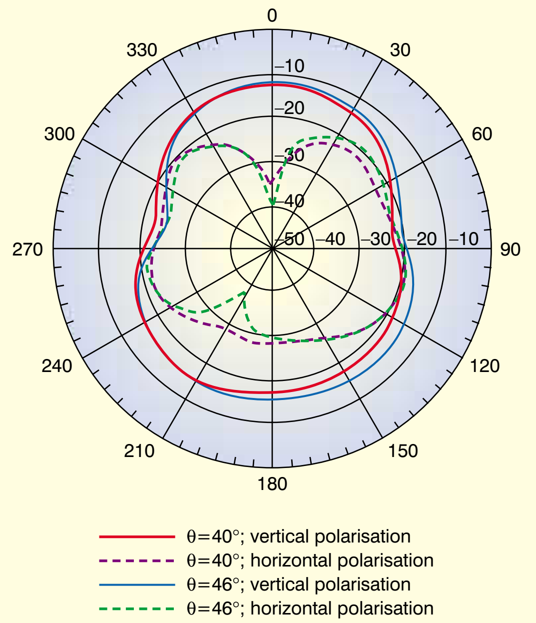


Fig. 3 Radiation patterns for a car of cabin width = 1·7 m and different vehicle lengths: (*a*) vertical polarisation; (*b*) horizontal polarisation.

Fig. 4 Radiation patterns for 2 different rear-screen slopes, θ.



very important. Ground conductivities and permittivities representing a range of grounds from rural to urban were used, though very little difference in the predicted radiation patterns resulted. Although the exact electrical parameters of the ground were not significant, its presence was vital if accurate predictions were to be produced.

The *width-to-length aspect ratio of the car body* is a dominant parameter on radiation patterns as the body is resonant at FM frequencies and behaves as a leaky cavity. The effect of altering the length of the car while keeping its width constant at 1·7 m is shown in Fig. 3. When the total length was 2·6 times the width, 10 dB nulls were observed at ±150° for vertical polarisation in the azimuthal plane, while 20 dB nulls occurred at ±60°. When the car length was reduced by 20%, the forward nulls fill by 9 dB. Vehicle-mounted antennas usually exhibit vertically polarised nulls at angles close to ±60° caused by the cabin length being close to half a wavelength. The gain with horizontal polarisation is much less affected by cabin length, the most notable change being a broadening in the forward null as length is decreased (Fig. 3*b*).

Lowering the roof from its correct level towards the boot-bonnet plane mainly affected the horizontally polarised fields by increasing the depth of a forward-directed null. The only notable difference to the vertical polarisation was an overall reduction in gain with the gain at rear angles affected most.

Although the height of the car roof did not strongly affect the correlation between measured and simulated patterns, the *relative positions of the roof support pillars* was important. The front, A, pillars most significantly affected the scattered fields in the cabin, and these fields then interacted with the door supports (B pillars). The A and B pillars were modelled as single wires and it was observed that their relative positions were important to within about 3% of a wavelength. Additionally, the slope of the A pillars had to be correct to ensure correct coupling between the vertical and horizontal polarisations. Although the A and B pillars could be adequately modelled as single wires, the surface area needed to be approximately that of the physical pillar areas. This was quite easily implemented with the thick-wire kernel in NEC and allowed the mesh to remain relatively simple. Finally, the total removal of the B pillars caused vertically polarised null depths of 13 dB and 20 dB at ±60° and ±130°, respectively. This finding was interesting as modern car manufacturing practice seeks to reduce the amount of metal in bodywork: the fabrication of the door pillars in plastic materials could adversely affect antenna omnidirectionality.

As the antenna is integrated directly onto the rear glass, the *slope of the screen* is expected to be significant to antenna performance. This is illustrated in Fig. 4, which shows results for screen slopes of 40° and 46°. The horizontally polarised fields were influenced most strongly by changes in rear-screen slope, both rear and forward nulls filling as the slope was reduced.

The modelling of the *rear, C, pillars* is important as these are immediately adjacent to the rear screen and have a significant influence on the radiation patterns. The C-pillar width affects both the vertical and horizontal polarisation patterns. Fig. 5 shows how a narrower C pillar results in a deeper horizontally polarised null at the rear, while the front horizontal gain is also reduced slightly and the nulls at ±70° deepen by several decibels. The main effect on the vertical polarisation when the C pillar is narrowed from 0·5 to 0·3 m is to increase the side gain by about 3 dB. The actual C pillar of the Nissan Gloria tapers towards the top; in the model, however, numerical errors result when adjacent wire volumes overlap as the wires converge. This inaccuracy was avoided by modelling the C pillars with parallel wires having a surface area equal to that of the physical roof support. No significant loss in accuracy was observed as a result of this simplification.

