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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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Phil. Trans. R. Soc. Lond. A 1996 **354**, 2425-2433
doi: 10.1098/rsta.1996.0109

Terahertz systems: the demands on devices

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Many potential applications for terahertz technology have been suggested at on time or another. These fall broadly into two categories, those which require the use of terahertz frequencies by their nature and those which are currently being developed at lower frequencies – below 100 GHz, say – but which might benefit from the use of shorter wavelengths were suitable technology available. Prominent among applications in the former category are astronomy and remote sensing. Two examples of satellite radiometer systems currently in the planning stages are MASTER and SOPRANO. The improvements in device technology which would greatly benefit these systems include the provision of a good solid-state local oscillator source capable of delivering at least 1 mW of power. Failing this improvements in the design and efficiency of frequency multipliers would be highly desirable. The development of the SBV may be significant here. As far as the mixer is concerned, apart from reductions in conversion loss and noise temperature improved device mount structures which are more rugged and reproducible than the conventional 'cats whisker' mount are urgently needed. If such mounts can be used for device integration so much the better.

There are specific applications for one-off scientific instruments for a variety of measurement applications. One example is given of a system designed to measure the scattering from a single-particle scatter. These measurements being in the nature of low frequency scale modelling of infrared scattering.

In the millimetre wave region, up to 100 GHz there are several highly commercial applications, in particular high frequency communications and automobile radar. The question is would these be better implemented at higher frequencies were suitable device technology available. The consensus of opinion among works in this field is that there is little advantage in such a move, however, recent advances in the new techniques of micromachining indicate that if, in particular, the source problem could be solved, there may indeed be practical advantages to be gained by the use of shorter wavelengths.

1. Introduction

Many systems applications of terahertz technology have been proposed at one time or another: satellite remote sensing; high resolution radar, e.g. automobile anti-collision radar; astronomy; plasma diagnostics, spectroscopy and other specialized instrumentation; digital communications.

Broadly speaking these fall into two categories, those which have been, or are being, realized at frequencies in the millimetre wave band, below about 100 GHz, and those which, by their nature, are higher frequency applications requiring the use of frequencies above 100 GHz. The most prominent examples from the second category are submillimetre satellite remote sensing and astronomy. In both of these areas there are existing systems requirements which are actively stimulating device related research. The terahertz devices needed for ground based millimetre and submillimetre wave astronomy are very similar to those needed for the high frequency radiometer systems required for remote sensing. For the purpose of this paper, therefore, I will group them together and take as examples two satellite systems currently in the planning stages: MASTER and SOPRANO.

Also above 100 GHz there are existing requirements for certain 'one-off' specialist instruments such as those used in plasma diagnostics and spectroscopy, etc. As an example I shall describe one such instrument, a novel interferometer, which has been constructed to measure the scattering of millimetre waves by a single-particle scatterer. I have chosen this system since it has not been reported in the literature previously and because, although the current version works at 94 GHz, this is an example where the frequency has been limited by the availability of suitable devices. Out of choice the instrument would have been constructed using a shorter wavelength

As far as the more 'mass market' applications are concerned radar and communications have been identified as the most promising possibilities. Here the advantages of working at millimetre wavelengths are clear and well documented: gain, bandwidth and size. There are also atmospheric considerations which can be significant. The windows of relatively low attenuation at 35, 94, 140 and 220 GHz are of particular interest for communications. Regions of high attenuation such as that caused by water vapour absorption are also important For example, in short range communications of the type used in local area networks it is obviously advantageous to work at a frequency at which the range of the signal is limited by atmospheric attenuation. This enables the re-use of channels thereby most effectively using precious bandwidth. In the case of automobile radar systems the size of an antenna which can be mounted in the front grill of a car is obviously limited and yet experiments have demonstrated that a beam half width of about 2° is optimum (Wrong *et al.* 1976). These two factors together indicate that short wavelength is needed. Again the atmospheric conditions are important. Here the most critical factor is the effect of scattering by raindrops (Currie & Brown 1987). This tends to increase as the wavelength is reduced towards the size of a typical drop. Other factors important for an application such as automobile radar are cost and manufactureability.

So far all of the work on communications and radar has been limited to frequencies below 100 GHz. The question is to what degree is this due to a lack of suitable technology at higher frequencies? Given such technology would it automatically follow that a move to shorter wavelengths would follow or are millimetre wave systems optimal for some applications?

