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MILLIMETER-WAVE MONOLITHIC INTEGRATED CIRCUITS

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ABSTRACT

This paper summarizes the progress, trends, and technical issues associated with monolithic millimeter-wave effort. Presented first is background information intended to set forth: a description of the opportunities which spur this effort; and a summary of some of the important technical challenges. Next, a discussion is provided of recent performance for semiconductor device types and circuit media which serve as building blocks for this technology. Then a description is provided of salient monolithic programs which benchmark the status of current effort. The paper concludes with a summary of technical issues and thrusts.

BACKGROUND

The opportunities offered by monolithic millimeter-wave technology span radar, communications, electronic warfare, and missile seekers. These opportunities relate to size (see Figure 1), weight, and cost reduction advantages over standard metal waveguide and hybrid integrated circuit implementations. Additionally, although potentially useful millimeter-wave semiconductor devices are being pursued in GaAs, InP, silicon, and silicon carbide, recent effort (e.g. (1)) in the VLSI arena may portend new opportunities for merging monolithic concepts in different materials for higher frequencies. However, specific technical challenges remain in realizing some important circuit building blocks.

CIRCUIT BUILDING BLOCKS

Circuit building blocks for monolithic millimeter-wave ICs encompass semiconductor devices and transmission line media. Table 1 lists most of the semiconductor device candidates for use in millimeter-wave source, mixer/detector, and modulator circuit functions. Of these, the most well established candidates are: the IMPATT, TED, and MESFET for sources; the Schottky diode, Josephson junction diode, and MESFET for mixers/detectors; and the PIN diode and MESFET as modulator elements. As is suggested by the multitude of source candidates, current efforts are exploring new concepts to achieve reasonably high output power levels (25 mW or higher) with reasonable efficiency (dc to RF) for above 60 GHz applications, especially in three-terminal device configurations. Some notable achievements in this pursuit involve the PBT, HJBT, and pseudomorphic FET. Lincoln Laboratories has reported a two-stage PBT amplifier with 17.3 dB gain at 40.5 GHz and a single-stage device producing 54 mW with 7.3 dB gain and 41% power-added (PA) efficiency at 20 GHz. General Electric Company reports a pseudomorphic HEMT in a strained-layer InGaAs material system which has achieved 6.7 dB gain at 94 GHz and 22 mW output power with 3 dB gain and 20 to 28% PA efficiency at 62 GHz. Rockwell has reported measured f_{max} of 105 GHz and f_t of 55 GHz for their HJBT in AlGaAs.

The transmission media most commonly considered for monolithic millimeter-wave ICs are standard microstrip, coplanar waveguide, and fin line or slot line. Figure 2 provides data on unloaded Q for these transmission line structures as well as other millimeter-wave circuit media, including non-monolithic structures such as metal waveguide (dashed line) and image line. This information provides a reasonable, relative assessment of the various candidates and illustrates that the monolithic oriented media (e.g. slot line, microstrip, coplanar waveguide) offer some of the lowest Q values available. Table 2 qualitatively summarizes some of the more significant circuit medium properties for monolithic-compatible media, hybrid IC compatible media, and metal waveguide.

It is becoming increasingly apparent that for monolithic IC designs new and more refined models are needed for semiconductor device representations and for treatment of device to circuit-medium interfaces (e.g. parasitic effect treatment), especially for these higher frequencies. Once such models are developed and verified, it would be desirable to have such design capability available in a mode which is widely accessible. Possibly CAD workstation equipment could incorporate a software base for such a purpose.

In the area of testing there are at least two important needs. One is to expand the commercial availability of error-correcting, automated network analyzer equipment to at least 100 GHz.

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Also, a need exists for on-chip wafer prober units to function accurately and reproducibly over the same frequency range.

RECENT/CURRENT MONOLITHIC EFFORTS

Monolithic efforts to date have focused primarily on non-transmitter related functions. This trend is observed in the listing of representative programs provided in Table 3. A notable exception in this list is the 32 GHz transceiver program (2). This program employs an approach where the output of a microwave source is frequency multiplied to provide a 32 GHz transmit signal. Other activities await efforts either to refine and improve existing source devices in planar format or to innovate devices for signal generation directly at the millimeter wave frequency of interest.

To best illustrate the technology being pursued in the monolithic receiver area, attention is drawn to the second entry in Table 3. This program provides a technology base for receivers to operate instantaneously over the full 75 to 110 GHz frequency range. The focus of this development is the receiver front end configuration depicted in Figure 3. This configuration requires: four mixers, four common IF amplifiers, four local oscillators, and an RF multiplexer. In selecting the RF and IF bands for this configuration, two extensive spur analyses were performed (3,4). Initial effort pursued development of the individual functions necessary for the realization of such a receiver front end. This effort included: a wideband mixer for a representative channel; an 8.5 to 17.5 GHz IF amplifier; a local oscillator for the channel; and small area filters and hybrids for the multiplexer. The layout of the balanced mixer is shown in Figure 4. This circuit is processed on a semi-insulating GaAs substrate with the resultant chip size being 0.75 in. x 0.75 in. x 0.004 in. The mixer uses a pair of Schottky diodes processed by VPE and has produced conversion loss over the 75 to 110 GHZ band of 5 to 9 dB.

