Fabrication and Characterization of Micromachined Rectangular Waveguide Components for Use at Millimeter-Wave and Terahertz Frequencies

John W. Digby, *Associate Member, IEEE*, Caroline E. McIntosh, *Member, IEEE*, Geoff M. Parkhurst, Brian M. Towlson, Silas Hadjiloucas, *Member, IEEE*, John W. Bowen, J. Martyn Chamberlain, *Member, IEEE*, Roger D. Pollard, *Fellow, IEEE*, Robert E. Miles, *Member, IEEE*, D. Paul Steenson, *Member, IEEE*, Lucas S. Karatzas, *Member, IEEE*, Nigel J. Cronin, and Steve R. Davies

***Abstract*—The fabrication and characterization of micromachined reduced-height air-filled rectangular waveguide components suitable for integration is reported in this paper. The lithographic technique used permits structures with heights of up to 100 μm to be successfully constructed in a repeatable manner. Waveguide S-parameter measurements at frequencies between 75–110 GHz using a vector network analyzer demonstrate low loss propagation in the TE_{10} mode reaching 0.2 dB per wavelength. Scanning electron microscope photographs of conventional and micromachined waveguides show that the fabrication technique can provide a superior surface finish than possible with commercially available components. In order to circumvent problems in efficiently coupling free-space propagating beams to the reduced-height G-band waveguides, as well as to characterize them using quasi-optical techniques, a novel integrated micromachined slotted horn antenna has been designed and fabricated. E-, H-, and D-plane far-field antenna pattern measurements at different frequencies using a quasi-optical setup show that the fabricated structures are optimized for 180-GHz operation with an E-plane half-power beamwidth of 32° elevated 35° above the substrate, a symmetrical H-plane pattern with a half-power beamwidth of 23° and a maximum D-plane cross-polar level of −33 dB. Far-field pattern simulations using HFSS show good agreement with experimental results.**

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J. W. Digby was with the School of Physics and Astronomy, The University of Nottingham, Nottingham NG7 2RD, U.K. He is now with One-2-One Personal Communications Ltd., Sunbury on Thames TW16 7DX, U.K.

C. E. McIntosh was with the Institute of Microwaves and Photonics, School of Electronic and Electrical Engineering, The University of Leeds, Leeds LS2 9JT, U.K. She is now with Raytheon RF Components, Andover, MA 02421 USA.

G. M. Parkhurst is with the School of Physics and Astronomy, The University of Nottingham, Nottingham NG7 2RD, U.K.

B. M. Towlson was with the Department of Cybernetics, The University of Reading, Reading RG6 6AY, U.K. He is now with the School of Electrical and Electronic Engineering, University of Nottingham, Nottingham NG7 2RD, U.K.

S. Hadjiloucas, J. W. Bowen, and L. S. Karatzas are with the Department of Cybernetics, The University of Reading, Reading RG6 6AY, U.K.

J. M. Chamberlain, R. D. Pollard, R. E. Miles, and D. P. Steenson are with the Institute of Microwaves and Photonics, School of Electronic and Electrical Engineering, The University of Leeds, Leeds LS2 9JT, U.K.

N. J. Cronin and S. R. Davies are with the School of Physics, University of Bath, Bath BA2 7AY, U.K.

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I. Introduction

RECENT applications of terahertz radiation in diverse areas such as imaging and surveillance, astronomy, plasma diagnostics, spectroscopy for chemistry, biology and medicine, combined with the ever greater bandwidth requirements of communications and the possibility of developing radars with greater resolution and reduced clutter indicate a need for low-cost terahertz technology with integrated subsystems [1]. Until recently, the absence of convenient solid-state sources and the lack of such low-cost technology for the fabrication of passive components has prevented progress in building complete systems with commercial potential that operate in this frequency range. This paper describes the use of lithographic technology to fabricate waveguide passive components and describes the measurement techniques necessary for their characterization.

As the frequency of operation of conventional rectangular waveguide approaches millimeter-wave and terahertz frequencies, the physical dimensions of the components decrease and "watchmaker" levels of precision are required for their manufacture by conventional methods. Although some progress has been made in the development of alternative transmission lines at these frequencies [2], these can be difficult to integrate with active devices, which effectively precludes mass production of components for commercial purposes. An alternative to the traditional method of machining very high-frequency rectangular waveguide components is to exploit the use of lithographic techniques for micromachining. The concept of micromachined integrated transmission-line components was first introduced by Cronin *et al.* [3], [4] who demonstrated a waveguide for operation at 600 GHz. The technique has the added advantage that active devices can be incorporated directly onto a semiconductor substrate to facilitate low-cost integrated circuit production [5]. Such components could eventually lead to the fabrication of integrated circuits at terahertz frequencies, and applications already exist at millimeter-wave frequencies, which would benefit from the introduction of this technology. There do not appear to be any other references to this approach, although it is noted that the use of dielectric-filled (polyimide) waveguide has also been reported [6] at 100 GHz, but with very substantial mismatches and loss.