Although the simulated radiation patterns were not sensitive to the exact height of the roof, they were influenced by the size of the mesh elements used. In fact the roof meshing proved to be more important than the element size anywhere else in the car model. Roof mesh elements 0·04λ long caused the simulated radiation patterns to be 3 dB below the correct gain levels; reducing the length of the mesh elements to 0·03λ gave gains which correlated well with measurement.

Simulated radiation pattern accuracy

When the model was meshed according to the points discussed in the preceding subsection, it was possible to achieve good agreement between simulation and measurement results. The vertical gain was modelled to within 1 dB of the measurement results, though it was more difficult to obtain such close horizontal-gain agreement. This was partly because the measured horizontal patterns were asymmetric. Despite the symmetry problem, it was possible to achieve agreement between simulated and measured horizontal gains to within about 3 dB. The conclusion can therefore be drawn that good simulated patterns can be obtained from highly, though carefully, simplified vehicle bodies.

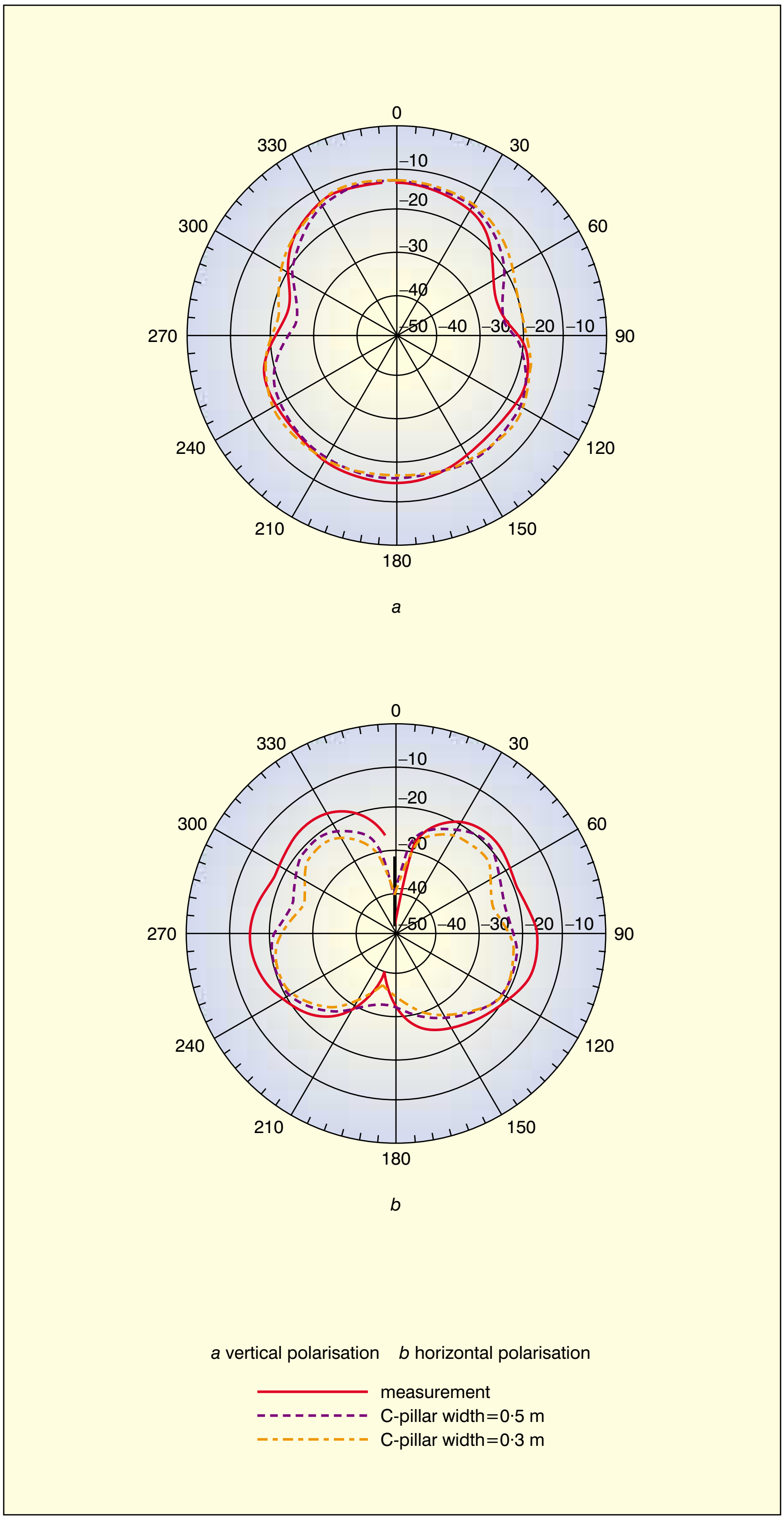


Fig. 5 Radiation patterns for different C pillar widths: (*a*) vertical polarisation; (*b*) horizontal polarisation.

