MONOLITHIC INTEGRATED CIRCUIT IMAGING RADIOMETERS

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ABSTRACT

The application of arrays of integrated circuit receiver to imaging of microwave and millimeter wave radiation is presented. Overall system concepts and both focal-plane and aperture-plane types of systems are discussed. Several functional block diagrams of the sensors are suggested and some examples of state-of-the-art units are presented.

INTRODUCTION AND SYSTEM CONCEPTS

At radio wavelengths radiometer systems are usually single-pixel instruments which measure the radiation emitted in one antenna beam area; this is in contrast to optical or infrared wavelengths where many thousands of pixels are simultaneously imaged by arrays of sensors. However, gallium-arsenide (GaAs) microwave monolithic integrated circuits (MIMIC's) have now reduced the size and cost of microwave sensors so that arrays with 100 to 10,000 receivers have become feasible. The applications of these microwave imaging arrays are in radar, earth sensing, radio astronomy, target seekers, and medical thermography. The overall system design, chip architecture, and state of the art of these devices will be explored in this paper.

As a starting point it must be realized that arrays sample the electric field as a function of spatial coordinates and this electric field is a Fourier transform of the emitted field intensity as a function of angles subtended by the array. In order to image the emitted power a discrete Fourier transform (DFT) of the spatial samples is required to remove the effects of the first naturally-occurring Fourier transform. This DFT can be implemented in a variety of different ways with receiver IC's utilized either before or after the transform as shown in Figure 1. The spatial DFT should not be confused with a time-to-frequency DFT which can be utilized to find the power spectrum of the incoming signal.

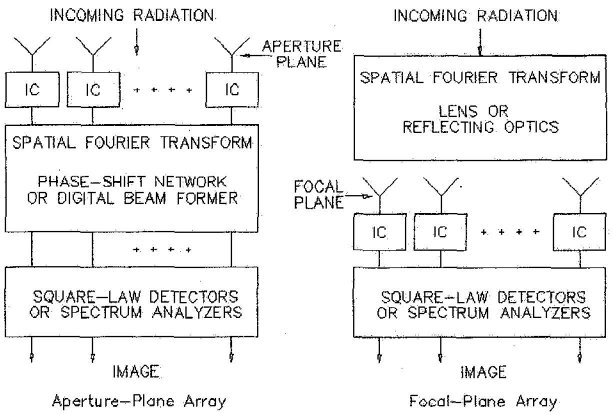

Figure 1. Two basic types of imaging arrays.

The aperture plane array shown in the left of Figure 1 utilizes MIMICs before a spatial DFT. In this case the MIMICs perform low-noise amplification and frequency conversion and the DFT is performed either in analog form, such as in a multiple-phase combining network (sometimes called a Butler matrix), or digitally by the DFT operation, which is usually implemented as a fast Fourier transform (FFT) within a special purpose processor. The output of the DFT is then either squared to give power or applied to a spectrum analyzer (which may be a FFT type of spectrum analyzer) to give power as a function of frequency. If the receiver outputs are combined with only one combination of phases set by variable phase-shifters the system is a simple one-pixel phased array.

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The focal plane array is shown on the right of Figure 1. In this case a spatial Fourier transform is performed by reflecting optics (i.e., a parabolic reflector) or by refracting optics (i.e., a lens). The antenna feeds are placed in the focal plane of the optics. The MIMICs perform the function of low-noise amplification and may include frequency conversion (followed by an external spectrum analyzer) or square-law detection. Note that the aperture plane array requires the preservation of phase in the MIMIC whereas the focal plane array does not.

It should also be noted that a focal plane array may utilize a linear sum of small feed antenna outputs to form a single pixel, as is illustrated in Figure 2. This technique allows pixel elements to overlap and provides more complete sampling of the focal plane image. Pixels that overlap at half-power points can be realized; this is not possible with single feeds because feeds large enough to provide good illumination of the primary reflector cannot be placed close enough together. An example of a phased-array antenna feed is given in [1].

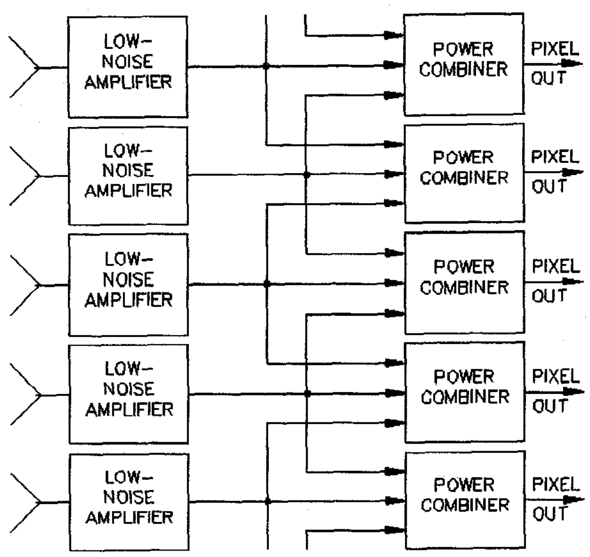

Figure 2 - Focal plane array showing overlapped feed elements.

