Millimeter-Wave Hybrid Microstrip Subsystems

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Abstract —**This paper reviews the application of hybrid open-microstrip technology to millimeter-wave (30–110 GHz) military subsystems. The relevant circuit techniques, active and passive devices, and construction methods are considered. Examples of components/subsystems are discussed.**

I. Introduction

MILLIMETER-WAVE system production requirements may be considered in two main categories of radar/communications (100–1000 units per system) and missile seekers (50 000–500 000 units per system). It is questionable whether many of the current custom hybrid built technologies, associated with low-volume manufacture, and based on the available transmission media such as waveguide, Finline, suspended stripline, microstrip etc., will all satisfy the demands of the low-cost, rugged, compact, and volume-manufacturability features of the seeker-type market.

The hybrid microstrip technology is one design approach which has been examined in depth. It has the significant advantage that the technology is based on the lower microwave frequency production experience. It provides a greater potential for multicircuit integration, including the incorporation of nonreciprocal devices, than any of the other hybrid transmission-line contenders. Its potential to meet the requirements of both the low- and high-volume categories is reviewed.

II. Hybrid Open Microstrip Structure

The form of millimeter-wave integrated circuits discussed in this paper is that based on hybrid thin-film stripline circuits, with chip devices mounted on a metallized quartz substrate.

A. Microstrip Transmission Line

As at lower frequencies, the microstrip transmission-line circuit is normally realized by conventional thin-film technology, with the conductor shape or circuit pattern determined by photo-etching. The conductor is gold, with the initial seed deposition of a thin layer of chromium or nickel–chromium. A conductor layer thickness of about 5 μm is commonly used, and this is achieved by electroplating or heavy vacuum deposition. The underlay (seed) metal, such as nickel–chromium may also be used to realize thin-film resistors directly in the circuit patterns.

It is desirable for the substrate choice that there should be no warping over the substrate surface and that the material is sufficiently rigid to enable drilling and machining. Conventionally, high-purity alumina (250 μm thick) is used up to about 20 GHz, but above this frequency the propogation characteristics of microstrip suggest that there is an advantage in reducing the relative permittivity of the substrate material, together with reducing the substrate thickness. Briefly, this reduces problems associated with dispersion and over-moding. Quartz (fused silica) meets all of the above demands. Single-crystal Z-cut is preferred, however, as it provides the advantage of a higher expansion coefficient which is a better thermal match to ferrites and metallic materials. Sources of the quartz material are synthetic and natural. These can provide four-inch square substrates. Circuits may be arrayed during the thin-film fabrication process for production purposes. The potential fragility of the thin quartz does not present a problem in its application, as it is soldered into the package housing, thus forming a very rugged structure capable of meeting the needs of military environmental conditions.

The preferred microstrip structure dimensions for acceptable transmission propogation with Z-cut quartz are 500-μm-wide lines on 250-μm-thick substrate and 250-μm-wide lines on 125-μm-thick substrate at 26–40 GHz and 75–110 GHz, respectively, for 50-Ω characteristics. The measured line losses are about 0.04 dB/mm and 0.08 dB/mm, respectively.

B. Waveguide to Microstrip Transitions

Transmission media transitions from waveguide to microstrip use either the stepped-ridge impedance transformer or E-plane probe-type structures [1]–[3].

Four steps are normally used for the stepped-ridge transformer type and this provides full waveguide bandwidth operation with an insertion loss/VSWR of about 0.25 dB/1.3:1 and 0.5 dB/1.5:1 at 26–40 GHz and 75–110 GHz, respectively. A reduction in the number of steps reduces the physical length to provide a more compact structure, but at the expense of bandwidth. Military hermeticity requirements may readily be met by the use of waveguide windows. However, this does tend to restrict the bandwidth to about 5 percent.

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The printed E-plane transition provides significant cost and mechanical advantages in waveguide to microstrip transformer designs. This transition operates by coupling from the E-field of the waveguide to that of the microstrip by a length of line acting as a probe transformer. The quartz substrate extends over the waveguide face; this produces a waveguide window simultaneously as the substrate is soldered in position, thus forming a hermetic seal. The performance is competitive with the stepped-ridge transition types with external glass waveguide seals, that is, 0.5-dB insertion loss and 1.3:1 VSWR for a 10-percent bandwidth in the 75–110-GHz frequency range.