As far as the devices themselves are concerned there are several special factors affecting their design and operation which need to be considered at terahertz frequencies. The first consideration is the relationship between the 'device' and the 'circuit'. At microwave frequencies and below it is possible to consider these as two separate entities. The device is mounted into the circuit. At terahertz frequencies it is no longer possible to make this separation. The metal features forming the device structure become a part of overall electromagnetic environment in which the active region is located. Their effect on performance may easily be the dominant factor. Thus the effectiveness of a new device at terahertz frequencies may well be critically effected by its geometry as well as the underlying physical processes involved in the device function.

Another critical factor for terahertz device operation is that of the relationship between the device and the antenna with which it is to operate. At very short wavelengths waveguides are lossy and therefore it is inevitable that any active device will be intimately coupled to an antenna in order that free space propagation can be established as quickly as possible. At the highest frequencies this often means that some form of antenna/waveguide structure will be integrated with the device itself. The number of waveguides and antennas which are suitable for terahertz operation is very limited and therefore if a novel device is of a form which cannot readily be incorporated into one of the known radiating structures it may be of limited use regardless of how good the intrinsic device properties are.

In this paper I intend to discuss several systems applications, some which are clearly terahertz by their very nature and some which are currently working below 100 GHz. For the former I shall describe some of the advances in device technology which are seen as desirable (essential?) to improve on their performance. For the lower frequency systems the question is can a case be made for higher frequency operation and if so what advances in terahertz device technology are required to bring this about. Obviously no clear answers are possible to such a complex question but I hope to raise some of the most relevant issues.

2. Satellite remote sensing

As examples of a terahertz systems I shall consider the MASTER (millimetre wave acquisition for stratosphere/troposphere exchanges research) and SOPRANO (submillimetre observation of processes in the atmosphere noteworthy for ozone) submillimetre wave radiometers. The current specifications of these systems are as shown in table 1. These specifications define the required sensitivity, bandwidth and resolution.

A radiometer of this type is always observing signals which have the characteristics of broadband noise. Such noise can be assigned a temperature which is the temperature of a black-body delivering the same noise power per unit bandwidth. The antenna temperature seen by the radiometer when observing a source (such as the atmosphere) is the equivalent black-body temperature of the power being delivered to the receiver by the antenna. A noisy receiver observing a source which produces an antenna temperature T_{A} gives an output which corresponds to an apparent antenna temperature T given by $T = T_{\mathrm{A}} + T_{\mathrm{N}}$, where T_{N} is the receiver noise temperature. By observing real calibration targets which are as 'black' as possible, fill the antenna beam and are of known temperatures T_{N} can be determined. Once the radiometer noise temperature is known the accuracy with which the temperature of a unknown source can be determined is given by the radiometer equation,

$$\Delta T \geqslant T_{\mathrm{N}}/\sqrt{\beta\tau}.$$

where β is the bandwidth and τ is the time spent observing the source.

Clearly, in a satellite borne system the time which can be spent looking at the source is limited. Also β is limited by the spectral resolution required. Thus to achieve any given accuracy a maximum acceptable value for T_{N} may be calculated.

If a system consists of a sequence of components then the total system noise

Table 1.

band	MASTER	SOPRANO
	spectral range (GHz)	
1	199–207	498.5–505.0
2	296–306	624.5–628.7
3	318–326	951.6–955.4
4	342–348	
	system noise temperature (K)	
1	3500	2500
2	5000	10000
3	5000	18000
4	5000	
	spectral resolution (MHz)	
normal	50	3
high	3	0.3

temperature is given by

$$T_s = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 \times G_2} + \dots,$$

where T_1, G_1 are the noise temperature and gain of the first component, T_2, T_3 are the noise temperature and gain of the second component, etc.

An obvious conclusion from this is that components early on a radiometer should be low noise and have as high a gain as possible.

At present there are no amplifiers available at the frequencies of interest to either MASTER or SOPRANO. All of the radiometers are therefore are of the heterodyne type shown . Here the first component (after the antenna) is a mixer which has loss rather than gain. This is followed by a high gain low noise amplifier. The system noise temperature in this simplified model then becomes

$$T_s \approx T_1 + L \times T_2,$$

where L is the conversion loss of the mixer ($1/G_1$). All other terms are negligible because of the high value of G_2. From this we can see that the noise temperature, and hence the sensitivity of the radiometer is determined principally by the mixer noise temperature, the mixer conversion loss and the IF amplifier noise temperature.

