Millimeter-Wave Components and Subsystems Built Using Microstrip Technology

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Abstract—**This paper describes how various circuit elements have been realized on microstrip for operation in the millimeter-wave bands. The manufacturing process for thin-film MIC's on single-crystal quartz is described. Designs for various circuit elements are discussed, and an integrated subsystem is described in which MIC techniques are used to produce a miniature millimeter-wave distance-measuring sensor. Range measurement results for the miniature sensor are presented.**

I. Introduction

MICROSTRIP line (microstrip) was first investigated as a transmission medium in the 1950's with the work of Wheeler [1] at the Hazeltine Corporation in the United States.

The first serious use of microstrip in the U.K. was at the GEC Hirst Research Centre in the early 1960's, where components for telecommunication systems were developed to operate around 6 GHz. Various circuit functions were elaborated, including couplers, mixers, and switches, with the development of nonreciprocal ferrite devices starting around 1968.

Microstrip development progressed upward in frequency, with 35 GHz components being developed in the mid 1970's and 94 GHz components in the 1980's. Microstrip components are now available to operate up to 220 GHz [2].

II. Applications

A. Microstrip Components

Microstrip provides a unique capability in which to realize all of the components necessary to form complete radar subsystems. In order to produce low-loss circuits for millimeter-wave operation, it is necessary to use a substrate material having a low dielectric constant.

The prime material for millimetric MIC's is Z-cut quartz; this material was selected over others in the mid 1970's when an extensive comparison was carried out. The main advantage of quartz is its physical stability; being a crystal material, its properties remain constant and predictable over the full military environment. However, for GEC-Marconi its greatest advantage is the thermal match it provides to most ferrite materials. This is essential if on-substrate isocirculators are to be realized.

The quartz substrates are used, in varying thicknesses depending on the frequency of operation; typically this would be 120 μm at 94 GHz. The selection of substrate thickness is based on achieving fundamental-mode propagation and avoiding the creation of higher order modes and surface waves. Quartz, having an effective dielectric constant of 4.4, provides acceptable substrate thickness with reasonable component geometries. The use of higher dielectric materials at these frequencies results in more difficult fabrication techniques which carry no real advantage.

Low-dielectric-constant materials other than quartz exist and in recent times their properties have become more acceptable. Such materials are finding use in certain applications; however these are limited and are unlikely to provide a real alternative to quartz in the foreseeable future for the higher millimetric bands, and are completely uncompatible with inserted ferrite technology.

Having selected a substrate, this must now be processed into an MIC. This is done using a standard photolithographic process, which has been refined for quartz. Once cut to thickness, the substrate is metallized. First a base layer of nichrome is deposited. The thickness of this material is carefully controlled so that an exact sheet resistivity can be achieved. This will be important later when the integral loads for couplers and isolators are formed. The next step in the procedure is to sputter the gold metallization onto the base layer. Both these processes are carried out on either side of the substrate; a further copper layer is added to what will become the ground plane.

This metallized substrate is then coated in photoresist, ready to receive the circuit pattern. This may be single or double sided, depending on the system design. Once completed, the unwanted metallization is removed, leaving the circuit pattern.

After cleaning, the substrate is prepared for mounting into its housing. The MIC box contains registration marks formed as part of the machining process; these align the substrate with reference to the input and output ports. A

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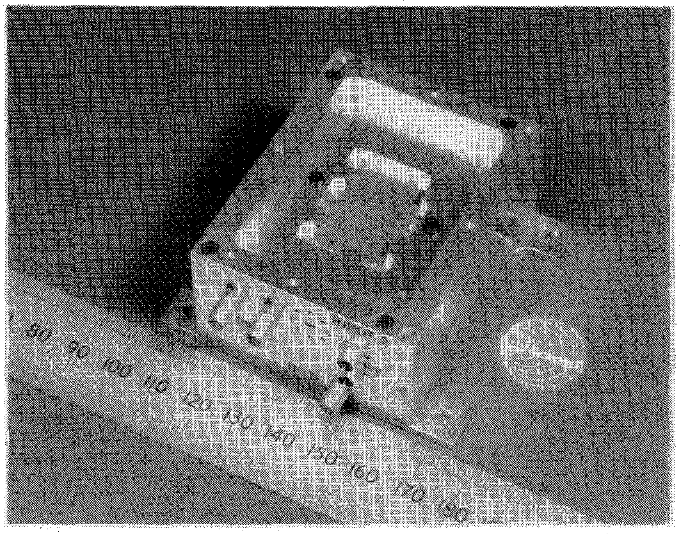


Fig. 1. Integrated millimeter-wave receiver.