C. Planar Active Devices

Forms of diodes which are currently being applied to microstrip circuits above about 30 GHz include: GaAs Schottky barrier beam-lead mixers [4], GaAs Schottky barrier coplanar mixers [5], Si p-i-n beam-lead switches/limiters [6], and a range of GaAs/Si chips using the micro-LID and pico-LID carriers [2].

Briefly, the beam-lead and planar devices offer the highest cutoff frequency, lowest series inductance, and, thus, highest frequency operation. The micro-LID and pico-LID are chip carriers which provide the versatility to realize particular forms of device, without the beam-lead/coplanar processing complexity; applications are high-power n-i-p/SBD mixers, GaAs/Si detectors, Si noise diodes, p-i-n/n-i-p diodes, low-barrier height devices and high reverse voltage up-converter diodes. (A n-i-p is a reverse polarity p-i-n diode. A n-i-p chip mounted in parallel with a n-type SBD chip in physical close proximity, electrically short circuits the SBD at high current levels, thus providing RF overload protection.)

D. Nonreciprocal Devices

The integration capability for nonreciprocal devices is a significant advantage of the hybrid-microstrip technology [7]. Satisfactory microstrip circulators may be realized up to 110 GHz by inserting and bonding a ferrite disk into a hole predrilled in the quartz substrate. The diameter of the ferrite disk is about 2 mm (substrate thickness 0.25 mm) and about 0.6 mm (substrate thickness 0.12 mm) at 35 GHz and 94 Ghz, respectively. A single samarium cobalt magnet is normally used to provide the magnetic bias. The three-port circulator is converted to a two-port isocirculator by terminating the third port with a matched load consisting of a 50 Ω thin-film resistor, either in discrete or integral form.

Typical performance insertion loss/VSWR characteristics for > 20-dB isolation and 10 percent bandwidth are 0.5 dB/1.3:1 and 1.0/1.5:1 in the 26–40 GHz and 75–110 GHz frequency ranges, respectively.

E. Packaging Techniques

Packaging and constructional techniques aims are to provide the integration advantages of small volume, low weight, high reliability, and meeting the environmental aspects of military systems. Many of the techniques already established and production-proven for microwave integrated circuits (MIC's) are applied to the millimeter-wave IC's. The use of quartz circuits does require an expansion matching material for the package, either for the box material or by use of an appropriate carrier metal.

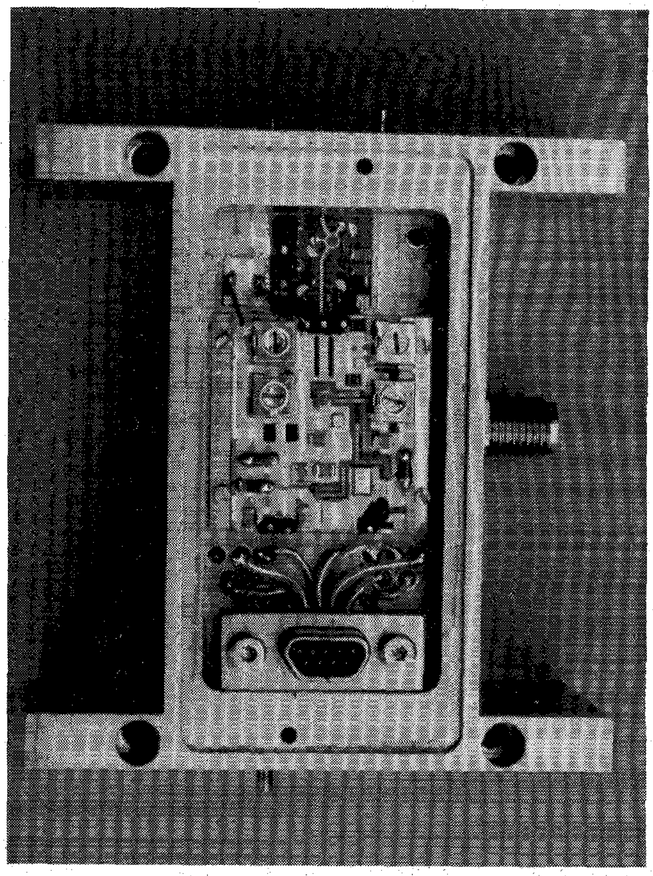

Fig. 1. Balanced mixer IF-BITE unit (V-band).