A recent treatise on focal plane arrays and imaging by Johansson [2] contains many references and presents a concise summary of the theory. A quantity of fundamental importance is the number of pixels N which can be imaged without significant loss of gain by a lens or reflector of diameter D and focal length F. Johansson, following the work of Ruze [3] and others, finds this to be $N=360\ (F/D)^4$. Thus, for a prime focus parabolic reflector with a typical F/D = 0.4, N = 9, but with a typical Cassegrain system with effective F/D = 3, N=29,160. These calculations are only valid when the reflector and subreflector have a diameter of many wavelengths and thus apply for large, narrow-beam antennas at high frequencies.

TRANSISTOR-BASED RADIOMETER MIMICs

A block diagram of a complete RF to DC sensor that is feasible for monolithic integration on a single chip at millimeter wavelengths is shown in Figure 3. A TRF type of receiver (no local oscillator) is suggested for measurements of broad-band continuum radiation. The chip requires multiple stages of RF amplification with approximately 50 dB of total gain which is sufficient to drive a diode square-law detector. The millivolt-level output of the square-law detector would drive an external operational amplifier chip, which would supply low-pass filtering and amplify the signal to volt level prior to multiplexing and A/D conversion. A diode noise generator could be included on the receiver chip to provide gain calibration of the receiver and realization of a noise-adding radiometer [4]. Thus, a simple continuum (no spectral analysis) radiometer is produced by two small chips per pixel.

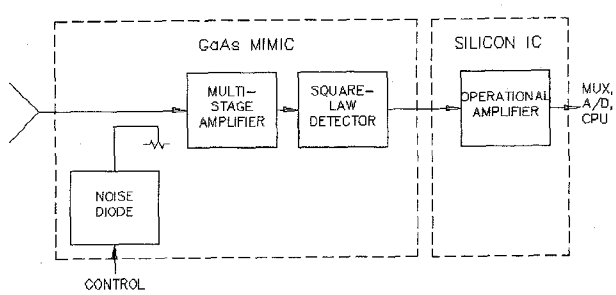

Figure 3 - Block diagram of tuned radio-frequency (TRF) receiver integrated circuit appropriate for focal-plane array continuum radiometer applications.

Monolithic IC amplifiers now exist for frequencies up to 100 GHz; a photograph layout of a 4-stage amplifier developed at Martin Marietta Laboratories is shown in Figure 4. More information is given by Trippe et al., [5]. This chip has produced a gain of 18.5 dB with a 4.3-dB noise figure at 81 GHz; a ten-stage amplifier with 50-dB gain should be feasible.

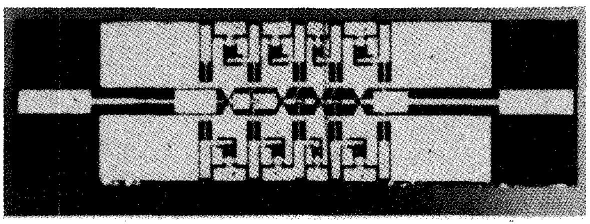

Figure 4 - Four-stage millimeter-wave low-noise amplifier MIMIC. The chip utilizes P-MODFET devices having 0.1-micron gate length and contains integral probes for coupling to waveguide. Chip size is 1.25 mm by 4.2 mm.

A superheterodyne receiver-type of chip is shown in Figure 5. In this case a low-noise amplifier with gain in the 10- to 20-dB range is used to establish a low noise figure before down conversion to an IF frequency. In the example shown, an 80- to 90-GHz RF band is converted to an 8- to 18-GHz IF frequency where it can be amplified by other chips prior to square-law detection or spectral analysis.

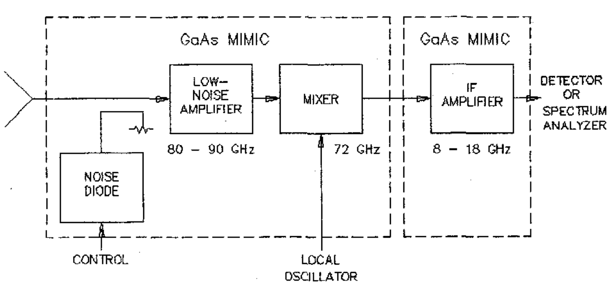

Figure 5 - Block diagram of a superheterodyne receiver-type of integrated circuit appropriate for either focal plane or aperture plane arrays.

DIODE-BASED RADIOMETER MIMICs

At frequencies above 100 GHz, low-noise amplifiers are not presently available and local oscillator sources are more complex. A desirable chip configuration for 600-GHz operation is shown in Figure 6.