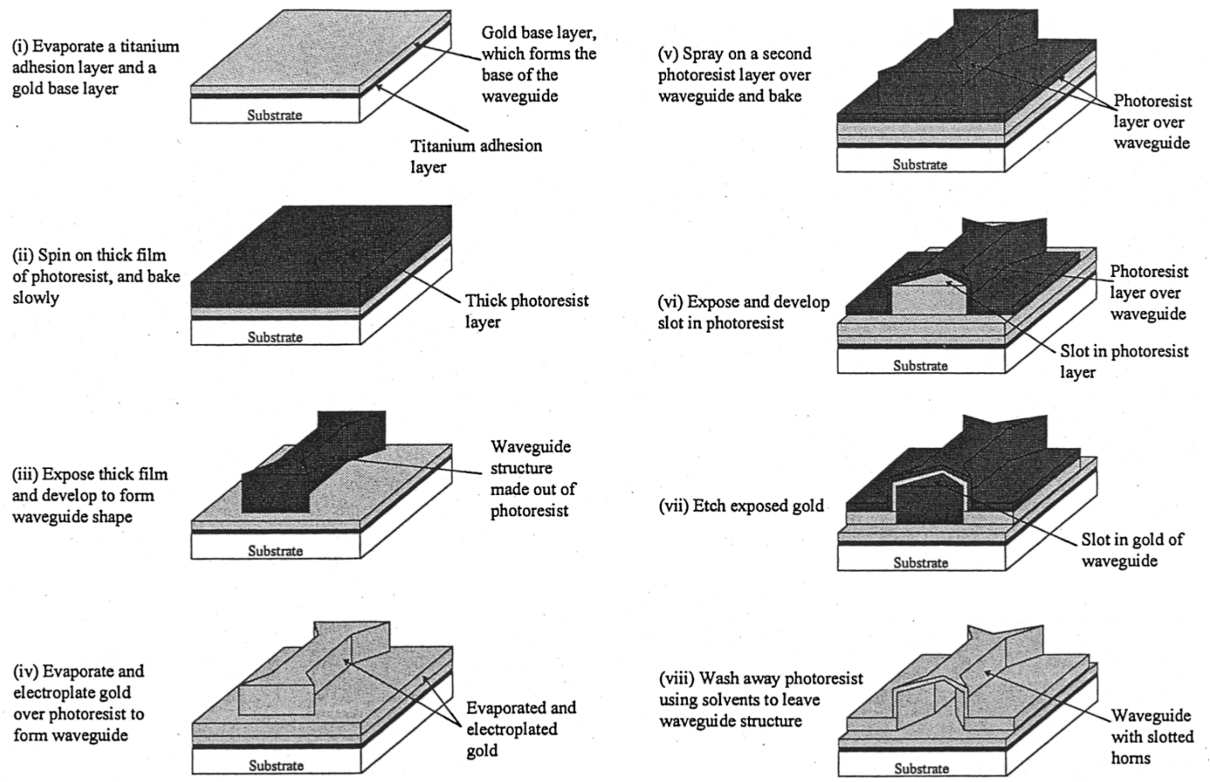

Fig. 1. Fabrication of G-band waveguide with slotted horn antennas using micromachining techniques.

In this paper, we describe the fabrication procedure for micromachined waveguides using a lithographic technique. The fundamental problem with S-parameter measurements of these micromachined waveguides is the difficulty of repeatable power coupling into, and out of, the on-chip waveguides. Consequently, a special gradually tapered test fixture has been constructed, minimizing the mismatch at the ports of the micromachined waveguide and providing direct connection capability into conventional waveguide. We present S-parameter attenuation measurements using this test fixture coupled to a Hewlett-Packard HP8510C W-band vector network analyzer (VNA) operating between 75–110 GHz. In order to efficiently couple a free-space propagating beam to on-chip rectangular waveguides and to demonstrate the ability of the lithographic technique in integrating passive components, suitable antennas had to be designed. Since the fabrication of a horn in the E-plane is impossible in this planar technology [7], an integrated micromachined slotted H-plane horn antenna has been fabricated for use at G-band (140–220 GHz). The antenna pattern has been simulated using a three-dimensional (3-D) electromagnetic-field solver (Hewlett-Packard's and Ansoft's HFSS) and the results compared with far-field measurements [8]. The present approach to the design of antennas is a novel one [7], and complements other significant efforts toward the design of submillimeter-wave integrated antennas, offering the possibility of exploiting the large bandwidths available [9] for future terahertz communications systems.

II. Fabrication of Waveguide Components Using Lithographic Micromachining

The lithographic micromachining fabrication process is summarized in Fig. 1. To construct waveguides and integrated horn antennas, an initial layer of titanium (30 nm), followed by a layer of gold (with thickness greater than one skin depth at the cutoff frequency) is evaporated onto the substrate to form the bottom wall of the waveguide and horn [see Fig. 1(i)]. A 100-μm-thick layer of photoresist is then spun on top of this gold layer and baked slowly [see Fig. 1(ii)]. This photoresist layer is exposed and developed to define the shape of the waveguide and horn structures [see Fig. 1(iii)], and another layer of gold is evaporated over the photoresist former, which is then electroplated for extra strength [see Fig. 1(iv)]. To create the slotted horn antennas a thin layer of photoresist is sprayed over the whole structure and baked [see Fig. 1(v)]. This new resist layer is exposed and developed using a second mask, with alignment marks, to reveal accurately a slot in the top of the resist [see Fig. 1(vi)]. The exposed gold is etched away to produce a slot in the top of the horn antenna [see Fig. 1(vii)]. Removal of all the photoresist with solvents leaves an air-filled rectangular waveguide integrated with a slotted horn antenna [see Fig. 1(viii)]. A photograph of a waveguide with an integrated antenna at each end produced using this technique is shown in Fig. 2.

The micromachined waveguides for S-parameter characterization were produced using the process described above up the stage shown in Fig. 1(iv). Any semiconductor wafer protruding

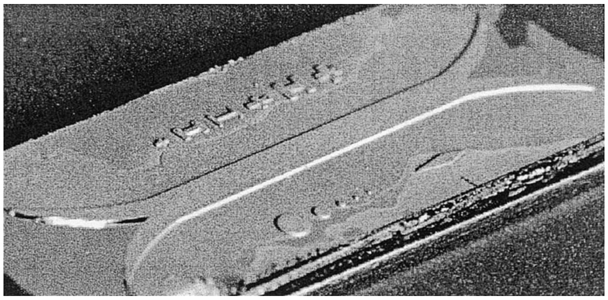

Fig. 2. Photograph of micromachined waveguide with antennas.

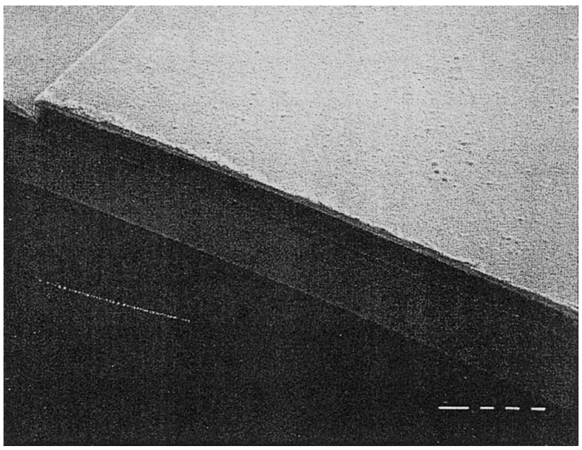

Fig. 3. SEM photograph of the end of a micromachined waveguide.

in front of the waveguides is then removed by filing away the wafer parallel to the open ends of the waveguides. Finally, the photoresist is removed using solvents, leaving an air-filled rectangular waveguide with open ends at the edge of the semiconductor wafer. A scanning electron microscope (SEM) photograph of one of the ends of such a waveguide is shown in Fig. 3. This manual filing procedure is only required for waveguide characterization purposes using a network analyzer and can be obviated if a suitable antenna that permits quasi-optical characterization is integrated at the end of the waveguide structure.