III. Components

The versatility of the hybrid microstrip technology for component applications has been demonstrated by the wide range of commercial products for use up to 110 GHz which have been developed to provide the basis for system development or measurement instrumentation. Examples are: balanced mixers, two- and three-port harmonic mixers, broad-band detectors, solid-state noise sources, p-i-n diode switches, etc. Simple circuit integration, for example, a p-i-n diode switch with a 94 GHz balanced mixer and an isocirculator with a 94-GHz solid-state noise source, is a regular component feature. The component circuit functions also provide the design base for complex multicircuit integration.

IV. Subsystems

Practical millimeter-wave subsystem requirements dictate high complexity in terms of RF, low-frequency circuitry, and high-reliability construction, with the design aims of low cost, compactness, and production reproducibility, by the minimization of component packages and interconnections. The hybrid microstrip design approach is to integrate as many RF circuit functions as possible on a

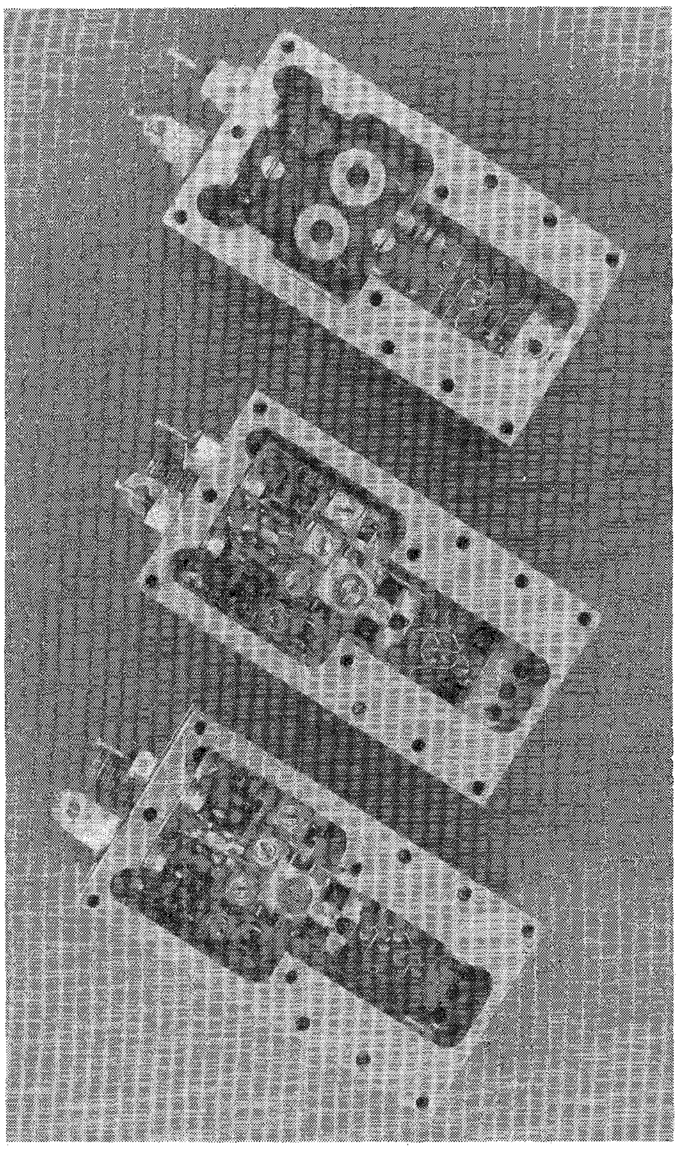

Fig. 2. *V*- and *W*-band SSB down converters, and *W*-band FM CW units.

single substrate, and then incorporate the RF and low-frequency processing circuits in a single package. Some examples are described below.