Spatial diversity using an on-glass antenna

In the on-glass antenna shown in Fig. 1 the slot between the excited horizontal antenna wire and the demister grid forms the main radiating element. Fig.6 shows the measured vertical radiation patterns for slot widths, *G*, of 5 and 10 mm. The asymmetry in the measured patterns is useful as it facilitates the use of pattern diversity using a single antenna, with shunts switched in along the slot length.

3 Multiband telephone antennas

This section describes advances made on telephone antennas and presents two low-profile dual-band designs operating at 900 and 1800 MHz, the first a wide-bandwidth planar inverted-F antenna (PIFA)[4,5] and the second a hybrid design based on an antenna by Delavaud[6]. Both antennas were designed to fit under plastic panels on a

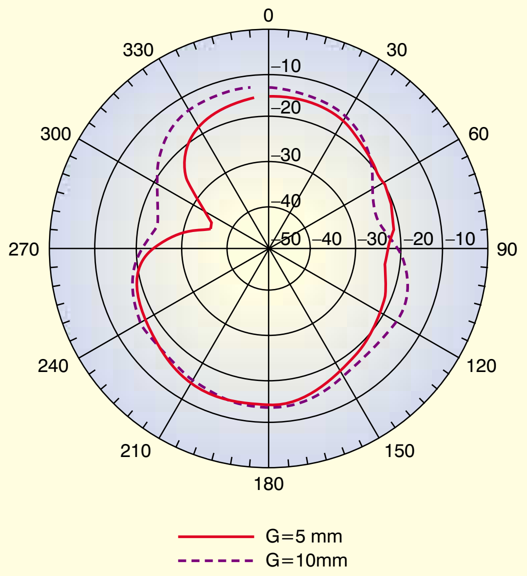


Fig. 6 Measured vertically polarised radiation patterns for different coupling gap widths.

vehicle. They were initially designed for dual-band operation at 900/1800 MHz, but more recently operation at the 2 GHz UMTS (Universal Mobile Telecommunication System) band was included. In each case the antennas are fed by a single coaxial feed, possess good bandwidth characteristics and provide full azimuth coverage around the vehicle.

Dual-band PIFA telephone antenna

Fig. 7 shows the geometry of a PIFA antenna designed to operate at the 900 and 1800 MHz telephone bands. The conductors have been cut away to provide a dual resonant-frequency response with wide bandwidths[5]. This antenna was specifically designed as an emergency call antenna to be mounted in the bumper of a car. It was tested in various different positions. The aim was to give equal radiation performance around the car and to examine blocking effects due to the bodywork. The current distribution plots show that at 900 MHz the outer parts of the structure are responsible for the radiation. At the higher band the inner section is excited. Fig. 8 compares the measured and computed return loss for this antenna. The agreement is good at the upper band but less so at the lower band. Nevertheless a good bandwidth is measured at each band with a voltage standing-wave ratio (VSWR) of less than 16.

The current excitations shown in Fig. 9 indicate that the outer region resonates at the lower 900 MHz band while the inner section resonates near 1800 MHz. The corresponding current patterns on an antenna from