The use of a lithographic procedure results in the quality of the waveguide interior walls being determined by the resist surface quality, which proves to be far superior to that of conventionally machined guide. Fig. 4 compares the inside walls of a micromachined and a commercially available W-band waveguide. It can be observed that the micromachined waveguide has no obvious features greater than 1 μm in size. Although such excellent surface finish implies a very low-loss performance for full height micromachined waveguides, the height limitations imposed by the type of resist currently used restrict the investigations to reduced height guide, which has an intrinsically greater attenuation than the full-height guide. Recent advances in resist technology indicate that the fabrication of full-height waveguide will soon be possible at 200 GHz. 700-μm-high structures fabricated with SU-8 photoresist [10] have already been produced in one of our laboratories [11], showing its potential in constructing taller structures with high aspect ratios. This is of importance as more complex structures

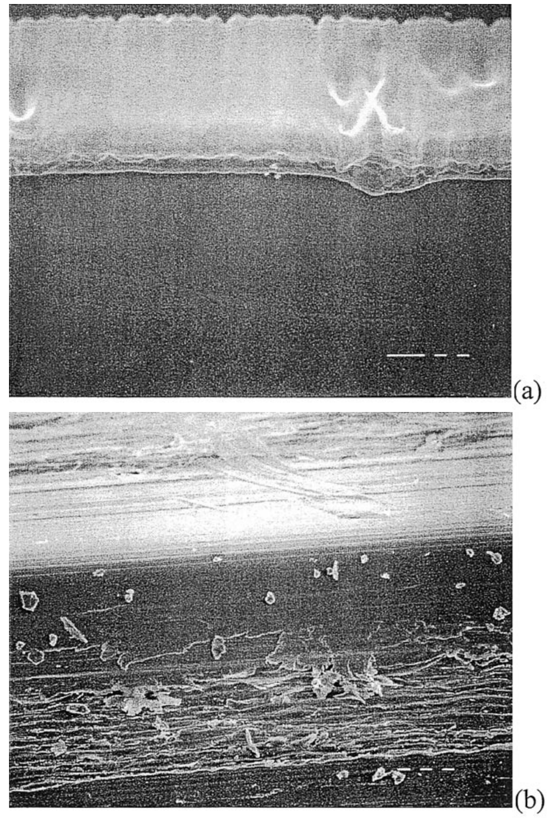

Fig. 4. SEM photograph showing inside wall quality of: (a) micromachined and (b) conventionally available waveguide.

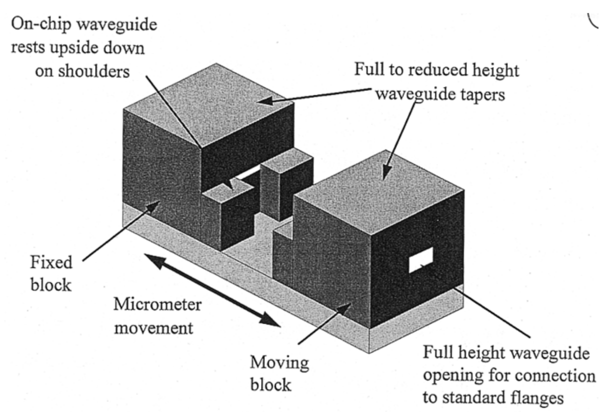

Fig. 5. W-band test fixture.

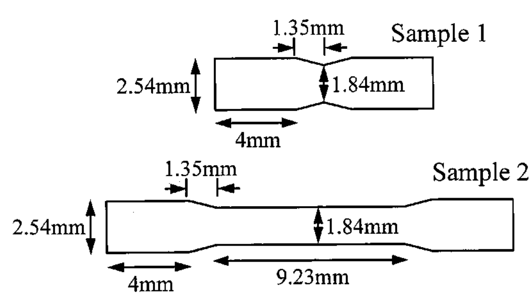

Fig. 6. W-band waveguide samples.

(e.g., cylindrical cavities) might have to be produced and integrated with waveguides in the future.

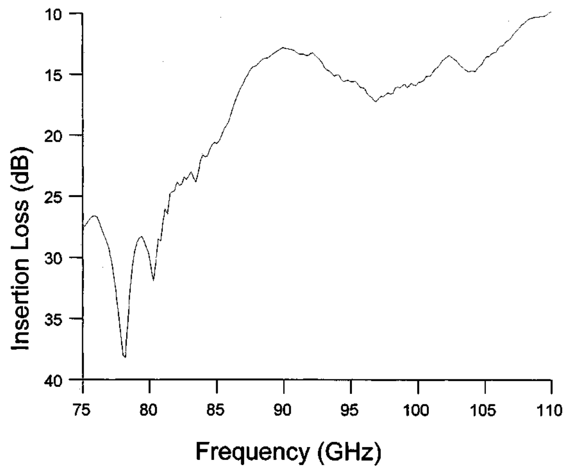

Fig. 7. Measured insertion loss of: (a) sample 1 and (b) 2. Measured insertion loss includes the test fixture insertion loss.

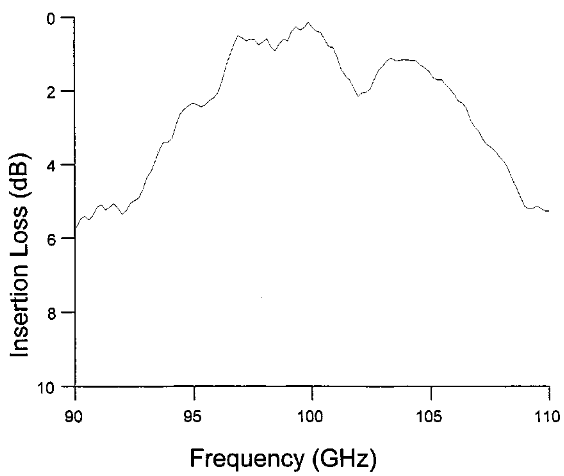

Fig. 8. Measured attenuation of 9.23-mm length of 1.84-mm-wide waveguide.

III. S-Parameter Measurements of Micromachined Waveguides

A. Test Fixture Design and Micromachined Waveguide Samples

A major consideration in the design of the test fixture was the alignment of the micromachined waveguides with those in the test fixture itself. It is desirable that such a test fixture should enable the delicate micromachined structure to be inserted in a repeatable manner so that the openings coincide exactly each time a sample is inserted. The solution adopted was to construct, by conventional machining, two sections of tapered W-band waveguide, starting at full height (for connection to the VNA ports) and ending in reduced height (for connection to the micromachined waveguide). An additional feature of this design was that shoulders protruded from the reduced height sides of these transition sections to support the delicate micromachined structure under test (Fig. 5).

