MICROWAVE AND MILLIMETRE-WAVE STARING ARRAY TECHNOLOGY

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ABSTRACT

Microwave receivers are described incorporating lens-fed planar antennas with semiconductor components integrated on a common substrate, in an area small enough for packing into monolithic two-dimensional arrays. Such receivers have been built to operate at 10 and 35 GHz, including a monolithic silicon 4×4 array for 35 GHz. A radar demonstrator has also been built, using a hybrid array, and has shown direction-finding accuracy comparable to monopulse, in a staring array with no moving parts.

INTRODUCTION

This paper describes a staring, multi-beam, focal-plane array technology and radar development which has evolved from research into lens-fed microwave and millimetre-wave receivers with integral antennas [1]. The key components are a high permittivity dielectric lens and a focal-plane array of receivers in intimate contact with the lens (Figure 1). The lens generates a multiplicity of simultaneous narrow beams, each with its own direction of look, covering between them the total field of view. Each beam is focussed to a unique position on the lens focal plane. Combining this with an array of receivers in the focal plane creates an array of high-gain receivers which collectively stare across a wide field of view, with no moving parts and without separate beamforming circuitry.

LENS AND ANTENNA DESIGN

Each receiver is built round a crossed-dipole antenna, in which one dipole receives the signal and the other the local oscillator. Such dipoles on a high permittivity substrate, such as alumina, form a cone beam predominantly directed through the substrate [1, 2, etc]. Radiation is therefore fed through the substrate, to take advantage of this. The opposite face of the substrate is made ellipsoidal, forming an immersion lens which focusses incoming plane waves on to the dipoles. Various lenses have been designed to maximise field of view and aperture efficiency, and to minimise weight, while providing a flat focal plane and optimum spacing for the dipoles in an array. The lenses comprise single or multiple components, and have been designed by ray-tracing methods with optimisation, using software developed at RSRE for infra-red optics. Figure 2 shows a two-component lens. It has an aperture of 105 mm and an f-number of approximately unity. Both elements of this lens were manufactured from high-grade alumina ($\epsilon_r = 9.8$), with quarter-wavelength polystyrene ($\epsilon_r = 2.5$) anti-reflection coatings. Figure 3 shows measured radiation patterns for this lens at 35 GHz: the field of view extends beyond $\pm 20°$ before the gain degrades significantly. The beamwidth is 5°, and the first E-plane sidelobes are -17 dB, as expected for an uniformly

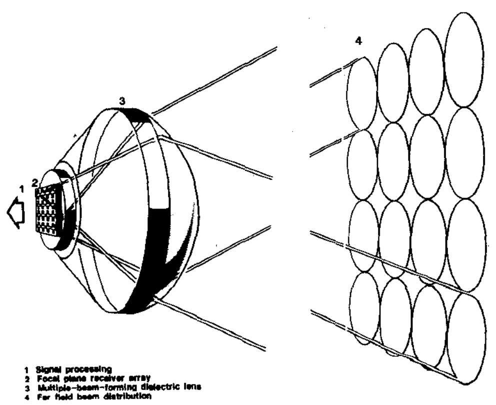

FIG 1: Staring Array Concept

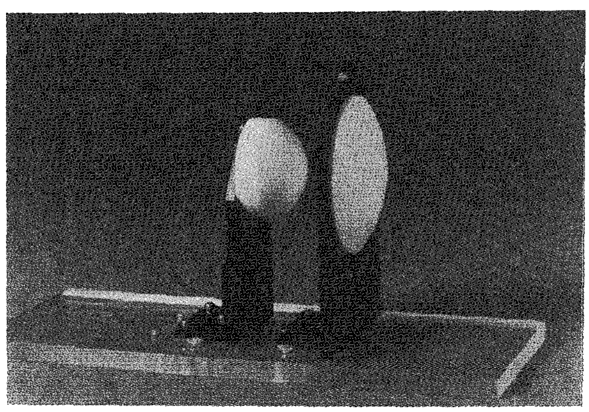

FIG 2: Two-Component Lens

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illuminated circular aperture of this diameter. The widest field of view demonstrated to date, with an alternative lens design, is ±45°.