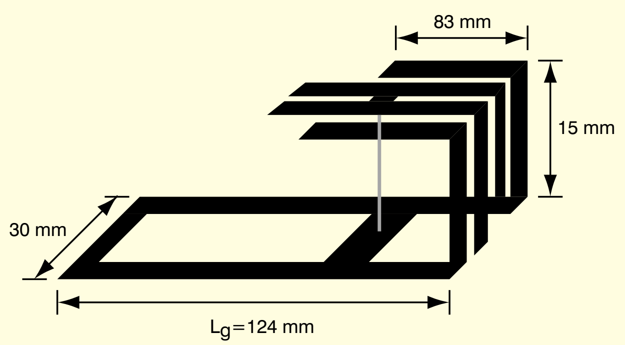


Fig. 7 Dual-band planar inverted-F antenna

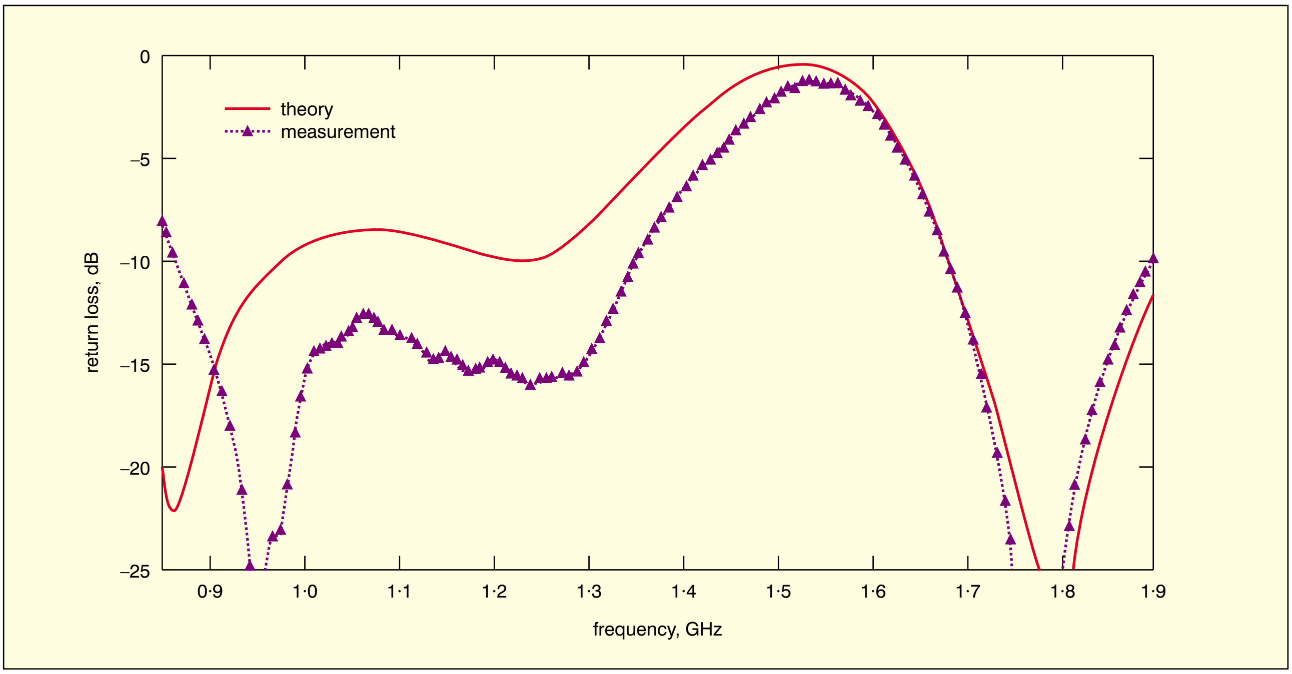


Fig. 8 Measured (——) and simulated (▲) return loss of the dual-band PIFA

which metal had not been cut away were very similar, low currents flowing in the excluded areas. As a bonus, an improved bandwidth is obtained when the conductors are cut away.

The vertically polarised radiation pattern measurements are shown for the 900 MHz band in Figs. 10 and 11. The red crosses on the car drawing give the position of the antenna/s, which in both cases were just behind the plastic bumper. The PIFAs were mounted with the side L_g (see Fig. 7) vertical to give vertical polarisation. The antenna alone gives monopole-like radiation patterns in this orientation and hence an omnidirectional azimuth coverage.

In Fig. 10, with the antenna placed in the centre of the bumper, the forward visiblity is good but the car body blocks radiation directed towards the rear. Similar blocking is found in other positions. Therefore two antennas were used, the best coverage being obtained when the antennas were placed on opposite corners of the bumpers front and rear as shown in Fig. 11. Here we