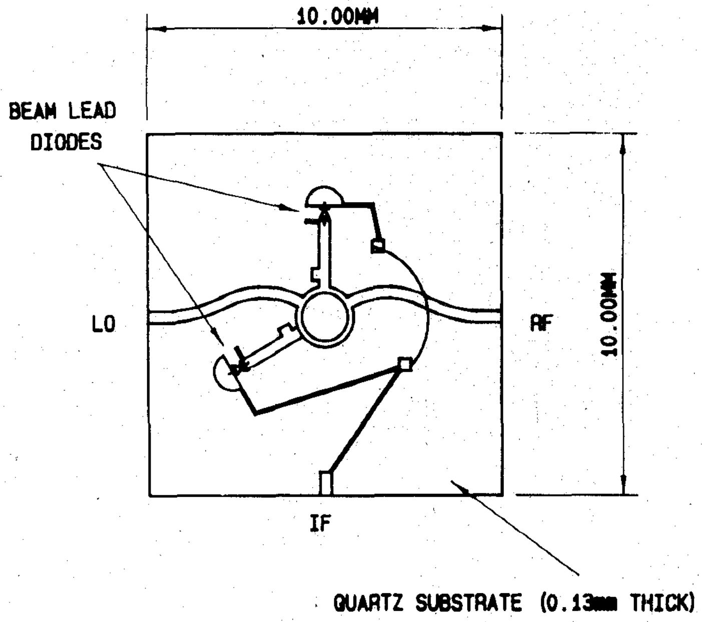


Fig. 2. Millimeter-wave balanced mixer (94 GHz).

solder preform of defined thickness is placed underneath the substrate and the assembly is weighted down and heated to allow the solder to flow. Once assembled in this manner, the substrate material becomes extremely robust and can be subjected to all of the normal assembly procedures, for example, thermocompression bonding. A fully assembled receiver is shown in Fig. 1.

Having successfully developed this technique, the number of circuit elements which have been designed has steadily increased. Now all of the circuit elements which a designer would require are available. These are stored as part of a library for computer-aided design for MIC's (CADMIC); from this store proven components may be selected for inclusion in a receiver design. Examples of these are

couplers	p-i-n limiters
3 dB hybrid	antennas
90° hybrid	amplifiers
Lange	transitions
proximity	oscillators
mixers	isocirculators
detectors	limiters

B. Couplers and Mixers

The coupler is a simple component which forms the basis of many other functions, particularly the important down-conversion mixer. The 3 dB hybrid, or rat-race, design has found most use in this application; its broad band ($>10\%$) bandwidth gives reliable operation with good conversion performance, typically 6.0 dB at 94 GHz. Its configuration is relatively simple; two of the coupler arms are terminated in single-ended mixers, and the signal and local oscillator power is applied to the mixer diodes from the two remaining ports. The intermediate frequency generated is extracted from a single coaxial output by combining each of the diode outputs (see Fig. 2). An RF filter section allows this IF signal to pass and a dc bias to be applied to the diodes to reduce the local oscillator drive. The low conversion loss achieved is dependent upon the cutoff frequency of the mixer diodes; these are low-capacitance GPS DC1346 beam lead devices. This device has a junction capacitance of 0.010 pF, a series resistance of 6 Ω, and hence a cutoff frequency of about 2500 GHz.

C. Nonreciprocal Devices

The technology for inserting ferrite disks into hard dielectric substrates has been fully exploited at microwave frequencies. This expertise has in recent years been applied to the millimeter-wave frequencies so that now the insertion of ferrite is an established procedure [3].

Once the ferrite material has been fitted into the substrate the normal process of thin-film metallization and etching can take place. The matching elements for the circulator junction are defined at this time, and provided that the correct design has been selected it can be expected to perform without adjustment on test. Therefore, using such a technique, within the tolerance of the processing the designer will know the performance of the first circuit and the 100 000th.