More recently a loaded plastic alternative to alumina has been developed under MoD funding by Marconi Electric Devices Limited. This has similar electromagnetic properties to alumina, but is about half the weight, and can be moulded rather than machined, which should significantly reduce the manufacturing cost of lenses.

A moment-method theoretical technique has been developed for planar antennas on a dielectric surface, which gives the current distribution, and hence electromagnetic field wherever it is required. This has been used to compute the antenna impedance, and Figure 4 shows an example for a dipole on alumina. The substrate permittivity reduces the resonant frequency and impedance by a factor of approximately $\sqrt{(\epsilon_r + 1)/2}$, compared to a similar dipole in air. The resonance is quite broad, and the impedance lies in the range $30 - 100\Omega$ over a very wide band, which is suitable for matching to Schottky barrier diodes and other devices. Dipoles for 35 GHz operation are thus nominally 1.8 mm long on alumina; the length and width can be adjusted somewhat to provide the best match and facilitate array packing.

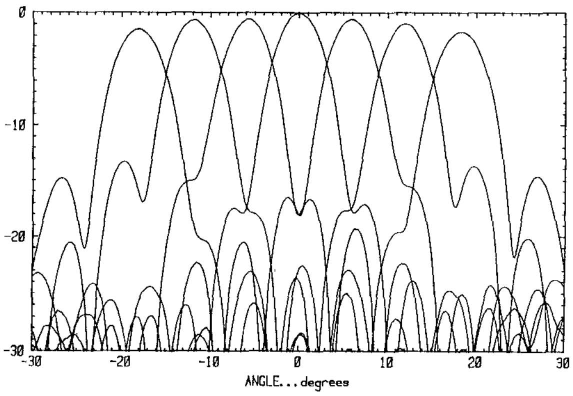

FIG 3: Radiation Patterns of Two-Component Lens

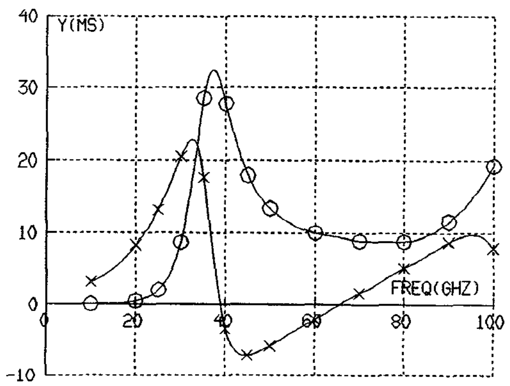

FIG 4: Admittance of Dipole on Alumina
(0=real part, X=imag part)

BALANCED MIXER AND IF AMPLIFIER

Crossed dipoles, aligned parallel to signal and local oscillator (LO), provide a convenient means to drive a quad diode mixer (Figure 5). There are three basic mixer configurations: the standard cyclic ring, a parallel arrangement, and the anti-cyclic arrangement shown in Figure 5. These configurations present the same RF impedance near 50Ω, but they imply different bias and IF connections, and this affects their ease of implementation. The configuration of Figure 5 allows the integration of an IF amplifier placed on or under one of the dipole arms, eliminating the need for lines carrying unamplified IF off the receiver. Matching between dipole and diodes can be improved with series inductance, which resonates with the capacitive part of the diodes' impedance: this can be achieved for the signal antenna by slots cut in the LO dipole arms.

Measurements of noise figure have been used to compare the single side-band conversion loss of the mixer configurations, and the effects on conversion loss of matching slots and potentially parasitic connections to the antennas. Thin and thick film hybrid receivers were fabricated on alumina, operating at 10 and 35 GHz. The measurement was of overall noise figure for the whole receiver, and the conversion loss was derived by subtraction of the IF amplifier noise figure, and 1.5 dB for the antenna and lens coupling efficiency. The minimum conversion loss at 10 GHz is 6.5 dB, improving to 5.2 dB with matching slots. These figures agree with mixer simulations, showing that there is no extra loss specific to this method of construction. No significant variation of minimum conversion loss with mixer configuration has been found, either by simulation or by experiment. It also appears that bondwires used for IF output connections have little effect on the antenna coupling. Similar results have been obtained at 35 GHz.