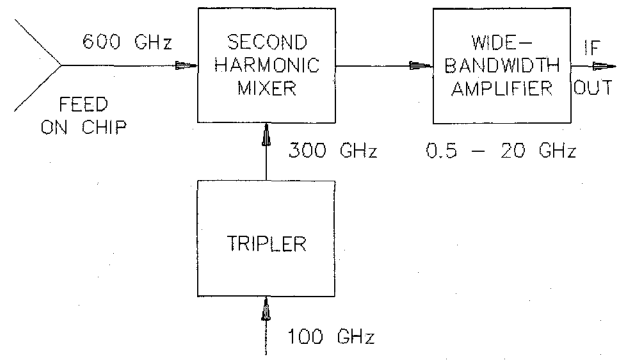

Figure 6. Proposed block diagram for a 600 GHz MIMIC receiver.

The chip would include a two-diode second harmonic mixer, a frequency tripler, and a wideband (0.5 to 20 GHz) IF amplifier. Because of the short wavelength, a feed antenna would probably also be included on the chip. This MIMIC is more complex to fabricate than the chips previously described because different epitaxial layers are required for the three types of devices on the chip, i.e., Schottky diode layers for the mixer, varactor diode layers for the multiplier, and FET or MODFET layers for the wideband amplifier. Either separate chips could be utilized or a single chip could be fabricated by techniques of ion implantation, selective epitaxy, or multilayer lithography.

Some first steps in the fabrication of IC's operating above 100 GHz have been made in our laboratory. Figure 7 shows a two-diode second harmonic mixer designed for operation at 200 Ghz; a close-up view of the diode region is shown in Figure 8.

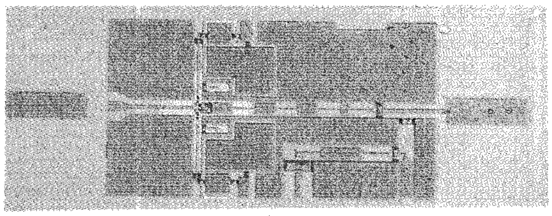

Figure 7. MIMIC two-diode second harmonic mixer for operation at 200 GHz; size is 2.95 mm by 1.25 mm. The RF input is at left and LO input is at right. The diodes can be individually biased to reduce the required local oscillator power.

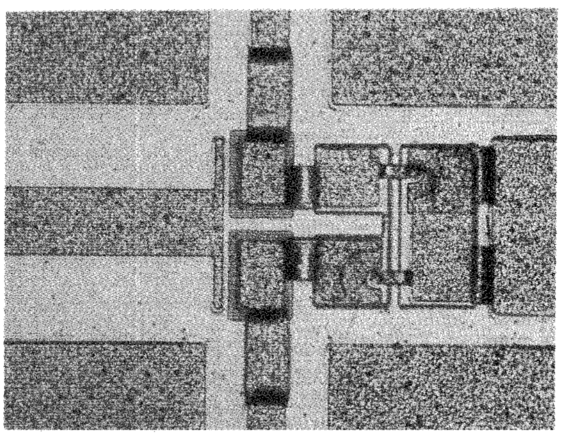

Figure 8. Close-up view of the diode region of the 200-GHz mixer shown in Figure 7. The size of the indicated view is approximately 200 by 300 microns. The mesa diodes have diameters of 2 microns and are contacted by 2-micron-wide air bridges.

REFERENCES

[1] D. Rascoe, R. Crist, A. L. Riley, T. Cooley, L. Duffy, D. Antsos, V. Lubecke, W. Chew, K.S. Yngvesson, and D. H. Schaubert, "Ka-Band Beam Steered Planar Array Feed," IEEE 1990 MTT-S Digest, pp. 809-812,

[2] J. F. Johansson, "Millimeter Wave Imaging Theory and Experiments," Research Report No. 151, Department of Radio and Space Science, Chalmers University of Technology, Gothenburg, Sweden, 1986.

[3] J. Ruze, "Lateral Feed Displacement in a Paraboloid," IEEE Trans. Antennas and Prop., Vol. AP-13, pp. 660-665, Sept. 1965.

[4] M. J. Yerbury, "A Gain-Stabilizing Detector for Use in Radio Astronomy," Cornell-Sydney University Astronomy Center Report No. 280, Cornell University, Ithaca, NY, 1974.

[5] M. Trippe, S. Weinreb, S. W. Duncan, A. Eskandarian, B. A. Golja, D. C. Martel, G. Mendenilla, B. Power, H. B. Sequeira, S. B. Southwick, S. P. Svensson, D. W. Tu, and N. E. Byer, "mm-Wave MIMIC Receiver Components," IEEE 1991 Monolithics Circuits Symposium Digest.