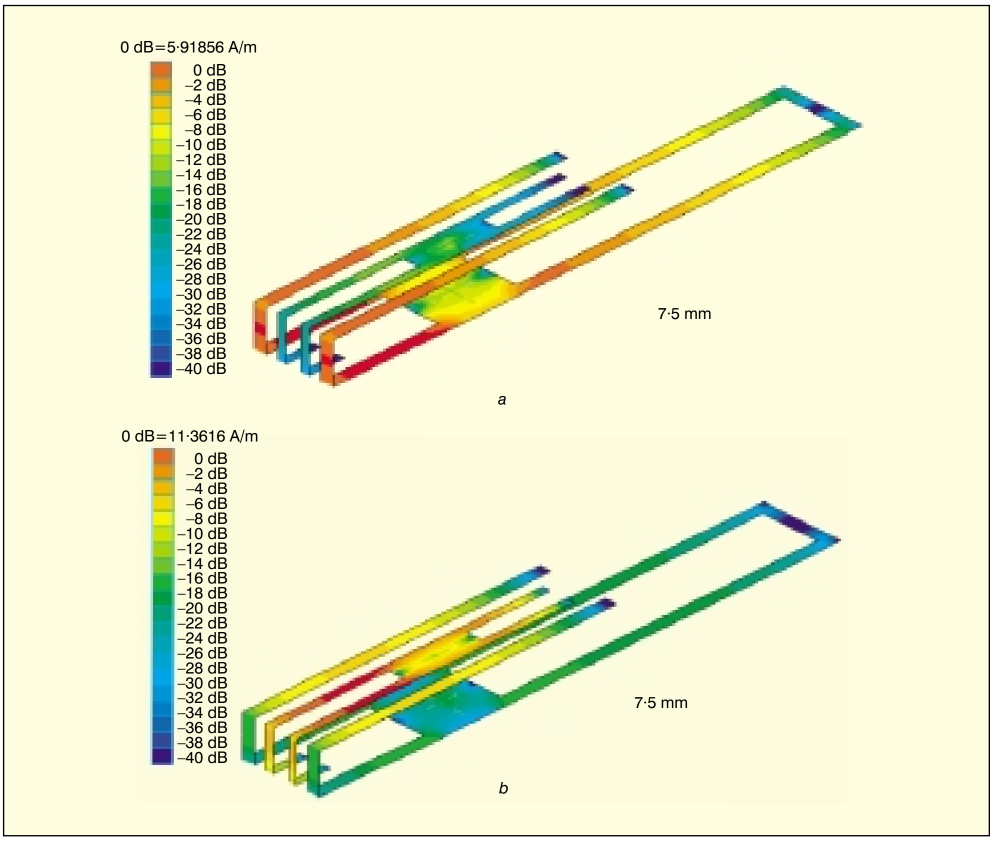


Fig. 9 Current excitation on the PIFA at (*a*) 900 MHz and (*b*) 1800 MHz

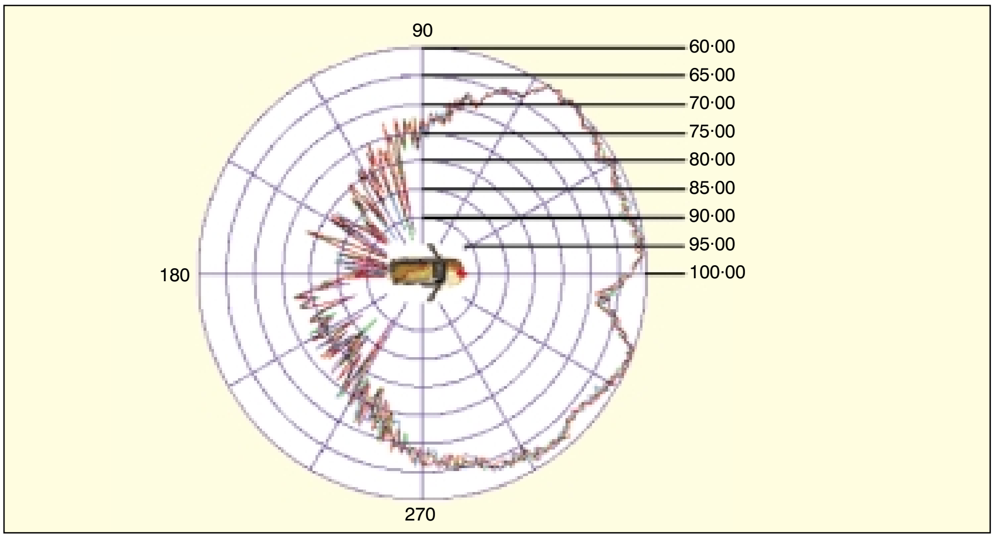


Fig. 10 Radiation pattern of the PIFA at 900 MHz when mounted in the middle of the front bumper