The greatest advantage of the inserted ferrite isocirculator is its application as an isolator. In this form the system designer may incorporate isolators wherever intercomponent reflections may be of concern or, alternatively, to achieve consistent input match. The 50 Ω loads for these devices are formed using the resistive NiCr base metallization layer deposited during manufacture, thereby avoiding additional component assembly operations. Using this technique isolations of over 25 dB may be obtained with approximately 0.3 dB insertion loss at 94 GHz. It is this unique ability above all which has allowed GEC-Marconi to develop quartz millimetric microstrip

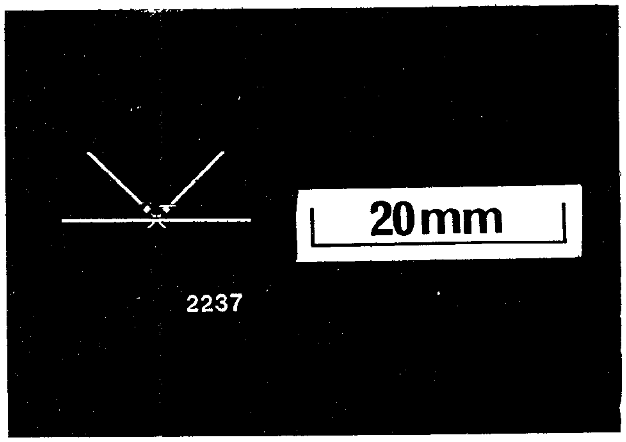


Fig. 3. MIC p-i-n switch (94 GHz).

and to realize its capability of producing high levels of component integration. The receiver shown in Fig. 1 contains seven ferrite devices and nine other circuit elements on a 24 mm×28 mm substrate.

Another important use of the inserted ferrite is as a transmit–receive duplexer. When used in this form in an FMCW radar, the sensitivity of the receiver is directly related to the levels of isolation achievable between the transmitter arm and the mixer input. Also in this pre–down-conversion position, insertion loss contributes directly to the overall noise figure.

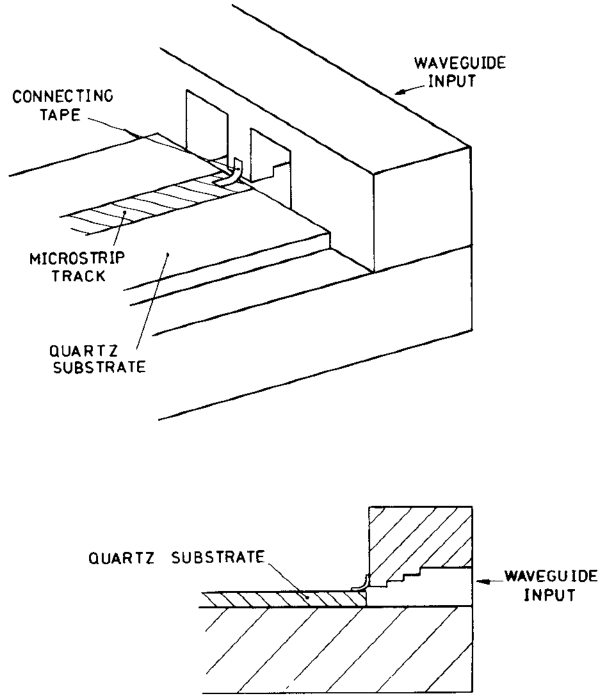
D. P-I-N Switches

A range of microstrip single-diode and double-diode p-i-n switch circuits has been developed. These circuits can produce narrow or broad-band switching characteristics as required. The basic circuit consist of a pair of low-capacitance beam lead p-i-n diodes mounted in parallel to the main 50 Ω transmission line.

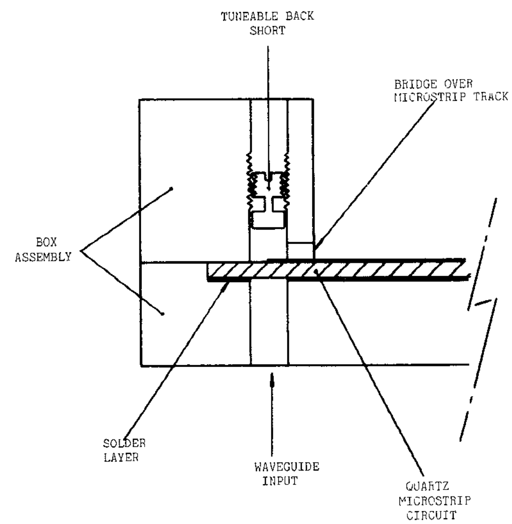
A typical narrow-band circuit is illustrated in Fig. 3. This consists of a pair of diodes separated by a quarter wavelength, with each diode circuit angled at 45° to the main feeder. Each diode is terminated by a capacitance which provides an RF short circuit, and an inductive stub is provided to tune out the diode capacitance. Forward bias is applied to each of the diodes via RF filters and a resistive network. This ensures that the bias current is shared equally between diodes.