35 GHz ARRAYS

Receiver arrays consisting of dipole-coupled detectors or mixers replicated on a single high permittivity substrate have

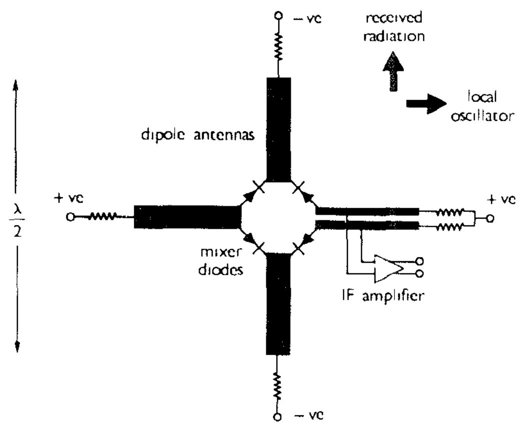

FIG 5: Individual Receiver Configuration

been reported by other workers [3]. Whilst retaining all the advantages of such receivers, the design of Figure 5 leads to enhanced performance and greater front-end circuit integration. The simplicity of the receiver circuitry and its total lack of RF transmission lines are especially advantageous for the realisation of arrays at millimetre wavelengths, and make for very simple and mass-producible construction. Arrays of this type have been fabricated in hybrid and monolithic technologies. The monolithic form can be fabricated in low-cost silicon, and does not require gallium arsenide, although the latter would be equally feasible.

The receivers in an array must be close enough to provide full sampling of the field of view, given the lens focal length and magnification, while leaving room for the antenna and other components without significant coupling between receivers and their IF and bias tracks. In the 35 GHz circuits, the dipoles on silicon or alumina need to be 1.5–1.8 mm long, and the other components occupy little extra area. A typical 100 mm diameter lens, with $\epsilon_r = 10$ and unity f-number, forms beams with a 3 dB width of 5° at 35 GHz. The lens magnification results in the beams being focussed to points separated at least 2 mm in the focal plane. Because the beam separation exceeds a dipole length with some margin, receivers can be spaced in a two-dimensional array to provide contiguous 3 dB beam coverage of the field of view that the array encompasses. Array packing is similarly possible at other RF frequencies, since all dimensions scale with the wavelength.

Figure 6 shows a 35 GHz 4×4 monolithic silicon array manufactured under MoD funding by Plessey Research Caswell Limited. The chip is 1 cm square, and contains 16 receivers of the design in Figure 5. Planar Schottky diodes are integrated at the centre of 1.5 mm crossed dipoles, and integrated bipolar IF amplifiers are buried beneath the split dipole arm. Consequently each receiver occupies an area little more than 1.5 mm square. At 35 GHz this array with a 100 mm aperture lens would provide a field of view of 20° by 20°, divided into 16 individual 5° beams. Fabrication practicalities and yield considerations suggest that "tiling" of a number of these arrays might be necessary if a wider field of view were required with monolithic technology.

An alternative method for the fabrication of larger receiver arrays is thick or thin film hybrid technology. Unlike monolithic circuits, hybrid circuits can be easily fabricated with areas up to 5 cm square or greater. This means that arrays can be made which contain many more receivers, and the field is view is then limited only by the distance over which the focal surface of the lens can be maintained flat. Figure 7 shows a 35 GHz thick-film 5×5 array with a hexagonal layout. Each crossed bow-tie was wire-bonded at its centre to matched Schottky diode chips to form the four-diode double-balanced mixer. DC bias was supplied to each receiver via chip resistors on the focal plane. IF was extracted from each mixer as in Figure 5, and routed via tracks to the perimeter of the array where the first stage of low-noise IF gain was provided. More recently thin-film techniques including the use of nichrome bias resistors have been adopted. Typical noise figures of receivers of this type were measured to be 8.5 dB (6.5 dB SSB conversion loss + 2.0 dB IF noise figure): with the added 2.0 dB antenna and lens losses the overall receiver noise figure is 10.5 dB.