The only reference position available on a sample of micromachined waveguide is given by the plane of the substrate. This substrate rests upside down on the test fixture shoulders so that the waveguide lies in the gap in between, therefore, the vertical

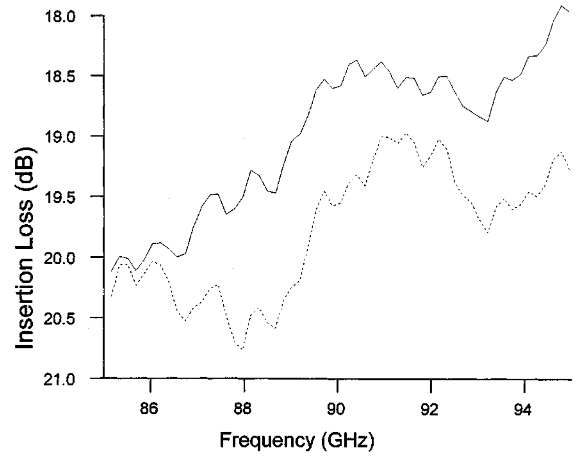

Fig. 9. Difference in insertion loss measurements on sample 2.

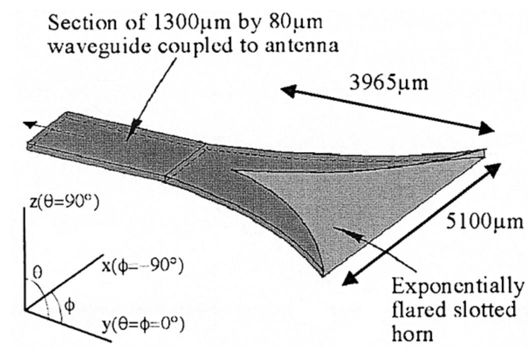

Fig. 10. Integrated antenna design.

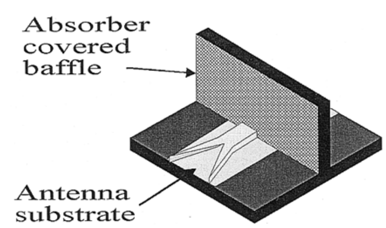

Fig. 11. Micromachined antenna mounting for far-field measurements.

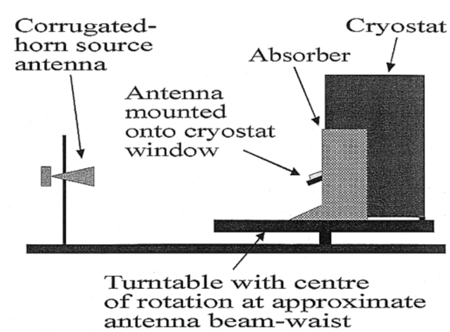

Fig. 12. Experimental setup for far-field measurements on the integrated horn antenna.

position of the waveguide is known exactly. This gap is machined to allow a comfortable fit, taking into account the thickness of the gold sidewalls of the guide, so that the waveguides are aligned always horizontally. Once the sample is inserted, the two tapered waveguides in the test fixture are moved together by

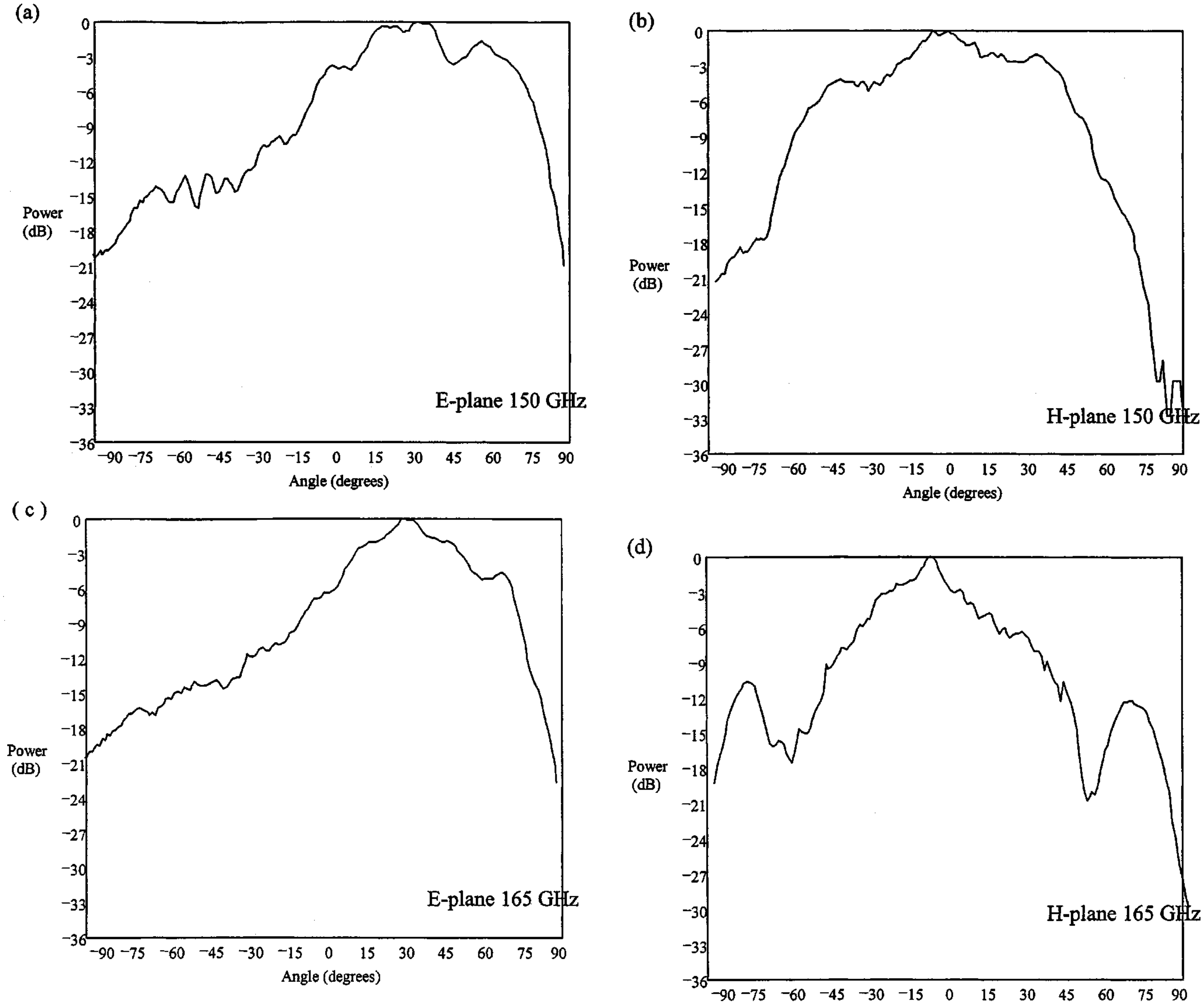

Fig. 13. Measured (continuous line) and simulated (dashed line) E-plane and corresponding H-plane co-polar far-field patterns for the integrated antenna at 150, 165, 180, and 197 GHz.

means of a micrometer screw until they are touching the sample, resulting in a repeatable connection.