In this type of circuit an attenuation greater than 30 dB can be achieved over a 8.5% bandwidth at 94 GHz. The zero bias insertion loss is approximately 1.0 dB over the same frequency range. For operation in the 75 to 110 GHz frequency range, the diode capacitance should be in the range 0.015 to 0.030 pF; this is achieved using the GPS DC2602.

In certain applications, broad-band switch characteristics are required. This can be obtained by arranging the diode circuits to be on opposite sides of the main feeder while maintaining a quarter-wavelength separation. Such an arrangement, very useful for instance as a modulator,



(a)



(b)

Fig. 4. (a) Stepped impedance transformer from waveguide to microstrip. (b) Schematic cross section through E-plane probe transition.

produces an attenuation of approximately 15 dB and an insertion loss of less than 1.5 dB per diode over the entire 75 to 110 GHz frequency range.

E. Transitions

In certain designs it will be necessary to access the microstrip transmission line from waveguide. This can be achieved via low-loss broad-band stepped ridge impedance transformers. These have been developed to provide full waveguide coverage over each of the bands from 40 to 140 GHz. Typical performance figures for such a transition in

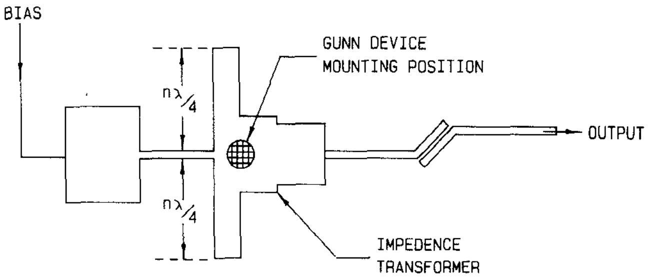


Fig. 5. Simple millimeter-wave microstrip Gunn oscillator.

waveguide 27 (WR10) are a return loss of approximately 23 dB and an insertion loss of less than 0.25 dB over the entire 75 to 110 GHz frequency range. Connection to the substrate is made by a gold tape fixed between the substrate and the final step of the transition (see Fig. 4(a)).

An alternative, simplified design has been developed for the waveguide-to-microstrip junction, which is known as the probe transition. In this design, the waveguide, instead of being parallel to the substrate, is orthogonal. The substrate ground plane metallization is locally removed from the quartz so that the substrate forms an effective window across the waveguide aperture. The microstrip line is designed to pass part way across this window and couple into the waveguide. A backshort section placed over the microstrip substrate increases the efficiency of this design.

While the performance of this configuration is narrower band than the stepped ridge design described earlier (approximately 10%), it provides the additional advantage of a hermetically sealed window at no extra cost (see Fig. 4(b)). This is an essential feature of any practical system which needs to meet a full military requirement. In addition the probe requires no physical bond to the waveguide, as in the case of the stepped ridge transition; this eliminates an operator-dependent process and a potential source of subsystem failure.

F. Oscillators

It is quite possible to construct oscillatory structures on microstrip which will operate in the millimeter-wave bands. Possibly the simplest structure consists of a Gunn effect device mounted in the center of an open circuit multiple-half-wave resonator with a transformer section out to 50 Ω microstrip (see Fig. 5).

Microstrip-based oscillators have been built to operate up to 94 GHz; however the main limitation on performance has always been high phase noise. Primarily a consequence of the low values of Q obtainable in microstrip resonators. Maximum values of Q obtainable from the shorted transmission line type of resonator are only around 100 owing to conductor, radiation and dielectric losses.

Some work has been done with alternative resonant structures mounted on microstrip. Workers at GPS [3] have investigated mounting a radial transmission line resonator above the microstrip with a Gunn diode beneath (Fig. 6). This work yielded improved resonator Q but as yet the power output available has been small.