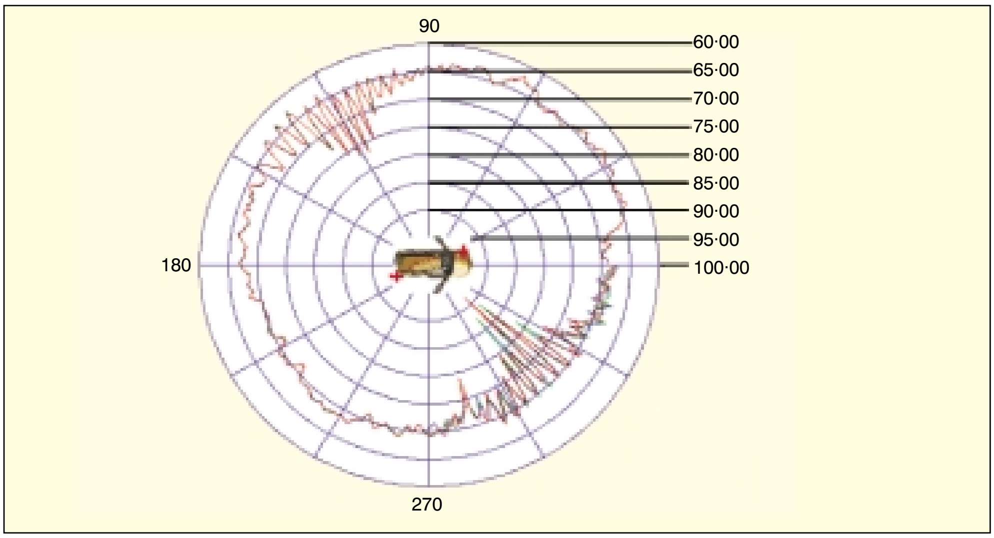


Fig. 11 Combined radiation pattern at 900 MHz of two PIFAs installed diagonally on two bumper corners

observe that there is good all-round coverage with ripple where the two radiation patterns overlap. A simple signal combiner was used to add the signals from the two antennas. At the higher frequency band similar results were measured, although the ripple increased due to increased scattering of the signal from the bodywork. This was corrected by correct phasing of the feed cables at each frequency.

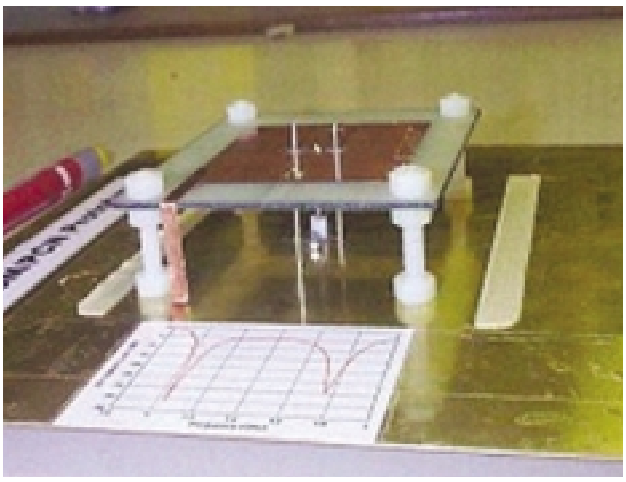


Fig. 12 Dual-band, 900/1800 MHz, hybrid antenna

Hybrid antenna

The antenna shown in Fig. 12 is a design based on the top-loaded monopole principle[6], in which an upper, 'patch' plate, to which the feed is connected, is shorted to a ground plane by a pair of pins that are strategically placed to tune the antenna to the 900 MHz band. (To a first approximation the pins can be regarded as inductances that form parallel resonant circuits with the capacitor formed by the parallel plates.) Two more pins pass through two 6 × 6 mm square clearance holes on the patch surface and extend beyond it. The holes are located at 5·5 mm from the centre of the patch. This second pair provide the DCS (Digital Cellular System) 1800 MHz operation. All pins are 1·2 mm in diameter. The upper patch is 56 mm square and is low profile, just 15 mm above the ground plane. Fig.13 shows the computed current distribution at the 1800 MHz band. The two pins protruding above the upper plate are responsible for the radiation at this band, see Fig.13, while the shorting pins together with the feed are responsible for the radiation at the lower band. The DCS-1800 band can be fine-tuned by adjusting the length of the corresponding pins. The GSM (Global System for Mobile) 900 MHz band remains unaffected from any change in the pin length.