Two waveguides of different lengths were fabricated for characterization purposes (Fig. 6). Both samples have a 4-mm length of 2.54-mm-wide waveguide at the ports, which then gradually tapers down to a width of 1.84 mm. The second sample was constructed with an additional 9.23 mm ($1.5\lambda_g$ at 95 GHz) length of 1.84-mm-wide waveguide between the two tapers. This waveguide width was chosen as it has a cutoff frequency of 81.5 GHz enabling a TE_{10} attenuation characteristic to be demonstrated in the measurement frequency range.

B. Measured Results

Attenuation measurements were performed using an HP8510C VNA operating at W-band (75–110 GHz). A thru-reflect-line (TRL) calibration [12] procedure was performed at the instrument waveguide test ports. The test fixture was then connected between the test ports and the samples inserted one at a time. The measured insertion loss of the two samples (plus the aluminum waveguide tapers in the test fixture) is shown in Fig. 7. The residual leakage between the ports is much less than -40 dB. The results show the characteristic shape expected from a waveguide close to its cutoff frequency (81.5 GHz) as well as TE_{10} mode propagation. Using standard formulas [13], theoretical calculations for air-filled gold-plated reduced-height rectangular waveguides operated in their TE_{10} mode were performed, showing an attenuation between 0.5–0.34 dB over a length of 9.23 mm in the 90–110-GHz frequency range. Subtracting the experimental attenuation between the two samples to account for the extra 9.23-mm length (Fig. 8), a measured attenuation between 0.2–5 dB is observed.

Discrepancies between theoretical and measured attenuation are mainly attributed to mismatches caused by the difficulty in filing the wafer accurately to the edge of the waveguide samples. Some additional loss may occur because the bottom wall of the waveguide has a thickness of only one skin depth. This could be improved by evaporating a thicker layer of gold onto the substrate before spinning on the photoresist, and is not a problem at higher frequencies where the skin depth is smaller. The measured attenuation is, however, significantly lower

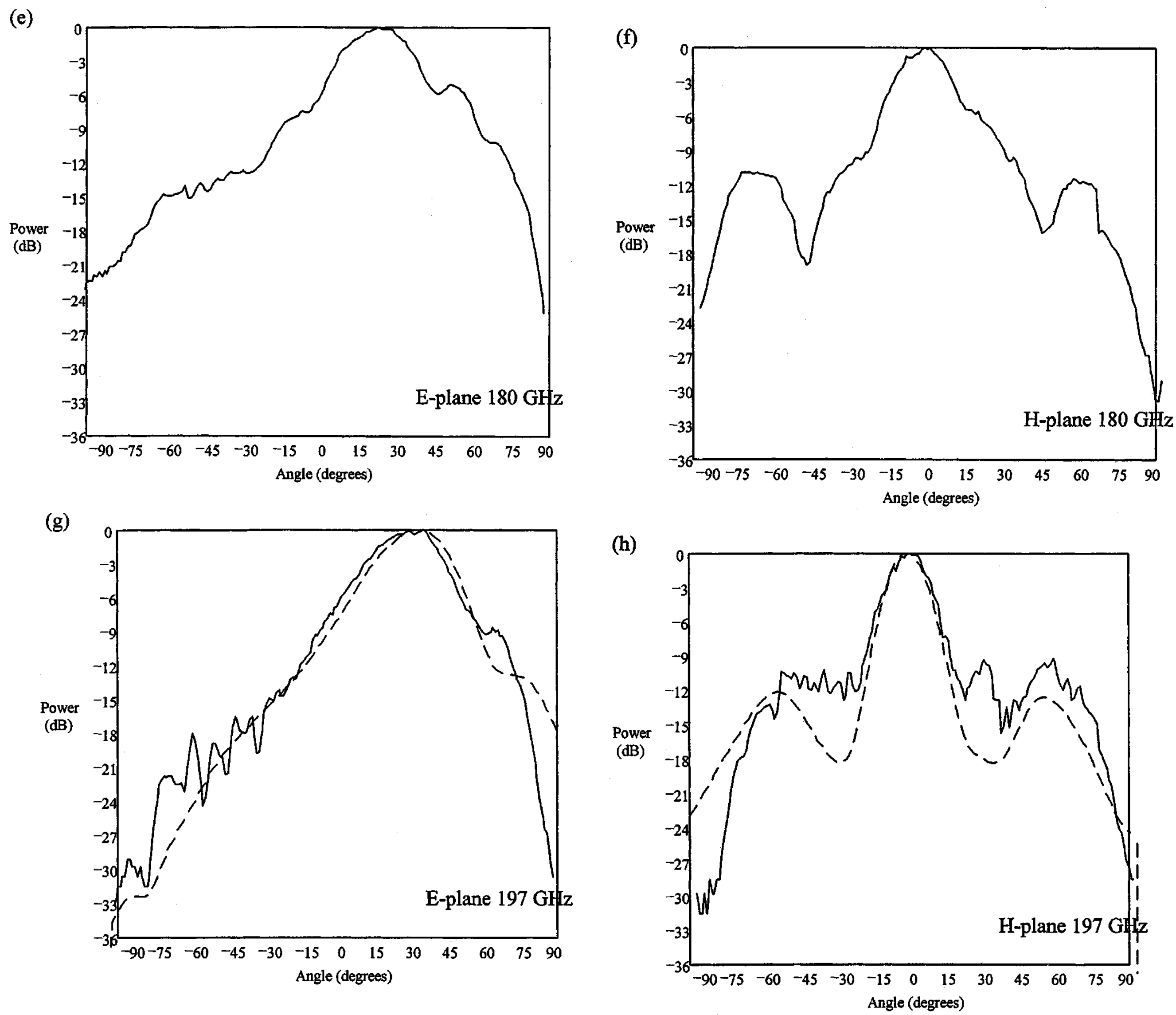

Fig. 13. *(Continued.)* Measured (continuous line) and simulated (dashed line) E-plane and corresponding H-plane co-polar far-field patterns for the integrated antenna at 150, 165, 180, and 197 GHz.

than for previously reported on-chip waveguide [6]. Fig. 9 shows two separate insertion-loss measurements performed on the same sample, showing an insertion loss repeatability of approximately ±0.5 dB.