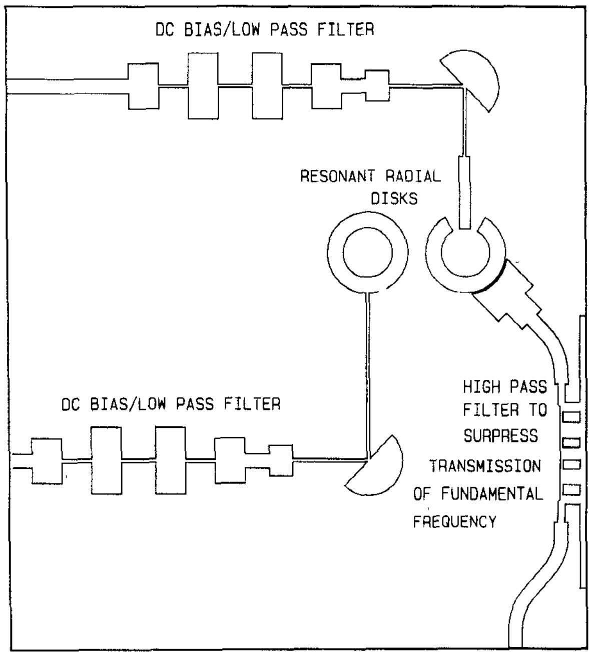


Fig. 6. Quartz microstrip radial disk second-harmonic millimeter-wave Gunn oscillator (parallel VCO microstrip circuit details).

The systems described later in this paper all make use of off-circuit cavity oscillators in order to provide the required power with low phase noise.

Recent developments in semiconductor technology have led to the production of HEMT devices that are capable of oscillating at frequencies above 100 GHz. This holds great promise for the development of millimeter-wave oscillators on microstrip since the use of a three-terminal device in the oscillator means that the resonator may be less tightly coupled into the circuit, thereby permitting higher values of loaded Q to be achieved with an attendant improvement in phase noise performance.

G. Integrated Subsystems

Miniaturized FMCW Radar Front End: A miniaturized FMCW radar front end has been designed and constructed with all the millimeter-wave circuit functions integrated onto a single microstrip "tile."

A block diagram of the subsystem is shown in Fig. 7. A cavity-based second harmonic mode Gunn voltage controlled oscillator is used to generate a signal around 94 GHz. The oscillator feeds an antenna via a circulator; this device is built using the inserted ferrite technique, with magnetic bias being provided by a high flux samarium cobalt magnet mounted beneath the circuit. Return signals from a target are collected by the antenna and pass via the circulator to a balanced mixer which makes use of beam-lead gallium arsenide Schottky barrier diodes. Local oscillator drive for the mixer is provided by a coupler on the oscillator output line.