The maximum return loss for the GSM band is −26 dB at

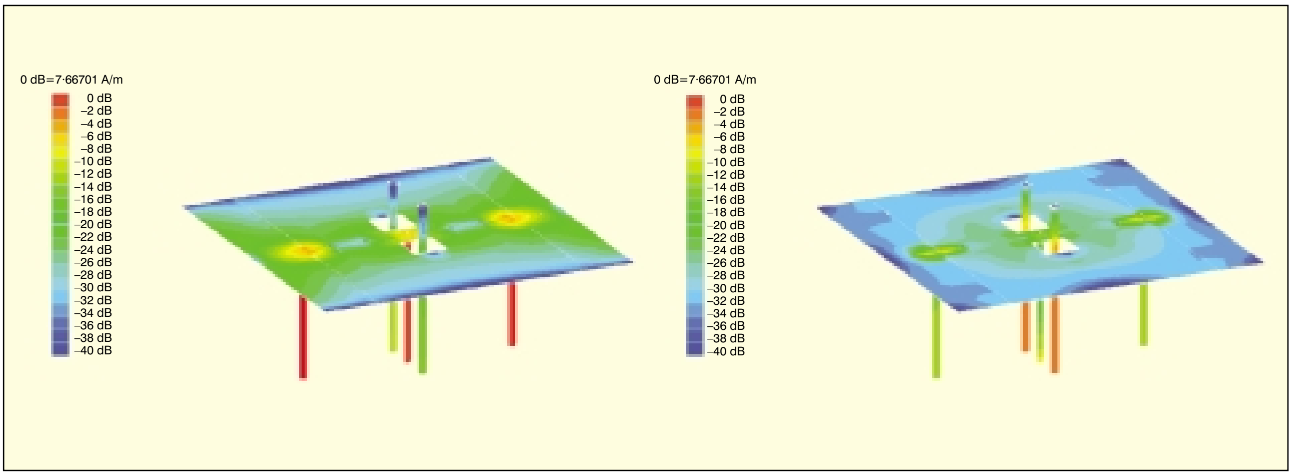


Fig.13 The left hand diagram represents current distribution in the lower band of operation, the right hand side represents the upper band.

0·925 GHz and for the DCS band is –27 dB at 1·785 GHz. The corresponding bandwidths are 90 MHz and 170 MHz, respectively. Fig. 14 shows the typical azimuth radiation pattern measured when the antenna is placed under and at the top of the rear screen (i.e. inside the vehicle, just below the roof) with the antenna earthed to the roof. It is compared with a roof-mounted monopole. The radiation to the rear of the car is slightly enhanced while that at the front is reduced when compared to the monopole (see Fig. 14).

In further work we have measured the radiation patterns (Fig. 15) for antennas situated about 10 mm below a plastic panel in the roofline of a vehicle. In this case a sample set of DAB (Digital Audio Broadcasting) antennas were measured that had the same hybrid antenna geometry as that described above. These patterns were measured at 10° intervals rather than continuously, hence the irregular plots. The monopole was not symmetrically mounted on the roof of the vehicle and hence its radiation pattern was not quite round. The hybrid antenna, hidden below the roofline, gave on average a performance that was within 2 dB of that of the roof-mounted monopole. This result illustrates that it is possible to get good performance from hidden antennas below the roofline. In years to come many vehicles are expected to have composite roof and body panels.

4 Conclusions

This paper has presented results for hidden antennas that can be placed on glass or under plastic panels on a car to provide reception at radio and telephone frequency bands.

The effects of the car body on antennas printed on glass have been investigated and we have concluded that it is the slope of the screen together with the relative positions of the various roof supports that has the dominant effect on the radiation patterns. The roof pillars tend to introduce deep nulls that are characteristically seen at azimuthal angles of ±60°. Interestingly, the door pillars can alleviate the nulling and it will be worthwhile assessing the effect of fabricating more body parts from lightweight non-conducting materials in the future. Our results show that on-car antennas can be modelled satisfactorily using simplified structures, provided that adequate meshing is used and that the physical areas of the roof-supporting structures are represented in the model. Finally, as expected, the ground plane must be included and a model able to include the dielectric of the glass would be essential if correct input impedances are to be obtained.

A wide-bandwidth dual-band PIFA antenna has been presented and its basic properties discussed. Based on information from modelling the currents, this PIFA antenna has been modified by removing metallic areas where the current flow is low. This improves the operating bandwidth. Using two antennas, placed at the corners of the bumpers, all-round coverage can be obtained with this antenna type.

A hybrid telephone antenna has also been described. This gives omnidirectional radiation patterns in azimuth

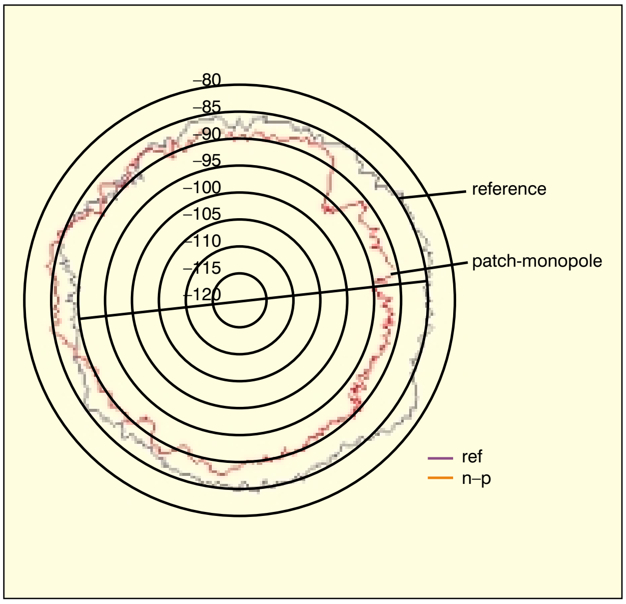


Fig. 14 Polar azimuth radiation pattern of the hybrid antenna at 900 MHz when the antenna is mounted at the top of the rear screen. The reference is a roof-mounted monopole.