The conversion loss of the mixer is a strongly dependant upon the local oscillator drive power. For any mixer there is an optimum LO power. In the case of a Schottky mixer this is around 1 mW. In my view providing this level of drive presents the greatest challenge to terahertz device technology and is also currently the most limiting factor on what can be achieved. Setting aside electron beam sources such as BWOs the only realistic source of LO power currently available above around

100 GHz is the harmonic multiplier driven by a lower frequency pump. To reach the highest frequencies several stages of multiplication are required (Raisanen 1990).

Another factor of crucial importance is the efficiency with which the mixer is coupled to the main antenna. The specifications for MASTER require a main beam efficiency of 98% with a receiver Gaussian beam waist of about 2.5 mm. Achieving such a high efficiency has proved to be difficult using anything other than a conventional corrugated feed horn, although recently progress has recently been made using a double slot antenna. As a part of the systems implications regarding the usefulness of any new device structure, one of the key considerations must be the relationship between the proposed device and one of the rather small number of effective terahertz antennas. All of these antennas require a specified feed (e.g. rectangular waveguide, coplanar line, etc.) and therefore coupling into such a feed must be considered if the device is to be practically useful. This is especially true since at terahertz frequencies the feed and the antenna may well need to be integrated with the active device.

MASTER and SOPRANO are two instruments taken from a whole series of proposed missions involving terahertz remote sensing from space craft. A list of typical programmes which emphasizes the range of applications in this region of the spectrum includes the following.

FIRST (far infrared and submillimetre space telescope): this is a 4.0 m telescope to be developed by ESA for astronomical observations in the range 500–2000 GHz.

SMIM (submillimetre intermediate mission): this is a 2.5 m telescope to be developed by ESA for astronomical observations in the range 400–1200 GHz.

SOFIA (stratospheric observatory for infrared astronomy): sponsored by NASA, this 2.5 m telescope will be launched in 1998 to provide frequent, high quality access to the infrared–submillimetre spectral region. The instrument will be housed in a modified Boeing 747 SP aircraft and will operate from 0.3–1000 THz.

SMMM (submillimetre moderate mission): sponsored by NASA for possible launch in 2001, this instrument is designed to provide a spectral survey of selected objects from 0.4–3 THz and imaging in the 1–3 THz range.

LDR (large deployable reflector): NASA have scheduled this instrument for launch around 2010. The LDR will view sources in the frequency range 0.1–10 THz using a 20 m diameter antenna.

SMMI (submillimetre interferometer): sponsored by NASA for possible launch in 2013, this instrument will be based at a lunar outpost where it will be used to view sources in the frequency range 0.3–10 THz with 100× better resolution than any other existing or proposed instrument. The antenna baseline is for a two-dimensional array of 5 m panels distributed over an array from 50 m to several kilometres in length.

Further missions are proposed for remote sensing applications particularly in the 1.8, 2.5 and 3.5 THz regions where strong OH lines exist. These are present in the atmosphere at all altitude ranges including the lower stratosphere. Their detection is needed to both understand and monitor atmospheric chemistry

3. Specialized terahertz instrumentation

Several systems fall into this category. Examples of the areas involving such instrumentation are plasma diagnostics and laboratory spectroscopy. As an example of such an instrument I shall consider a novel interferometer which has been designed to measure the scattering of electromagnetic waves at 94 GHz by a single particle

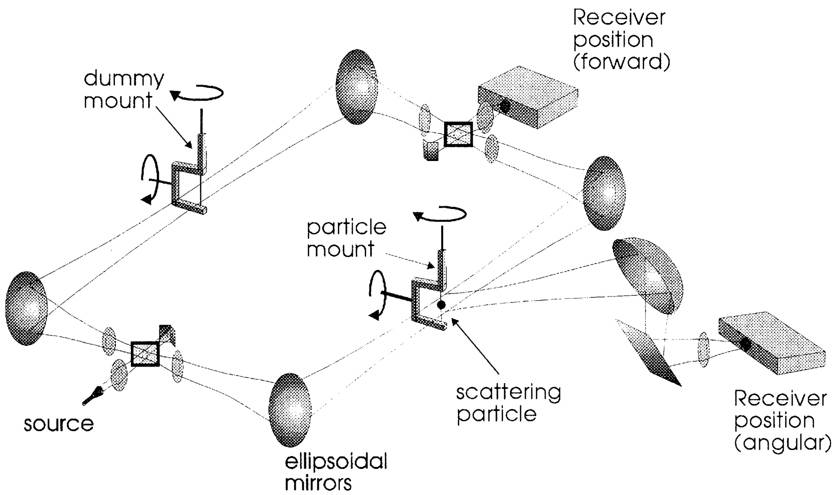

Figure 1. Single-particle scattering at 94 GHz.