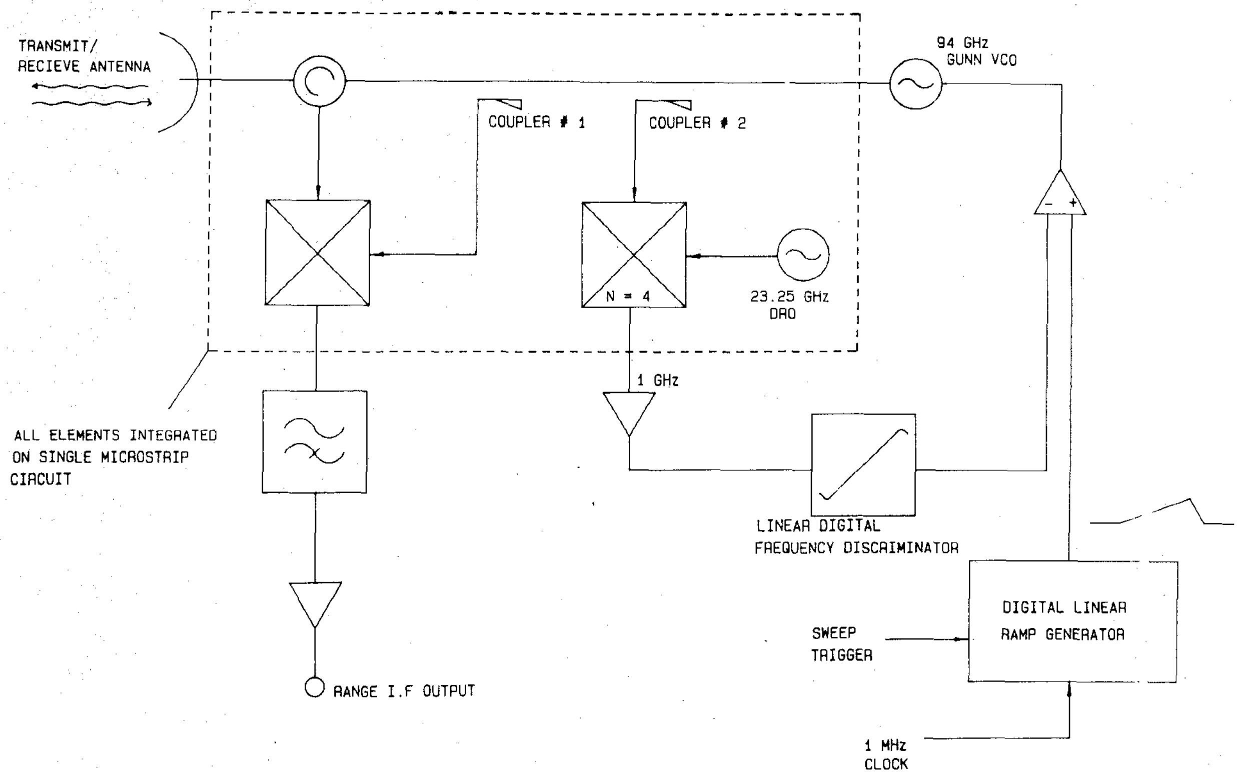


Fig. 7. Block diagram of 94 GHz FMCW radar.

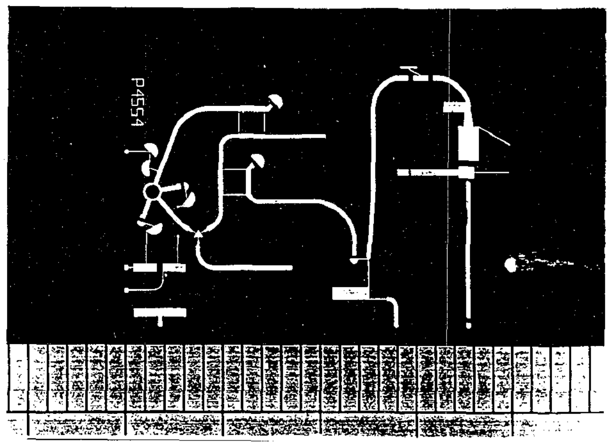


Fig. 8. Miniaturized Radar MIC (94 GHz).

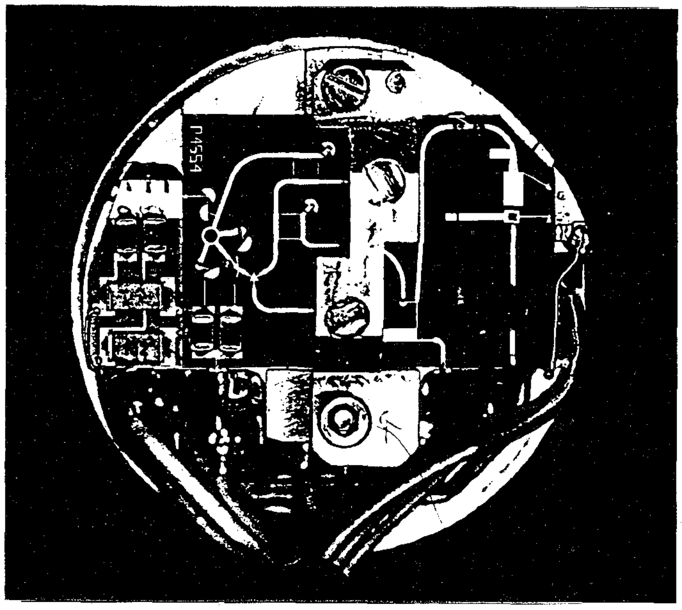


Fig. 9. Assembled FMCW sensor head.

The basic FMCW radar principle demands that the oscillator frequency sweep be linear, and the miniature radar achieves this by the use of a frequency feedback linearizer system [4]. A sample of the oscillator output is taken via a coupler to a harmonic mixer ($N = 4$), where it is mixed with a 23.25 GHz signal derived from a dielectric resonator stabilized FET oscillator. The resultant IF at around 1 GHz is fed to an emitter coupled logic (ECL) frequency divider and thence to a digital linear frequency discriminator. The linearizer generates an output voltage which is directly proportional to the oscillator frequency.