A. Balanced Mixer — IF Amplifier Units

The balanced mixer—IF amplifier unit shown in Fig. 1 is designed for operation at *V*-Band (50–75 GHz). A microstrip balanced mixer is incorporated with its IF amplifier and BITE circuitry in a single package. The balanced mixer consists essentially of a 3-dB rat-race coupler and two single-ended mixers using beam-lead GaAs Schottky barrier diodes; the circuit is formed on a quartz substrate 10 mm×10 mm×0.12 mm. Particularly attractive features of the mixer design basis are: wide instantaneous bandwidth (20 percent with no external tuning); 50-Ω IF output impedance; low conversion loss (6.0 dB up to 100 GHz); low-noise ratio (≈ 1.0); and high LO AM noise rejection (> 20 dB). The BITE and diode dc bias circuitry is shown in the top view of Fig. 1, the IF amplifier

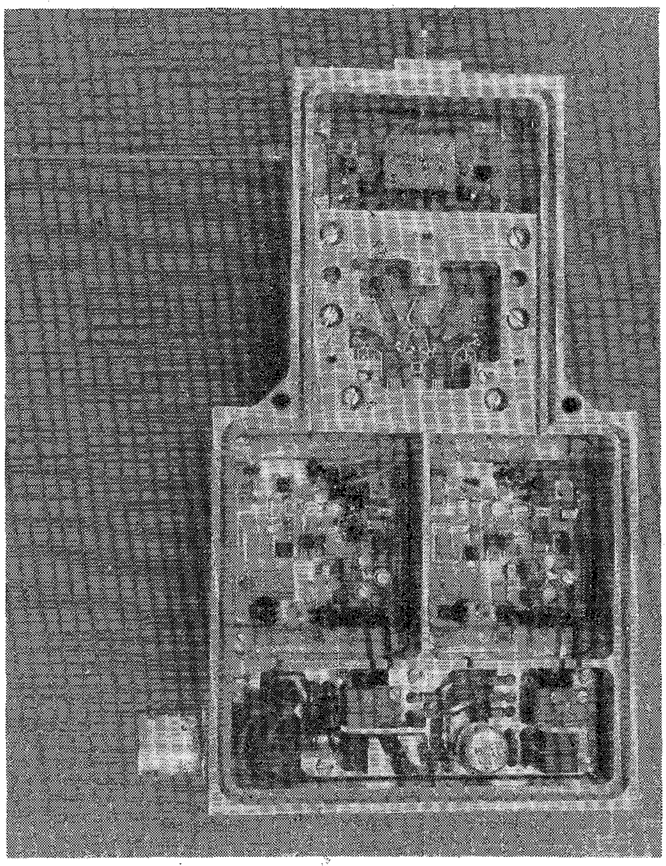

Fig. 3. SSB modulator unit (*W*-band).

is contained in the base of the box. The BITE circuitry monitors mixer diode and IF amplifier current, thus providing a fault indication.

B. SSB Down and Up-Converters (Image-Rejection Mixers)

Image-rejection mixers designed for *V*-band (50–75 GHz) and *W*-band (75–110 GHz) are shown in Fig. 2. Both units incorporate quartz circuits (10 mm×10 mm×0.12 mm), and diode bias and IF amplifier thick-film circuitry. The basis of the design is integration of two balanced mixers described previously, with signal-fed in-phase and LO in quadrature; a 90° IF phase shift is introduced by a 3-dB IF hybrid. (The *V*-band unit is at the bottom and the *W*-band unit is in the center of Fig. 2.)

C. Simple FM CW Receiver

Fig. 2 also demonstrates a simple 94-GHz FM CW receiver unit (top of photograph). The circuit includes 10-dB coupler, circulator, and balanced mixer circuit functions combined on a single substrate (10 mm×10 mm×0.12 mm).