The developed IF amplifier is shown in Figure 5. This GaAs chip is 2.18 mm x 1.50 mm x 0.1 mm and displays a two-stage amplifier employing two 1/2 x 300 μm FETs. MOM capacitors are used for both RF bypass and dc blocking purposes. High airbridges are processed to connect source pads and upper contacts of MOM capacitors. The design is expected to produce gain and noise figures of 11 to 13 dB and 2 to 4 dB, respectively, across the 8 to 18 GHz band. To date nominal gain of 7 to 9 dB and noise figures of 3 to 4 dB have been observed. These discrepancies are attributed to variations from design characteristics in the FETs and MOM capacitors.

The local oscillator function is being pursued both in MESFET form and in TED form. The MESFET approach is examining both oscillation directly at the frequencies of interest and the combination of half frequency oscillation followed by frequency doubling.

Finally, preliminary Lange couplers and interdigital bandpass filters have been developed to serve as functional elements for the multiplexer approach depicted in Figure 6.

TECHNICAL ISSUES/THRUSTS

The technical issues and thrusts of this technology span a broad range of facets. To date the GaAs MESFET appears to be the premier source candidate for many applications up to 60 or 70 GHz. Above these frequencies both traditional and novel devices are being pursued with strong focus on heterostructure devices. Source device materials focus heavily on GaAs; although InP, silicon, and silicon carbide are also receiving attention. GaAs Schottky diodes are the current workhorse for many monolithic mixer programs. Substantial effort in this area pursues wide instantaneous bandwidth mixing. Integrally associated with this pursuit are issues of receiver circuit architectures and in some cases, associated multiplexing concepts. Finally, the areas of device and circuit modeling, computer aided design, and automated, error-correcting testing need increased emphasis to expedite the advancement of this technology.

REFERENCES

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Table 1 DEVICE CANDIDATES

SOURCES:

- IMPATT
- TED
- MESFET
- MODFET
- HJBT
- CHINT
- NERFET
- OGST
- PBT
- PDBT
- CHIRP (superlattice)
- QUANTUM-WELL (QST)
- DIMPATT
- SSTWA
- SS-OROTRON
- SS-MAGNETRON
- SS-GYROTRON
- SPACE-HARMONIC AMPLIFIER
- PSEUDOMORPHIC MODFET

MIXER/DETECTOR:

- SCHOTTKY DIODE
- JJ/SIS
- MESFET
- MODFET
- CHIRP
- QUANTUM-WELL

MODULATORS:

- PIN
- MESFET

Table 3

MILLIMETER-WAVE MONOLITHIC IC EFFORTS

- 32 GHz TRANSCEIVER
- 75 TO 110 GHz RECEIVER TECHNOLOGY
- 27.5 TO 30 GHz RECEIVER
- 35 TO 38 GHz RECEIVER
- 44 GHz GaAs IMPATT OSCILLATOR
- 90 TO 100 GHz RECEIVER
- 110 GHz QUASI-OPTICAL MIXER
- 215 GHz DETECTOR DIODE ARRAY
- 44 GHz PIN PHASE SHIFTER
- K_a-BAND PIN DIODE WINDOW COMPONENTS
- 30 GHz MESFET ATTENUATOR
- 30 TO 50 GHz, 60 TO 65 GHz, AND 75 TO 100 GHz SWITCHES
- 44 GHz RECEIVER

Table 2 SUMMARY OF CIRCUIT MEDIUM PROPERTIES

PROPERTY	WAVEGUIDE	HYBRID IC'S	MONOLITHIC IC'S
APPLICABLE FREQUENCY	1 GHz TO 300 GHz	1 GHz TO APPROX 70 GHz	1 GHz TO 100 GHz$^+$
RELATIVE COST	HIGHEST	MODERATE TO HIGH	LOWEST
SIZE	LARGEST	MEDIUM	SMALLEST
RF COMPONENT AVAILABILITY	GREATEST	EXTENSIVE	LIMITED
BANDWIDTH CAPABILITY	LESS THAN OCTAVE	GREATER THAN OCTAVE	GREATEST
CONNECTOR AVAILABILITY	COMPLETE	COMPLETE	NEEDS DEVELOPMENT
SOLID-STATE DEVICE COMPATIBILITY	POOR	FAIR/GOOD	BEST
MODELING DATA BASE	COMPREHENSIVE	MODERATE	INCOMPLETE
POWER HANDLING	BEST	MODEST-ARRAYS NEEDED	MODEST-ARRAYS NEEDED
REPEATABILITY	POOR	FAIR	POTENTIALLY EXCELLENT
LOSSES	LOW	MODERATE	HIGHEST
VOLUME PRODUCTION SUITABILITY	POOR	MODERATE	BEST