RADAR DEMONSTRATOR

A 35 GHz heterodyne radar has been built, incorporating an array of nine thick-film receivers in a similar technology and format to that of Figure 7, combined with the lens of Figure 2, and a multiple channel IF- and signal-processor. The transmitter source was an injection-locked 150 mW IMPATT feeding a small-aperture horn placed beside the receiver lens, to floodlight the field of view of the receiver array. Thick-film in-phase and quadrature base-band circuitry was housed immediately behind the array within the cylindrical head. The radar sequentially detects and locates moving targets in pseudo-real time using a maximum likelihood parameter estimation algorithm. This compares the measured image with stored calibration data, and interpolates to find an accurate target position. By repeatedly carrying out this process, the staring radar has demonstrated its ability continuously to detect and locate moving cars. This is illustrated by Figure 8, in which the radar display is superimposed on a TV image of the radar's field of view. The significant feature is that the

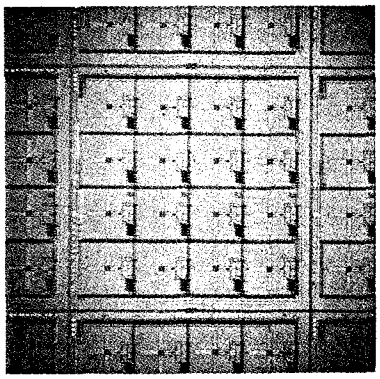

FIG 6: Monolithic Silicon Array

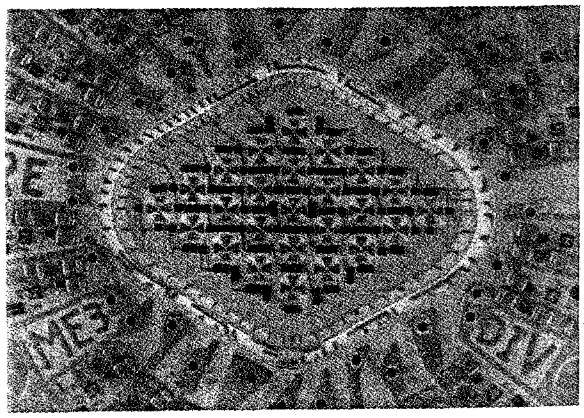

FIG 7: Thick-film Hybrid Array

cars are being simultaneously detected and located although they are separated by several beamwidths. Measurements indicate that the location accuracy in Figure 8 is at least as a good as that which could be achieved with a monopulse radar, which would have to be gimballed to cover the same field of view. Although the radar employed a single-target algorithm, more than one target could be resolved, even within a single 5° beamwidth, provided that they could be discriminated in Doppler frequency.

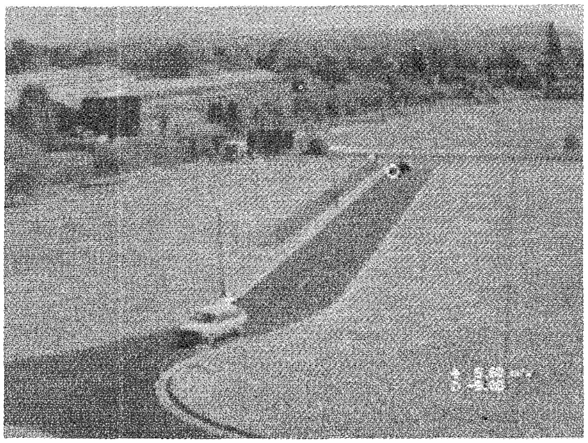

FIG 8: TV Scene with Radar Location

CONCLUSIONS

A 35 Ghz two-dimensional staring array technology has been demonstrated which has no moving parts or electronic beamforming, and which has a direction-finding accuracy at least as good as monopulse. Furthermore, it has the potential for implementation in other wavebands, and in monolithic silicon or gallium arsenide technology. It therefore represents a significant step towards the realisation of compact, low-cost arrays for radar and communications sensors operating in the upper microwave and millimetre-wave bands.

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