scatterer. Figure 1 is a schematic representation of this instrument. Forward scattering is measured both in magnitude and phase. Angular scattering is measured over the full 4π rad in magnitude only. Measurement of the forward wave is the most difficult since this must be determined in the presence of the much larger unscattered illuminating wave. In this instrument this is acheived by a quasi-optical bridge technique in which the unscattered wave is balanced out. Scattering from spheres as small as 2 mm in diameter can be measured with good signal to noise. The size of the instrument is determined by the need to create a beam waist large enough in diameter so that the particle is effectively illuminated by a plane wave. In this case the length of the interferometer is about 3 m.

From the point of view of terahertz technology the interesting thing about this work is that for the large part it is information about scattering at *infrared wavelengths* that is actually required . The measurements made at 94 GHz are *low frequency* scale modelling measurements. Clearly it would be advantageous for the accuracy of the model if the wavelength could be reduced so that the scale factor to the infrared was less. Furthermore the size of the instrument would be reduced. From the success of this work it appears that there may be some requirement for this type of scale model measurements to be carried out at terahertz frequencies.

4. Millimetre wave communications

The frequency band between 35 and 94 GHz has been used for a whole variety of communications applications. All types of information – audio, video, data and fax – have been successfully transmitted and received by prototype transceiver systems developed around the world. These have been the subject of a recent review article (Meinel 1995). The specific applications are numerous, e.g. short haul line of sight transmission links, mobile communications, local cellular radio networks, computer local area networks for linking to portable computers, wireless cable applications, and communications to moving vehicles such as cars.

The technology used to build these prototypes varies. Early versions were con-

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structed using standard wavguide components, however, the need to keep the cost of each unit as low as possible has led to the development of hybrid technologies like microstrip and finline. The active devices used are also variable with some systems using waveguide mounted Gunn or Impatt oscillators, others have used lower frequency varactor tuned DROs followed by frequency multipliers. Extensive use is made of the Schottky diode as a mixing element in various single ended and balanced configurations. Three terminal devices such as HEMTs and HBTs are also coming forward. Until recently hybrid integration has dominated but recently moves have been made towards the use of monolithic integration. At least one example exists of a system working at 50 GHz using three terminal devices only (Ogawa *et al.* 1989).

5. Millimetre wave radar

The idea of using millimetre wave radar in motor cars for anti-collision warning is now well established and will certainly become a reality soon. Millimetre waves have been chosen for this purpose for a variety of reasons. Firstly the size of the antenna is limited by the dimensions of the front grill of the average car. Experiments have shown that a beam width of around 3° is required which would result in a large antenna if microwaves were to be used. These are short range radars (100 m typically) so atmospheric attenuation is not so important; however, the effect of scattering by rain increases steadily throughout most of the millimetre wave band. Optical alternatives suffer from limited field of view, possible issues concerning safety and poor performance in adverse weather conditions. From a commercial point of view the system size and cost are also critical factors.

The type of systems being envisaged vary in complexity from relatively simple forward warning collision systems which provide a warning to the driver of a potential collision situation to autonomous intelligent cruise control which operates in an autonomous feedback loop to maintain a safe driving distance to the vehicle in front.

The technology being used in automotive radar systems varies. Probably the most promising because of its potential for low cost implementation, high reliability and compactness is the fully integrated MMIC approach. Recently a fully integrated W-band single chip transceiver for automobile radar has been reported (Chang *et al.* 1995). This is a single chip developed using 0.1 μm T-gate AlGaAs/InGaAs/GaAs PM HEMT technology. The output power from the transmit amplifier is greater than 10 mW giving a range of 2–100 m. Two antenna systems were evaluated with the final choice being an off-the-shelf optical lens. In preliminary test the system was reported as able to track targets up to more than 100 m range.

6. Systems motivated advances in device technology

Having briefly summarized some of the most important applications we are now in a position to drawn some conclusions about the sort of advances in device technology which would have direct bearing upon the systems currently being produced.

