MILLIMETRE-WAVE RADAR

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Abstract

There is an increasing interest in millimetric wave radars for applications which require compact systems with good resolution. The envisaged uses for such radars include obstacle avoidance for use in helicopters and weapon guidance for small munitions systems. The recent advances in mm-wave components together with the use of the FMCW technique has led to significant reductions in size, weight and cost. This paper describes the technology used to make such radars and presents some measurements made with a 94 GHz instrumentation radar.

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1. Introduction

The E-plane circuit technique has been shown in recent years to be a suitable technology for the manufacture of high performance mm-wave components from 27–140 GHz. A range of components, such as mixers, couplers, oscillators, etc. have been made which are ideal for low power systems.

The frequency modulation continuous wave (FMCW) technique is ideally matched to these components. FMCW is a mean power spread spectrum technique with good electronic counter-counter measures (ECCM) characteristics. Its application at millimetre wave frequencies allows compact systems to be built with very good resolution in both range and angle. This paper describes the use of the E-plane technology to make an FMCW instrumentation radar at 94 GHz. Some measurements made with this radar will be described and the prospects for the mass production of such systems will be discussed.

2. The principle of operation of FMCW radar

A FMCW radar is so called because instead of transmitting short pulses like a conventional radar it transmits a continuous frequency-modulated signal. If linear modulation is used, the returns from distant targets are received as beat tones with a frequency proportional to the target range.

Fig. 1 shows a typical frequency sweep pattern for an FMCW radar and fig. 2 shows a schematic of the instrumentation system. The transmitter fre-
frequency is modulated with a repeated linear sweep. The signal reflected back from a distant target is at a slightly different frequency from that being transmitted at any moment because of the time delay to the target and back. The received signal is multiplied with a sample of the current transmitted signal in the receiver mixer and a beat frequency, $f$, is produced proportional to the range of the target where,

$$f = \frac{2ar}{c},$$

(1)
where $a$ is the rate of the frequency sweep, $r$ is the target range and $c$ is the velocity of light.

The use of fast frequency sweeps allows small range differences to produce large frequency differences in the receiver. This means that the system can have very good range resolution. The range resolution can be altered simply by changing the frequency sweep rate. The heat frequency received from a moving target is, of course, modified by the normal doppler shift. In practice this effect can usually be made acceptably small by suitable choice of the sweep rate, or else other means can be found to compensate for it.

3. The E-plane mm-wave circuit technique

The E-plane circuit technique has been shown to be a suitable technology for the manufacture of high performance mm-wave components for frequencies from 27–140 GHz\textsuperscript{1,2).} The circuit patterns are defined on the substrate using standard photolithographic techniques and the mass production cost is potentially low. The wave guide housing may be machined or cast from solid aluminium or made from metallized moulded plastic.

A wide range of E-plane components have now been developed including PIN switches, attenuators, modulators, couplers, filters, mixers, circulators and oscillators.

E-plane mixers are required in the front ends of nearly all mm-wave systems. A range of mixers have been designed from 27–110 GHz. Typical examples are described below. Balanced mixers for operation at 35 GHz are in production at Mullard Hazel Grove (a Philips company) with overall single sideband (SSB) noise figures of 7 dB including a 2 dB contribution from the intermediate frequency (IF) amplifier.

At 94 GHz mixers have been made with SSB noise figures of 7.5 dB including a 1 dB contribution from the IF amplifier, centered at 30 MHz. The same mixers when operated in FMCW systems have noise figures of 17 dB at 100 kHz. This increase is due to the $1/f$ noise contribution from the mixer diodes, however it is still sufficiently low for short range radar systems.

Low power (10 mW) oscillators suitable for use as transmitters can be made using GaAs Gunn diodes operating in the second harmonic mode\textsuperscript{3).} These are not made using the E-plane technique but are made in conventional waveguide which is compatible with the E-plane components.

A miniature 94 GHz FMCW radar head has been produced using E-plane techniques. Fig. 3 shows the unit. It comprises a varactor tuned Gunn oscillator, a directional coupler, a load, a circulator and a balanced mixer. The complete unit measures $65 \times 50 \times 20$ mm.
Fig. 3. Photograph of integrated E-plane 94 GHz FMCW radar.