D. DSB Upconverter and Balanced Mixers

Fig. 3 shows a complex subsystem, for application at 94 GHz, comprised of a double-sideband modulator used as an upconverter, in which both the upper and lower sidebands are accessed separately and used as local oscillator feeds to two balanced mixers. The IF amplifiers, IF

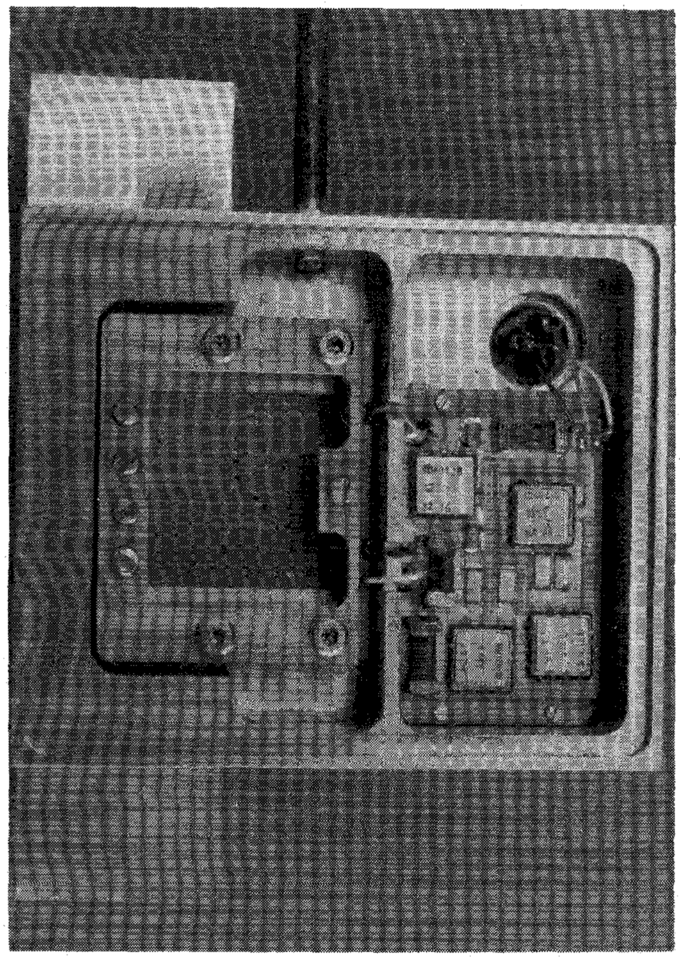

Fig. 4. Integrated hermetic sealed unit (*W*-band).

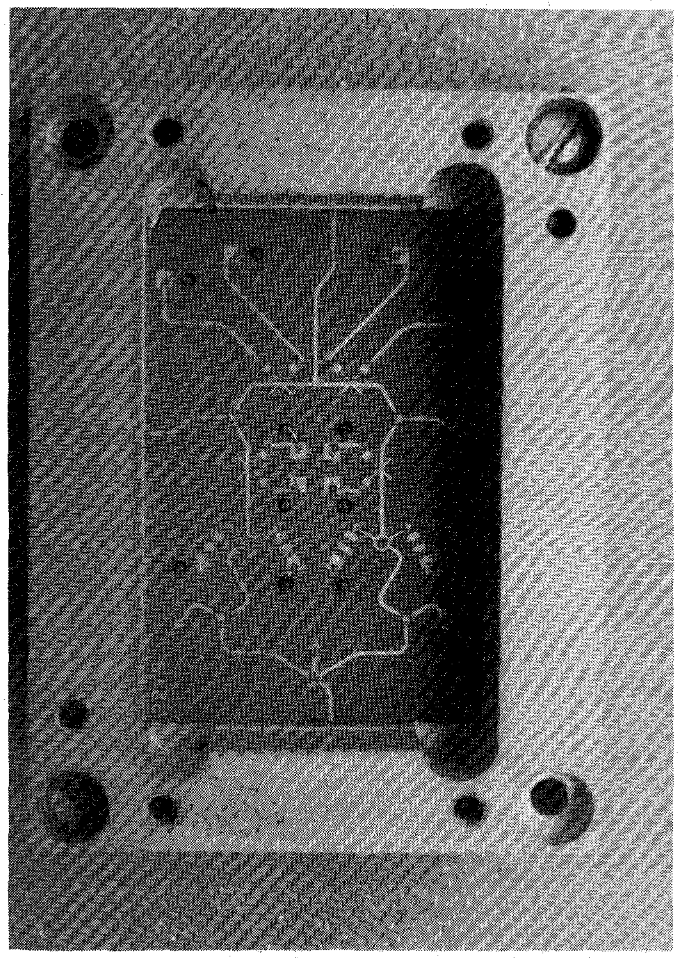

Fig. 5. Radar receiver/duplexer unit (*W*-band).

quadrature power divider, and voltage regulator diode bias circuitry are contained within the unit. The microstrip circuit substrate size is 26 mm×24 mm×0.12 mm.