Considering first remote sensing there are two really significant advances which could be made. Perhaps the most urgently needed of the two is the provision of a good solid state local oscillator source. This (or these) should be capable of generating at least 1 mW and should be efficient, rugged and reliable. For remote sensing the unit cost is not so critical. Clearly a fundamental oscillator capable of terahertz

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operation is the ideal. Failing this, improvements in multiplier technology could be very beneficial. Currently in order to generate power at , say, 900 GHz a two stage tripler is used to multiply up from 100 GHz. If we take the efficiency of each stage to be about 5% and the pump power to be 100 mW then the input to the second stage is about 5 mW and the output from the second stage is 250 μW which is marginally sufficient to drive a Schottky diode mixer. 100 mW is near to the maximum power it is possible to apply to a millimetre wave device so there is little point in increasing the pump power to the first stage. The second stage, however, is far from saturation. An increase in the efficiency of the first stage to 10% would be directly reflected in improved output. If both stages had 15% efficiency the output at 900 GHz increases to 2.25 mW which is probably all that is required. Work on multipliers both in terms of their design and the development of novel devices such as the single barrier varactor is thus highly relevant to remote sensing applications.

As far as the mixer is concerned it is still the case that the best performance of all at terahertz frequencies (anything above about 500 GHz) is achieved by the conventional 'cats whisker' contacted Schotky diode mixer connected to a circular corrugated feed horn. This structure, although effective, is not really desirable for space borne applications. There is therefore a need for work on novel, integrateable, devices and device mounts which can match or surpass the whiskered mixer. Here the need for absolutely minimal parasitics and efficient coupling to an antenna capable of 98% main beam efficiency need to be borne in mind. The device itself can be intrinsically very fast but if these two criteria cannot be achieved then it is not useful for systems applications

Turning to communications and radar applications the question is are there any reasons for seeking to move to frequencies above 100 GHz. The consensus of opinion from those working on these applications seems to be that there are no strong reasons at present. HEMT and HBT technology is now firmly established up to 100 GHz. If we take the case of automobile radar for example the choice of frequencies around 90 GHz seems to be good. The high frequency is needed to reduce antenna size but to go higher would result in increased problems with scattering from by rain. Furthermore, above 100 GHz the ever present problems caused by the absence of a suitable source outweigh any potential benefits. Long multiplier chains are acceptable in expensive satellite radiometer systems but are not ideal in low cost consumer electronics.

Paradoxically if the source problem were solved there may be many good reasons for moving up to terahertz frequencies for mass produced systems. The dimensions involve at millimetre wavelengths are particularly difficult from a production point of view. The overall sizes and the tolerances involved in feed horns and waveguide cavities (which are still used in Gunn oscillators for example) are small enough to be taxing for conventional machining and yet they are too large for the new techniques of micromachining. For example a rectangular waveguide for 100 GHz measures 2 mm × 1 mm. A similar waveguide for use at 1 THz would measure 200 μm × 100 μm. The former must be made by conventional techniques but the later is of a size which could be made by techniques similar to conventional semiconductor processing.

Even in the absence of new developments on the oscillator front there may be some potential for communications systems between 100 and 200 Ghz. Here the characteristic dimensions are just within the range of some of the LIGA micromachining techniques (Brown *et al.* 1995) being developed and one stage of multiplication up from a lower frequency oscillator may be acceptable. Atmospheric conditions may also be useful for applications where the range of transmission is required to be limited since there is strong water vapour absorption around 180 GHz. The same type of comments apply to radar applications. Even in the case of the fully integrated radar system referenced above the transceiver chip is interface to conventional rectangular feed horns by two fine-line transitions and sections of rectangular waveguide. As the cost of the chip comes down with mass production these elements could become the major cost items in the whole system. Were the frequency higher micromachining might enable them to be incorporated into the IC in a more cost effective way.

7. Conclusions

The area most immediately demanding advances in terahertz device technology is space borne remote sensing. Here there is a need for improved oscillators, mixers, antennas, integration techniques and fabrication technology. Work on frequency multipliers could be most fruitful in the short term. There are a lot of planned missions going forward into the next century which will continue to generate a demand for research in this area.

Between 50 and 100 GHz there are highly commercial applications which are already in an advanced stage of development. Present opinion is that there is no immediate need for these to be extended to higher frequencies. However, the new techniques of micromachining could alter this situation were there to be improvements in the oscillator situation. Even as things stand a case can be made for work on communications systems in the band 100–200 GHz. Automobile radar systems are well served by developments in millimetre wave IC technology but the interface to antenna systems could yet argue for a move to higher frequencies.

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