Fig. 4. Metallized plastic version of the integrated 94 GHz FMCW radar head.
The housing for the unit shown in fig. 3 is made from numerically controlled machined aluminium. For mass production (i.e. greater than 10,000 units) this housing could be made by injection moulding plastic and then metallizing with an appropriate coating. Fig. 4 shows a metallized plastic version of the unit shown in fig. 3. Fig. 5 shows a view of this unit opened to reveal the circuit elements.

This demonstrates that the mm-wave component technology is suitable for mass-production using today’s technology.

Fig. 5. Metallized plastic radar head opened to reveal circuit elements.

3.1. Instrumentation radar system

An instrumentation radar system has been made at PRL using the type of components described above. The system is as shown in the block diagram in fig. 2.

Because the transmitter runs continuously, instead of being pulsed, the FMCW system uses the oscillator very efficiently. Continuous transmissions are also harder to intercept and classify than pulse transmissions. This is necessary for military systems, where it is important that the radar does not make the vehicle carrying it easier to detect. The microwave circuitry is also
very simple which, when using compact components at short wavelengths, produces physically small radar systems with very good resolution.

The complete front end unit of the PRL 94 GHz instrumentation radar is shown in fig. 6. Its size is determined by the aerial, which has a diameter of 300 mm, giving a beamwidth of only 0.7 degrees at this frequency 4).

An automatic gain control system expands the overall dynamic range of the system from around 60 dB to around 100 dB. An anti-aliasing filter limits the bandwidth of the received signals, and thereby sets the maximum indicated range for the radar. The whole sweep time can be used to examine signals from ranges of interest, in contrast to a pulse radar where time must be allowed for the reception of echoes from beyond the maximum indicated range before the next pulse can be transmitted. The use of FMCW can thereby reduce the processing speed required in a radar by eliminating this redundancy.

5. Frequency analysis

The signals received by the radar will generally contain several different frequencies, corresponding to targets at different ranges, so FMCW radars need some sort of frequency analyser to separate these returns.
The instrumentation radar uses a digital frequency analyser which implements the mathematical technique known as the fast fourier transform (FFT) to perform this function. The FFT is connected to a real time display via a microcomputer which is also used to record the radar returns for off-line analysis.

Fig. 7 shows a typical FFT processor for such a system. It is a single Eurocard board, 160 mm × 110 mm, and consumes about 7 watts of power. This particular unit can perform a 64 point FFT in about 500 microseconds.

6. Results obtained

Fig. 8 shows a typical return from the system. The raw signal is an amplified version of the signal out of the receiver mixer and the lower trace shows the signal after processing by the FFT. The latter corresponds to the basic radar display of signal strength against range. This trace clearly shows a distant target, which can be identified with the strong high-frequency component of the raw signal. The FFT output also shows a much smaller signal at closer range. The system noise floor has been averaged over 100 samples of the signal. It
shows a cut off at very short range, to avoid overloading of the system with reflections from the antenna itself, as well as the high frequency (long range) cut-off introduced by the anti-aliasing filter.

The ability to detect small targets in front of large distant targets, which is conferred by the use of the FFT, is obviously vital for any obstacle avoidance system.

The more distant target in fig. 8 is a power pylon which has a radar cross section ($R_{CS}$) of about 20 square metres and which is at a range of about 300 m. The signal to noise ratio for this target is about 34 dB. Power pylons are obviously important targets which must be seen by obstacle avoidance systems for aircraft, but this pylon also has about the same $R_{CS}$ as a large van, which is the sort of threat a ground based obstacle avoidance system might have to recognise, or the sort of target which a smart weapon system might have to find.

6.1. Power cables

Power cables form a major hazard to low flying helicopters. Measurements of the $R_{CS}$ of power cables have therefore been made with the instrumentation radar\(^6\) to determine their detectability to a 94 GHz obstacle avoidance radar. Figs 9a and 9b show the variation in radar cross section with angle of incidence for a typical British power cable of the ‘Horse’ variety, measured in
The results are presented for both vertical and horizontal polarisation. The general form of these returns is of a number of large returns at discrete angles with much smaller returns from other directions. This pattern has been predicted and observed before [7]. The angular positions of the large returns are determined by the manner in which the cables are wound.