A negative feedback loop is established by summing the linearizer output voltage and the tuning input voltage at the VCO tuning port. The quartz microstrip tile measures only 20 mm × 13.5 mm and is 0.127 mm thick (see Fig. 8). The completed radar front end is approximately 28 mm in diameter.

The VCO is housed in a cavity beneath the MIC and is coupled to the circuit using a microstrip probe transition. The MIC feeds the antenna via a circular waveguide, which is coupled by a second microstrip probe transition. The integrated radar front end also houses IF preamplifier circuits and bias networks built on alumina substrates

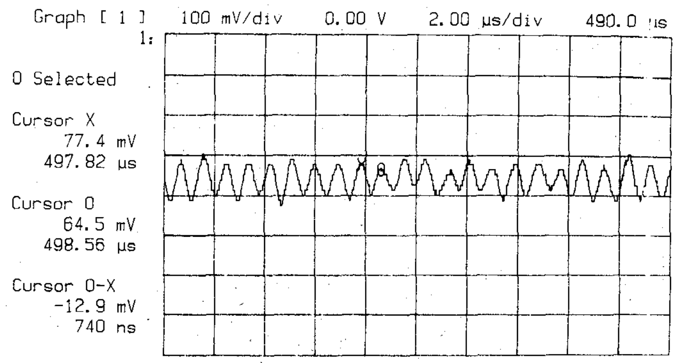


Fig. 10. 100 m^2 reflector; 3 m altitude; range, 675 m.

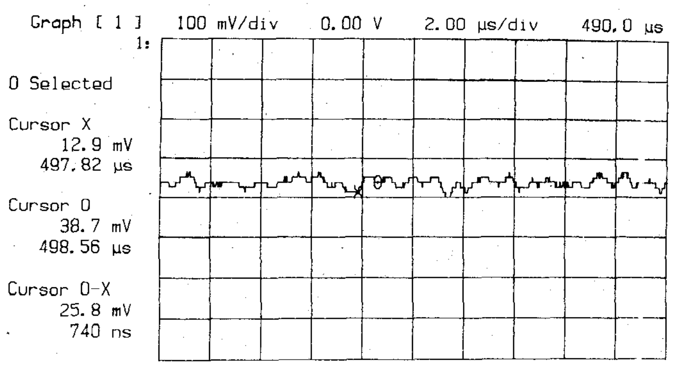


Fig. 11. Tree clutter; range 680 m.

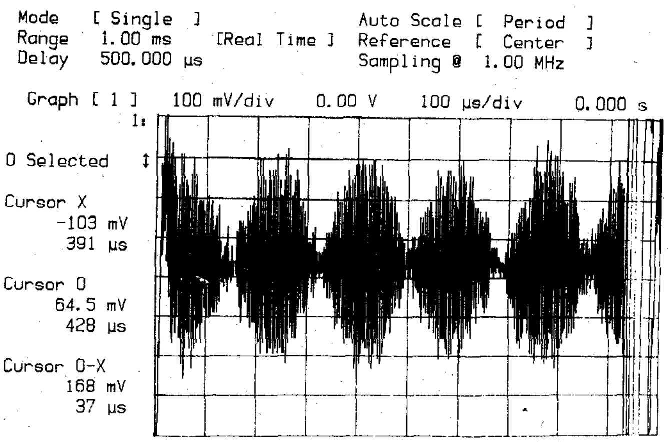


Fig. 12. Two 50 m^2 reflectors. Altitude 0.05 m. $R_1 = 111$ m; $R_2 = 113$ m.

using thick-film hybrid techniques (see Fig. 9). The radar head has been tested and is capable of sensing targets at a range in excess of 500 m.

Fig. 10 shows the IF output for a 100 m^2 reflector at a range of 675 m. The reflector was mounted 3 m above the earth with a background of trees in leaf. The clutter return from the tree foliage above is shown in Fig. 11.

The high linearity of the radar is demonstrated in Fig. 12, where two targets 2 m apart are resolved only 0.05 m above meadow grass at a range of 111 m. In all the above tests the radar head was mounted at a height of 20 m above the earth.