IV. Micromachined Integrated Antenna

The underlying design philosophy of the present fabrication technique is to avoid the use of mechanical connections wherever possible and to rely on lithographic methods of component construction. However, owing to the limitations imposed by the height of the photoresist former, it is only possible to produce a reduced-height waveguide horn flared in the H-plane. This limitation has a significant effect on the beam shape in the E-plane, notably poorer directive gain. The cutting of a tapered slot from the upper surface of a basic H-plane sectoral horn results in a design that does not suffer the disadvantage of a restricted aperture height. Although the slot allows the E-field to extend beyond the confines of the waveguide, as long as the slot is narrow enough, elements of this extended field in close proximity to one another are in antiphase, and no beam is radiated. As the slot is widened, components opposing those welling up from the slot become more diffuse, thus, the latter tends to dominate. Thus, radiation will eventually occur. Since the E-field distribution has been broadened beyond the height of the aperture, the launched beam should display a reduced E-plane beamwidth. Though this beam is astigmatic, adjustment of the horn parameters (flare angle, aperture width, slot angle, and position of the slot apex relative to the start of the horn flare) should make it possible to produce a pattern with similar E- and H-plane beamwidths. Preliminary far-field tests on slotted horns with different design parameters were carried out using X-band scale models and measured using a microwave antenna range [14]. The principal planes of the co-polar amplitude measurements, without ground plane, agreed well with HFSS simulation results, especially in terms of the main lobe elevation, 3-dB widths, and first sidelobe position and level. The cross-polar measurements showed peak

TABLE I
SUMMARY OF THE 180-GHz PROTOTYPE MEASUREMENTS (SL = PEAK SIDELOBE LEVEL, XL = PEAK CROSS-POLAR LEVEL)

Frequency	*E*-plane			*H*-plane			*D*-plane		
	θ_{3dB}	SL	XL	θ_{3dB}	SL	XL	θ_{3dB}	SL	XL
149.8 GHz	53°	-4 dB	-	59°	-4 dB	-	-	-	-8 dB
164.8 GHz	40°	-5 dB	-	29°	-7 dB	-	-	-	-7 dB
180.4 GHz	32°	-6 dB	-11 dB	23°	-11 dB	-7dB	25°	-12 dB	-12 dB
197 GHz	35°	-10 dB	-18 dB	18°	-9 dB	-14dB	14°	-12 dB	-7 dB
Simulation	34°	-10 dB	-	17°	-8 dB	-	-	-	-

levels of −8 dB, indicating that the design is fairly well linearly polarized, and thus would be useful in applications where this is an issue. The addition of the ground plane gave little effect, a marginal broadening in the E-plane, and perhaps a slight narrowing in the H-plane, of the main lobe, together with slightly reduced sidelobes and increased cross-polar levels. The marginal quality of these effects shows that the presence of a substrate in the final micromachined antenna should have no major detrimental effect on its performance. An S_{11} of 0.013 (−19 dB) corresponding to a VSWR of 1.03 (0.12 dB) was measured by pointing the antenna at a sheet of absorber material, and measuring the reflected wave amplitude from the horn, as the frequency was swept across the available range. Simulation results showed an S_{11} of 0.029, (−15 dB). This compares favorably with that of existing antenna designs—e.g., the corrugated horn with a VSWR of at least 1.1 or the family of end-firing tapered slot antennas, with VSWR's of 1.4–1.7—indicating that the slotted horn provides a good coupling to free space. A number of simulations were run in order to optimize the slotted horn design for full height waveguide. Once an adequate antenna design for full height waveguide was available, attention was turned to developing the same for the eighth height guide to be used at the lower frequency ranges. HFSS simulations showed that simply using the full height design at reduced height gave a beam that was unacceptably broad, and multilobed, in both planes. A variation on the slotted horn, where both the horn and slot were exponentially rather than linearly flared (Fig. 10) provided the best far-field antenna pattern at G-band. By fabricating two such integrated antennas with a connecting length of micromachined waveguide, a suitable structure was created for far-field pattern measurements using a quasi-optical measurement system. A number of these 180-GHz eighth height structures were fabricated for testing. These were baffled in position in front of the cryostat window of a [4] He-cooled cyclotron-enhanced InSb hot-electron bolometer detector, using Al tape and silver epoxy to provide a radiation tight seal around the middle section of waveguide (Fig. 11). Absorber material was then placed around the baffle and on the surroundings in order to cut out any stray reflections. For H-plane measurements, a bracket was designed to hold the antenna at such an angle as to direct the main lobe horizontally toward the source's beam waist. A tunable (125–197 GHz) backward wave oscillator (BWO) square wave modulated at 5 kHz and fitted with a conical horn served as a source. The detector output was amplified and demodulated using a phase sensitive detector (PSD).

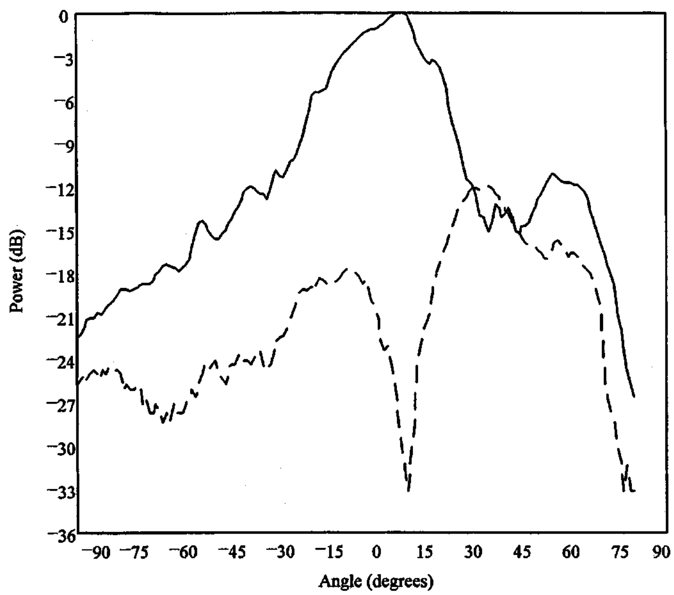

Fig. 14. Measured 45° phi cut co-polar and cross-polar (dashed line) far-field pattern for the integrated antenna at 180 GHz.