The measurements made on one side of the broadside return are shown. The returns on the other side of the broadside were measured to confirm that the major features of the pattern were symmetrical. The theoretical radar cross section of the equivalent smooth cable at the same range would be 7.1 m². The total radar cross sections for all the returns from the cable were 6.7 m² for vertical polarization and 3.6 m² for horizontal polarization. The positions and numbers of the returns are compatible with the winding details of the cable. The level of the non-specular returns seen with vertical polarization are lower than was observed by Al-Khatib [7], in particular for the backscatter at angles beyond the last specular return. It is therefore unlikely that the continuous backscatter can be relied upon in any 94 GHz radar cable detection scheme. A variation in the amplitude of the different returns was observed, which differed between horizontal and vertical polarization. A similar effect was observed by Al-Khatib [7], but differing considerably in detail.

6.1.1. Multiple conductors

In Great Britain double, or quadruple conductors, separated by small spacers, are sometimes used instead of single conductors. Fig. 10 shows the
The general pattern of the returns was similar to that of a single conductor, with the positions of the specular returns being again determined by the winding details of the individual conductors.

The multiple conductor arrangement introduces two additional effects into the behaviour of the cables. The cable spacers have a significant radar cross-section, measured to be 0.12 m$^2$, and the returns from the four cables interfere with one another. Fig. 11 shows the fading characteristic of a quadruple conductor set. There was a gentle breeze blowing at the time this measurement was made.

Both the occurrence of deep fades and the presence of cable spacers may alter the performance of a cable detection system. It is known that not all countries use multiple conductors and these differences in national practice may need to be taken into account in designing a millimetric cable detection system.
6.2. Ship returns

The radar has also been used to measure the radar cross-section of some small ships.

Fig. 12 shows the return from a small ship at about 260 m range. The good range resolution available resolves two reflectors within the target, to improve aiming of a weapon onto the ship or to reduce the chance of losing the target in a fade. The two reflectors were approximately $35 \text{ m}^2$ and $10 \text{ m}^2$ RCS.

![Fig. 12. Return from a ship 3.3 m$^2$ range cell.](image)

Fig. 13 shows the variation in the radar cross-section of a small ship, of about 30 tons displacement, tracked over a period of 1.5 seconds. The mean radar cross-section of the ship was measured as $75 \text{ m}^2$. The fluctuations in the radar cross-section are relatively slight because the ship contained a number of reflectors as in fig. 12 which were resolved separately by the radar and which fluctuated independently. This ability to resolve the separate sections of a complex target is an advantage inherent in the intrinsic frequency agility of the FMCW technique.

![Fig. 13. Fading characteristic of a small boat.](image)
6.3. *Sea clutter*

In order to assess the performance against naval targets it is necessary to have measurements of the return from the sea in order to establish that it is not greater than that from the ship. The RCS of the sea is measured in square metres per square metre of sea surface illuminated and is expressed in decibels.

Table I shows some measurements of the radar returns from sea clutter which were made with horizontal polarization. The sea was between states 1 and 2, which is pretty calm.

<table>
<thead>
<tr>
<th>depression angle</th>
<th>$\sigma_o$ dBm$^2$/m$^2$</th>
</tr>
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<tbody>
<tr>
<td>3°</td>
<td>-40</td>
</tr>
<tr>
<td>30°</td>
<td>-27</td>
</tr>
<tr>
<td>45°</td>
<td>-24</td>
</tr>
<tr>
<td>55°</td>
<td>-18</td>
</tr>
<tr>
<td>90°</td>
<td>+13</td>
</tr>
</tbody>
</table>

These results are plotted in fig. 14 and a smooth curve has been interpolated through them.

![Graph showing sea clutter returns](image)

Fig. 14. Sea clutter returns, sea state 1-2.
R. N. Bates and A. G. Stove

7. Conclusions

The results shown demonstrate the performance of 94 GHz FMCW radar systems. It shows that small solid state oscillators can generate sufficient power to be used in conjunction with other low cost millimetre wave components in systems exploiting the FMCW technique to produce low cost, compact 94 GHz radars with very good performance for a wide range of target acquisition, obstacle avoidance, guidance and navigation applications. Other work at PRL has involved the more detailed evaluation of millimetre-wave radar in a number of these areas.

REFERENCES