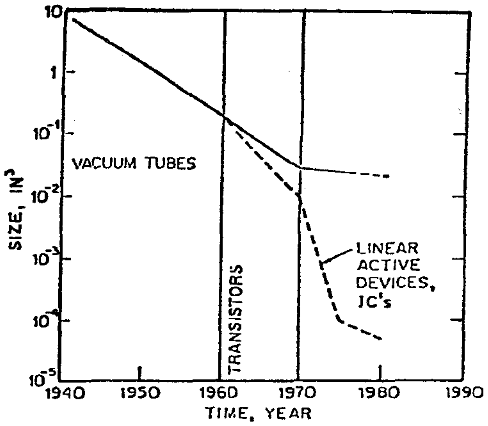

Fig. 1 Component Size Reduction

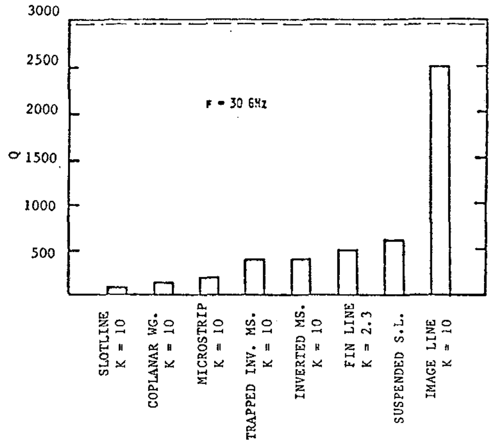

Fig. 2 Representative T-Line Unloaded Q's

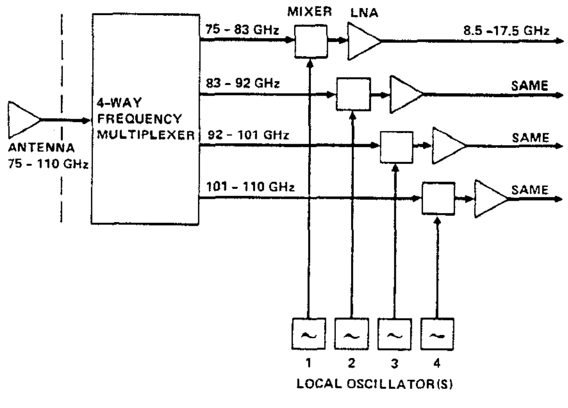

Fig. 3 Four-Channel Receiver Front End

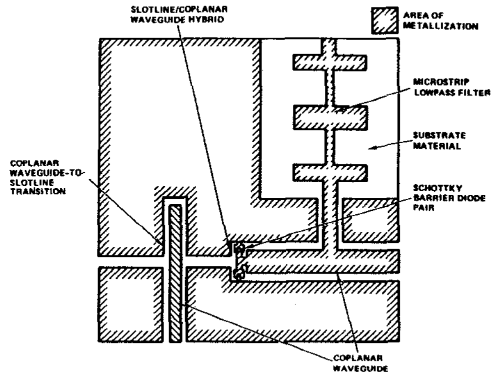

Fig. 4 Planar Balanced Monolithic Mixer Circuit

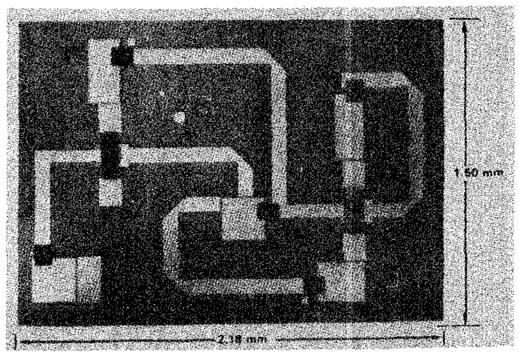

Fig. 5 8 to 18 GHz Monolithic Low Noise Amplifier

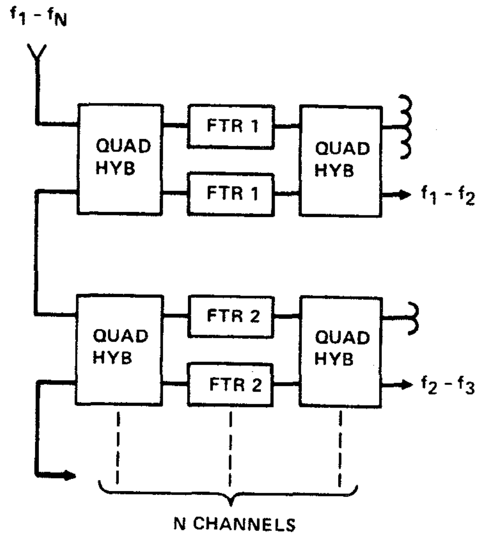

Fig. 6 Multiplexer Configuration