The complete test antenna and cryostat structure was rotated using a rotary table in the far-field of the source beam (Fig. 12). For both the H-plane co-polar and E-plane cross-polar measurements, the source signal polarization was rotated 90° by means of a Martin–Puplett interferometer. Co-and cross-polar patterns were measured in the E-, H-, and D-planes (45° phi cut) at 150, 165, 180 and 197 GHz. The antenna had poor directivity at frequencies below 150 GHz.

The E- and H-plane co-polar patterns for all frequencies are given in Fig. 13, and the co- and cross-polar D-plane patterns at 197 GHz in Fig. 14, while the key parameters for all the measurements are summarized in Table I, together with those predicted by the simulations, for comparison. The good agreement between measured and simulated antenna patterns imply that the directivity of 16.45 (12.16 dB) calculated by HFSS should apply to the actual antenna. H-plane patterns were taken at an elevation of 35°, the angle of the main lobe, as observed in the E-plane.

From Table I, a general trend of decreasing beamwidth with increasing frequency can be seen. This is as expected since, with decreasing wavelength, the electrical size of the horn aperture is increased. The useful lower operating frequency limit for the antenna, in terms of radiation characteristics, seems to be about 165 GHz, or maybe a little less since, by 150 GHz, the main lobe has merged with one of the primary sidelobes to give a broad multipeaked pattern. An upper limit will probably be that of the fundamental mode operation of the waveguide, i.e., 230 GHz, since above this, multiple modes will be present, producing unpredictable effects. With minor modification of the design, it is expected that a symmetrical beam pattern with 3-dB widths of less than 30° should be possible.

V. Conclusions

A new fabrication process for millimeter-wave and terahertz rectangular waveguide components has been described and used to produce a range of micromachined reduced-height W- and G-band waveguide structures. Attenuation in the W-band guides has been measured using a VNA in the frequency range from 75 to 110 GHz. To facilitate these measurements, a test fixture has been constructed, which allows repeatable alignment without damage to the on-chip waveguides. The measured cutoff frequency indicates TE_{10} mode propagation. The measured insertion loss of a known length of waveguide is somewhat higher than calculated and this was attributed to mismatch effects and the extreme difficulty in obtaining precisely parallel conditions between the substrate and waveguide ends. Improvements in the fabrication technique resulted in attenuation measurements, which were significantly lower than previously reported (17 dB in [6]) showing losses that are as low as 0.2 dB per wavelength, would be quite acceptable for system applications. Although repeatability in the measurement procedure was reasonable, this could be further improved using etching or laser ablation to remove the excess wafer in front of the waveguide.

In order to efficiently couple power from a free-space propagating beam to reduced-height waveguide structures, a new G-band slotted horn antenna optimized for 180-GHz operation has been designed and fabricated. Antenna pattern measurements show a main peak at 35° and excellent cross-polar response in the D-plane. Good agreement between experimental results and HFSS simulations was seen.

The present lithographic technique is appropriate for the realization of passive waveguide components for use across the entire terahertz frequency range where the present designs may be directly scaled to smaller dimensions. Current effort concentrates in integrating active devices [5] such as resonant tunnel diodes [15] and mixers [16].

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John W. Digby (S'97–A'99) received the B.Sc. degree in physics from Imperial College, London University, London, U.K., in 1995, and the Ph.D. degree from Nottingham University, Nottingham, U.K., in 1999. His doctoral research concerned the construction of an integrated down-converter for operation at 200 GHz.

He then joined Alenia Marconi Systems (Radar Systems), Frimley, U.K., where he was involved with power amplifiers and various other microwave components in the frequency range of 1–60 GHz. He is currently involved with One-2-One Personal Communications Ltd., Sunbury on Thames, U.K. (a U.K. mobile network operator) as a member of the Network Switching Group.

Caroline E. McIntosh (S'94–M'96) was born in Hull, U.K., in 1969. She received the B.Eng. degree (with honors) and the Ph.D. degree from The University of Leeds, Leeds, U.K., in 1991 and 1996, respectively. Her Ph.D. research concerned improving the speed and accuracy of microwave noise figures and noise parameter measurements, with particular emphasis to on-wafer measurements.

From 1995 to 1998, she was a Post-Doctoral Research Fellow in the Institute of Microwaves and Photonics, The University of Leeds, where she was involved with the fabrication and characterization of low-cost micromachined waveguide components for use at millimeter-wave and terahertz frequencies. Since 1998, she has been a Senior Monolithic-Microwave Integrated-Circuit (MMIC) Design Engineer with Raytheon RF Components, Andover, MA, where she is currently involved with the design of millimeter-wave MMIC's for point-to-point radio applications.

Geoff M. Parkhurst received the B.Sc. degree in physics from Nottingham University, Nottingham, U.K., in 1994, and is currently working toward the Ph.D. degree on the fabrication and characterization of low-cost micromachined waveguide components for use at millimeter-wave and terahertz frequencies.

Brian M. Towlson received the B.Sc. degree (with honors) in physics from the University of Manchester, Manchester, U.K., in 1994, and the Ph.D. degree in cybernetics from The University of Reading, Reading, U.K., in 1999 for his research into passive terahertz imaging.

He is currently a Research Associate in the School of Electrical and Electronic Engineering, University of Nottingham, Nottingham, U.K., where he is involved with the application of super-resolution algorithms to optical microscope images.

Silas Hadjiloucas (M'94) was born in Athens, Greece, in 1966. He received the B.Sc. and M.Phil. degrees in pure and applied biology from The University of Leeds, Leeds, U.K., in 1989 and 1992, respectively, and the Ph.D. degree in cybernetics from The University of Reading, Reading, U.K., in 1996.

Since October 1997, he has been an EC Training and Mobility of Researchers (TMR) Post-Doctoral Research Fellow involved with terahertz instrumentation as part of the International Terahertz Action (INTERACT) Project at The University of Reading and DLR Berlin. In January 2000, he was appointed a Lecturer in the Department of Cybernetics, The University of Reading. He has authored or co-authored several papers relate to feedback, instrumentation, optics, biology, and terahertz measurement techniques.

Dr. Hadjiloucas is a member of the Institute of Biology, the Institute of Measurement and Control, the Institute of Physics, and the Optical Society of America.