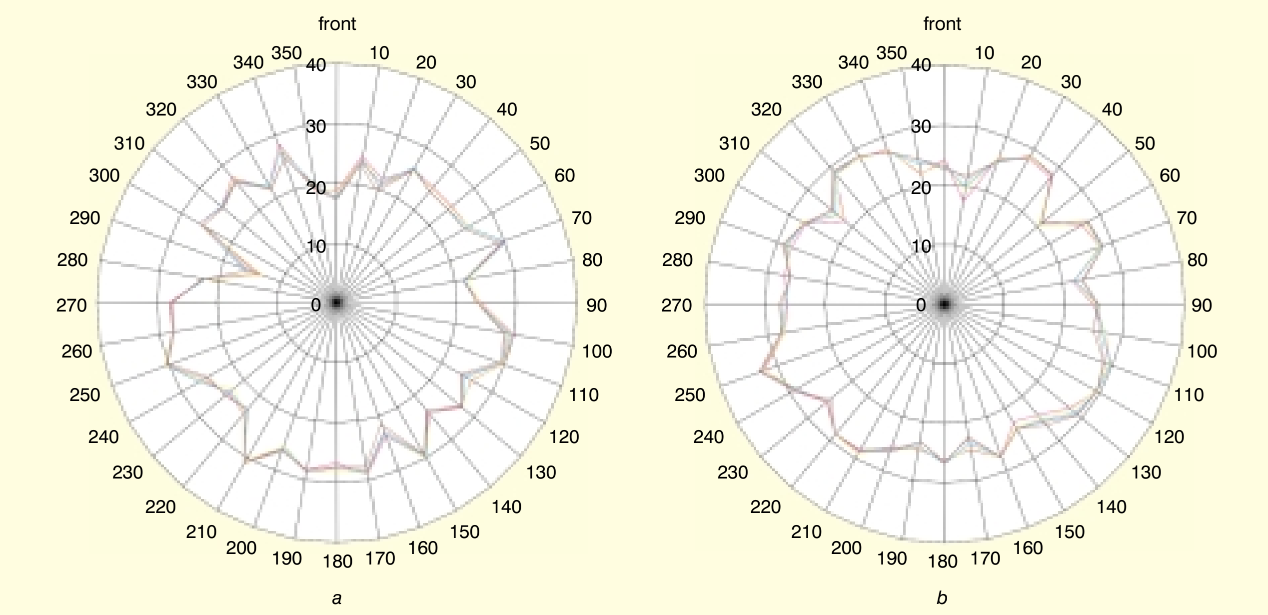


Fig. 15 (*a*) Radiation pattern at 1470 MHz of the hybrid antenna when mounted below a plastic roof panel; (*b*) radiation pattern at 1470 MHz of a roof-mounted monopole. The different lines represent a set of plots for the same antenna, i.e. an average effect is obtained.

while providing wide bandwidths at two frequency bands: 900 and 1800 MHz. This antenna has a low profile. When roof mounted or hidden under a plastic panel there is little degradation in its performance.

Acknowledgments

The authors thank the UK Engineering and Physical Sciences Research Council, the Department of Trade and Industry, Harada Industries Europe, Nissan Europe and Rover Group for support.

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Received 17th May 2002

John Batchelor graduated from the University of Kent in 1991 with a BSc degree in Communication Engineering. He obtained a PhD degree in Higher Mode Microstrip Antennas in 1995. After working as a Research Fellow, he was appointed as a Lecturer at the University of Kent in 1997. His research interests include on-glass antenna modelling for vehicular systems, genetic algorithm design of convoluted radiating elements, electromagnetic bandgap structures, and microstrip antennas on ferrite substrates. He has acted as a consultant to Harada Industries since 1998.

Address: Department of Electronics, The University of Kent, Canterbury, Kent, CT2 7NT, UK
E-mail: j.c.batchelor@ukc.ac.uk

Richard Langley has had a long career in antenna systems in both academia and industry. He is currently Professor of Antenna Systems at the University of Kent. For many years he did research on frequency-selective surfaces, applying them in the satellite and defence fields. This led to his current interest in electromagnetic bandgap materials. His interests have also expanded into printed and microstrip antennas for mobile applications especially for use in vehicle antennas. In 1997 he founded the European Technology Centre for Harada Industries Japan, the world's leading vehicle antenna systems manufacturer. He was Director of the Centre until recently when he returned to academic life. Richard is joint Honorary Editor for *IEE Proceedings Microwaves, Antennas and Propagation*.

Address: Department of Electronics, The University of Kent, Canterbury, Kent, CT2 7NT, UK
E-mail: r.j.langley@ukc.ac.uk