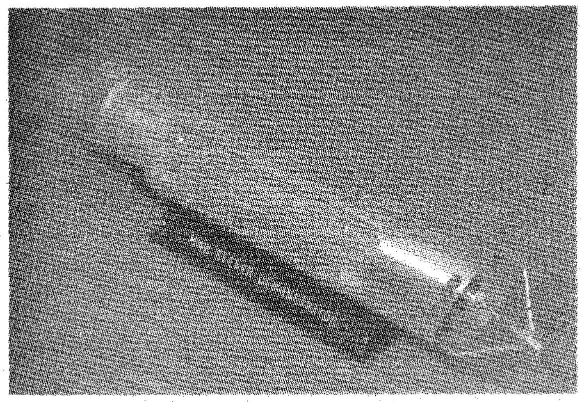


Fig. 13. FMCW seeker.

Fig. 14. Radar trials scene showing helicopter-carried seeker locked onto a tank.

H. Integrated Systems

From the foregoing discussions of microstrip components it may be seen that this medium offers a very flexible approach to the problems posed by millimetric sensors. From the design libraries which exist, components and subsystems may be readily configured to fit desired requirements with only minimal limitation on layout and with a high probability of first time success. Sensor systems ranging from 100 mm to 300 mm in diameter have been developed using this technology. In addition extensive air-carry and tower-based trials have shown the maturity of the hardware. An early example can be seen in Fig. 13. This is a dual polarization FMCW radar built in 1983; it uses a subsystem similar to that shown in Fig. 1 and is packaged within 110 mm. This system underwent helicopter trials to demonstrate the full range of submunition performance requirements (Fig. 14).

Later generations of seekers have been built to address specific applications. Fig. 15 shows a 120 mm terminally guided submunition seeker including digital signal processing. This system employs novel techniques to couple energy from the MIC to the antenna. Measured performance shows that this type of sensor is capable of meeting the small-caliber munition design aims.

Such small-diameter systems have been tested in a range of environments. Perhaps the worst of these is the gun launched requirement.

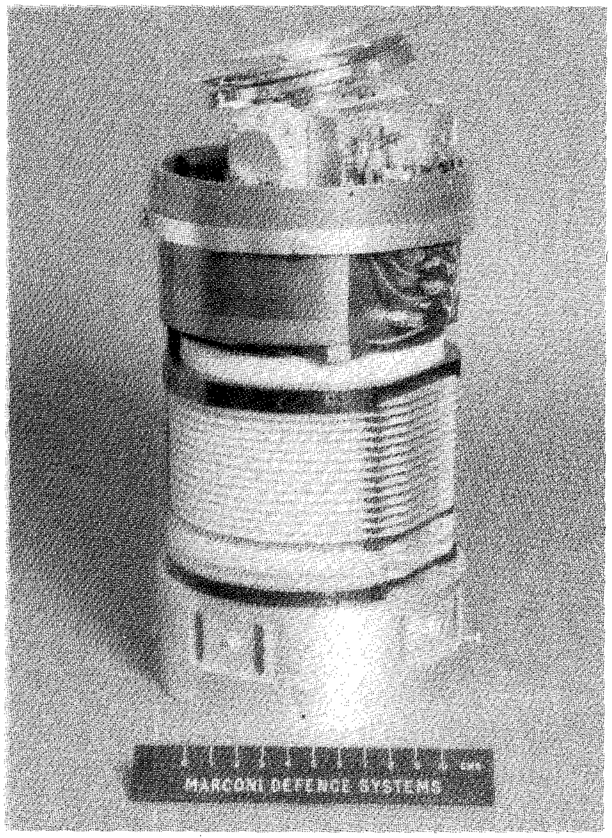


Fig. 15. 120 mm guided submunition seeker.

An area of interest in the antiarmor field is smart projectiles. These may be either mortars or shells (typically 155 m). A series of trials carried out by Marconi have shown that the microstrip and associated technology is capable of surviving the most severe environment. Recent work using nonstabilized rounds subjected the hardware to axial and rotational forces in excess of 13 000g. No degradation in performance was observed from the experiments, which had not been designed to be specifically g-hard. This is a graphic illustration of the robustness inherent in the technology.

III. Conclusions

This paper has described the evaluation of microstrip as a transmission medium for components and subsystems operating in the millimeter wavebands.

A wide range of circuit functions has been developed and integrated into high-performance millimeter-wave transceivers.

The MIC manufacturing process is suitable for high-value manufacturing of highly integrated subsystems since manufacturing costs for the circuits are almost independent of the number of circuit functions.

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