John W. Bowen was born in Malvern, Worcestershire, U.K., in 1963. He received the degree in physics from Queen Mary College, University of London, London, U.K., in 1985, and the Ph.D. degree from the University of London, in 1993, for research into techniques for wide-band millimeter-wave spectrometry

He has been a consultant for QMC Instruments Ltd., and a Research Associate at Queen Mary and Westfield College, University of London. Since 1993, he has been a Lecturer in the Department of Cybernetics, The University of Reading, Reading, U.K., where he heads the Instrumentation and Signal Processing Research Group. His research interests include quasi-optical systems design, millimeter and submillimeter-wave spectrometry and device characterization, solid-state noise sources, and terahertz antennas.

Dr. Bowen is a member of the Europe-wide EC-funded International Terahertz Action (INTERACT) network. He was awarded the 1989 U.K. National Physical Laboratory Metrology Award for his suggestion for a new wide-band solid-state noise source for millimeter-wave spectrometry.

J. Martyn Chamberlain (M'97) received the D.Phil. degree from Oxford University, Oxford, U.K., in 1972.

From 1972 to 199, he was a Lecturer, Senior Lecturer, and Reader in experimental physics at the University of Nottingham, Nottingham, U.K. He is currently a Professor of engineering physics in the Institute of Microwaves and Photonics, School of Electronic and Electrical Engineering, The University of Leeds, Leeds, U.K. His research background is in terahertz-frequency investigations of electron transport phenomena in low-dimensional systems and devices, realization of compact terahertz frequency active devices, including novel semiconductor devices (both electronic and optical), and small-scale vacuum electronics. He has contributed to U.K. programs in the application of micromachining for terahertz applications. He has recently become involved in all-optical terahertz generation techniques and coordinates a large European program in that area. He has authored or co-authored approximately 130 papers, edited two books, and holds two patents.

Roger D. Pollard (M'77–SM'91–F'97) was born in London, U.K., in 1946. He received the B.Sc. and Ph.D. degrees in electrical and electronic engineering from The University of Leeds, Leeds, U.K.

He holds the Agilent Technologies Chair in High Frequency Measurements and is Head of the School of Electronic and Electrical Engineering, The University of Leeds, where he has been a faculty member since 1974. He is an active member of the Institute of Microwaves and Photonics (one of the constituent parts of the school), which has over 40 active researchers, a strong graduate program, and has made contributions to microwave passive and active device research. The activity has significant industrial collaboration as well as a presence in continuing education. His personal research interests are in microwave network measurements, calibration and error correction, microwave and millimeter-wave circuits, terahertz technology, and large-signal and nonlinear characterization. He has been a consultant to Agilent Technologies (previously Hewlett-Packard Company), Santa Rosa, CA, since 1981. He has authored or co-authored over 100 technical papers and holds three patents.

Dr. Pollard is a Chartered Engineer and a member of the Institution of Electrical Engineers, (IEE), U.K. He is an active IEEE volunteer, as an elected member of the Administrative Committee and 1998 Past President of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S), and is currently Chair of IEEE's Electronic Products Committee. He is a member of the Editorial Board of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES and has been on the Technical Program Committee for the IEEE MTT-S International Microwave Symposium since 1986. He is also an editor of the IEEE Press RF and Microwave Technology book series.

Robert E. Miles (M'82) was born in Kettering, U.K. He received the B.Sc. and External Ph.D. degrees from Imperial College, London University, London, U.K., in 1964 and 1972, respectively.

From 1964 to 1972, he was a Research Scientist with Zenith Radio Research (U.K.), where he was involved with the surface properties of IV–VI compound semiconductors. In 1982, after a period as a lteacher, he joined the Department of Electronic and Electrical Engineering, The University of Leeds, Leeds, U.K., as a Research Engineer, where he was involved with the problems of ion implantation and device modeling in GaAs. In 1983, he became a Lecturer at the University of Bradford, Bradford, U.K., where he continued his interests in compound semiconductors. In 1985, he rejoined the Institute of Microwaves and Photonics, The University of Leeds, where he is currently a Reader in semiconductor materials and devices.

D. Paul Steenson (M'96) graduated from the University of Manchester Institute of Science and Technology (UMIST), Manchester, U.K., in 1984, and the Ph.D. degree for his study of the high-frequency applications of double-barrier resonant tunnel diodes from Nottingham University, Nottingham, U.K., in 1993. His Ph.D. research focused on the use of these devices in self-oscillating mixers and harmonic multipliers.

In 1984, he joined Philips Microwave and Philips Components, where he was involved in all aspects of the manufacturing diode detectors and mixers in GaAs, germanium, and silicon. Since 1994, he has been a Senior Research Engineer at the Institute of Microwave and Photonics, School of Electronic and Electrical Engineering, The University of Leeds, Leeds, U.K., where he is involved with quasi-optical terahertz techniques, device modeling, and micromachining of components for use at terahertz frequencies.

Lucas S. Karatzas (M'97) was born in Athens, Greece, in 1967. He received the B.Sc. degree (honors) in cybernetics and control engineering with mathematics and the Ph.D. degree for the design and development of an optical force-feedback microphone from The University of Reading, Reading, U.K., in 1990 and 1994, respectively.

From 1994 to 1997, he was a Post-Doctoral Research Fellow in the Department of Cybernetics, University of Reading, as part of the EPSRC-funded Terahertz Integrated Technology Initiative Network (TINTIN). In 1997 and 1998, he was a Lecturer in the Department of Cybernetics. Since completion of his National Service in the Greek Artillery (1998–1999), he has been an EC-funded Training and Mobility of Researchers (TMR) Post-Doctoral Research Fellow, as part of the International Terahertz Action Network (INTERACT). He shares his time between the Department of Physics, University of Bath, Bath, U.K., and the Department of Cybernetics, The University of Reading. His main research interests are instrumentation and measurement techniques, and more specifically, optical sensing devices, lasers, fiber optics, microphones, feedback instruments, quasi-optical systems, millimeter and submillimeter waves, and biological measurements. He has authored or co-authored 35 publications on these topics.

Dr. Karatzas is a member of the Institute of Physics (CPhys MInstP).

Nigel J. Cronin is currently a Professor of medical electronics at the University of Bath, Bath, U.K. His previous research interests have included micromachining and its applications to terahertz technology, development of novel micromachined submillimeter devices, instrumentation for submillimeter-wave radio astronomy, and remote sensing.

Steve R. Davies is currently a Lecturer in the School of Physics, The University of Bath, Bath, U.K. His research interests include micromachining and its applications to terahertz technology, development of novel micromachined submillimetric devices, instrumentation for submillimeter-wave radio astronomy and remote sensing, and development of semiconductor and superconducting detector devices for such applications.