This unit illustrates several advanced techniques used to provide performance and mechanical advantages, which are now being applied to hybrid microstrip military millimeter-wave front-end designs. For example: low LO drive mixer designs are utilized which provide 7-dB conversion loss for 1.0-mW drive level; beam-lead p-i-n diodes are used as limiters, with bias derived from the beam-lead mixer diodes, to protect the mixers against CW power overload such that the unit withstands an input power of 1-W CW; the waveguide to microstrip *E*-plane probe transition design is used to provide sealed waveguide windows and a compact structure; the package is hermetically sealed, a pumping stem is used for leak testing, and the unit is backfilled with an argon/helium mixture before the pumping stem is pinched off.

An additional 94-Ghz sub-system, which uses the probe transition design approach to provide an integrated hermetic sealed military environment unit, is illustrated in Fig. 4.

E. Radar Receivers/Duplexers

A unit which performs the function of a dual-channel radar receiver/duplexer, operating at 94 GHz, is shown in Fig. 5. This clearly illustrates the high-level integration potential of the hybrid microstrip technology. The circuit contains two balanced mixers, four p-i-n switches, two isocirculators, two circulators, a rat-race power splitter, and a "tee" power splitter. The circuits are all fabricated on a single-quartz substrate (30 mm×20 mm×0.12 mm). Low-frequency thick-film circuitry is contained in the base of the package.

V. Local Oscillator

The essential circuit function, which is not yet available using hybrid microstrip technology with an acceptable system performance, is the local oscillator. The current practical system approach to the application of millimeter-wave integrated receivers is to adopt the lower frequency MIC experience and provide a circuit port for an externally connected "bolt-on" waveguide oscillator. This currently provides the best oscillator performance characteristics in terms of noise, stability tunability, ruggedness, etc. Very compact (20-mm cube) varactor-tuned GaAs Gunn VCO's are now being designed. These units can provide about 15-mW power, 2-GHz electronic tuning range at 94 GHz, with low noise, good stability characteristics, etc. [8].

The design approach of an externally connected oscillator is acceptable for many applications; microstrip integration, however, is still a preferred feature. Current forms, although simple in construction, still suffer from the major disadvantage of low Q, poor stability, and poor noise characteristics. A compromise between an externally connected waveguide oscillator and a microstrip integrated oscillator is to use partially integrated oscillator structures. This implies incorporating the high-Q waveguide cavity in a sub-assembly structure [9].

VI. Conclusions

Millimeter wavelength hybrid microstrip technology is built on a production MIC basis which is finding wide applications at microwave frequencies. The technology is now considered to be sufficiently established to meet millimeter-wave system requirements. As generally accepted at microwaves, the technology also provides a more versatile basis at millimeter-wavelengths than any other hybrid technology.

It is of significant interest to note that it is the low-frequency circuitry and waveguide flange connections which dominate and depict the sub-system package size, not the RF quartz substrate circuits. There would be little advantage in reducing the substrate size by the use of higher permittivity materials; more compact forms of waveguide flange and low-frequency circuitry would provide greater benefit. The main present limitation on fulfilling a complete front-end design basis is the realization of an acceptable performance integrated oscillator. The ultimate application of integrated oscillators offers a particular advantage in compactness and implies that the package will require only antenna port RF connections.

In conclusion, it is considered that this technology provides a very competitive basis and is a leading contender (over the next 10 years) to meet the volume production demands of the missile-seeker market. Circuit designs are well understood and repeatable; production techniques are applicable to active devices, quartz circuit fabrication, and packaging; volume quantities will obviously require the introduction of production practices that provide reduced costs.

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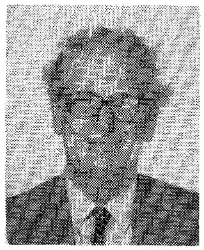

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