Ka-Band Front End With Monolithic, Hybrid, and Lumped-Element IC's

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Abstract —A *Ka*-band front end has been developed which integrates a low-loss wide-band monolithic mixer, a two-stage hybrid IF amplifier, and a lumped-element Gunn local oscillator (LO). Small size (0.5 cubic in), high performance, and potentially low production cost have been demonstrated through the application of highly compatible IC construction techniques.

I. Introduction

In recent years, it has become increasingly important to reduce the size and cost of millimeter-wave (MMW) receiver front ends. Applications, where such reductions are particularly important, include electronic warfare (EW) frequency-extension programs, radiometric seekers, and phased-array radars. To address these needs, we are currently engaged in a multiyear development program. The object of the program is to develop MMW IC components and to integrate them to form general-purpose demonstration receivers. Of special interest is the *Ka*-band receiver front end, which was briefly outlined at the 1985 MTT-S Symposium [1] and is described here in detail.

Although monolithic techniques are favored for high-volume production runs, the hybrid IC approach appears to be better suited to limited production runs. Therefore, to keep our investigation general, we have chosen to include both monolithic and hybrid IC's in our work. However, by utilizing the same materials and processes in many of our monolithic and "hybrid" circuits[1] we have the ability to tailor our generic components to specific applications as they arise. Thus, circuits that currently require some bonding operations can be upgraded to fully monolithic circuits when required.

II. Preferred Design Approach

After studying a wide range of alternative construction techniques and block diagrams for the demonstration front end, a preferred design approach was chosen. It was decided that most circuits would be developed in microstrip, with semi-insulating GaAs as the substrate material. *Ka*-band was chosen as the RF band, to address a wide range of forward-looking programs. (The design and construction techniques that were utilized, however, are applicable to other RF bands in the range of 1–120 GHz.) To maximize the unloaded Q in the selected RF band, the thickness of the substrate was chosen to be 5 mil [2]. Regarding the block diagram of the demonstration front end, it was decided that the hardware should at minimum include a balanced mixer, a two-stage IF amplifier, and a local oscillator (LO).

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[1]The term "hybrid" is used in this paper to include those circuits which mix monolithic elements and discrete devices on a single substrate. Such circuits, which are comparable in size to fully monolithic circuits, are sometimes called quasi-monolithic.

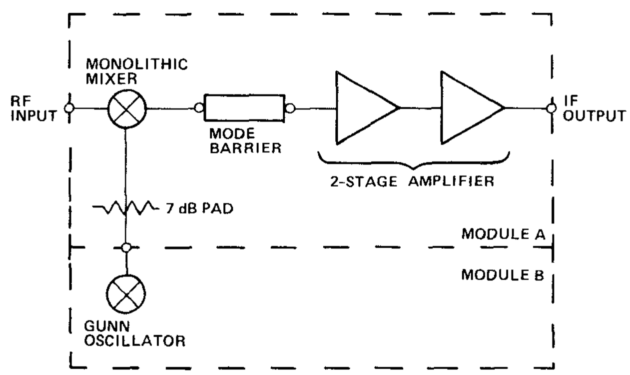


Fig. 1. Block diagram of an integrated front end.

Fig. 1 shows the block diagram of the preferred front end, which is assembled in two modules. This configuration was selected to address a broad range of system applications and exploit the capabilities of compatible IC construction techniques. Module A includes a monolithic balanced mixer and a two-stage IF amplifier. Rather than directly integrating these components, and risking LO feedthrough via higher order modes, a short length of 50-Ω line (a mode barrier) is utilized. Also contained in Module A is a 7-dB pad, which ensures a good LO input SWR during unpumped (start-up) conditions. Module A can be tested with a remote LO, or it can be integrated with the Gunn LO contained in Module B. Details on the front-end components and their constituent device and circuit elements are contained in the following sections.

III. Monolithic Mixer

The entire balanced *Ka*-band mixer and an enlarged view of one mixer diode are shown in Fig. 2(a) and (b), respectively. The entire mixer circuit measures 5 by 140 by

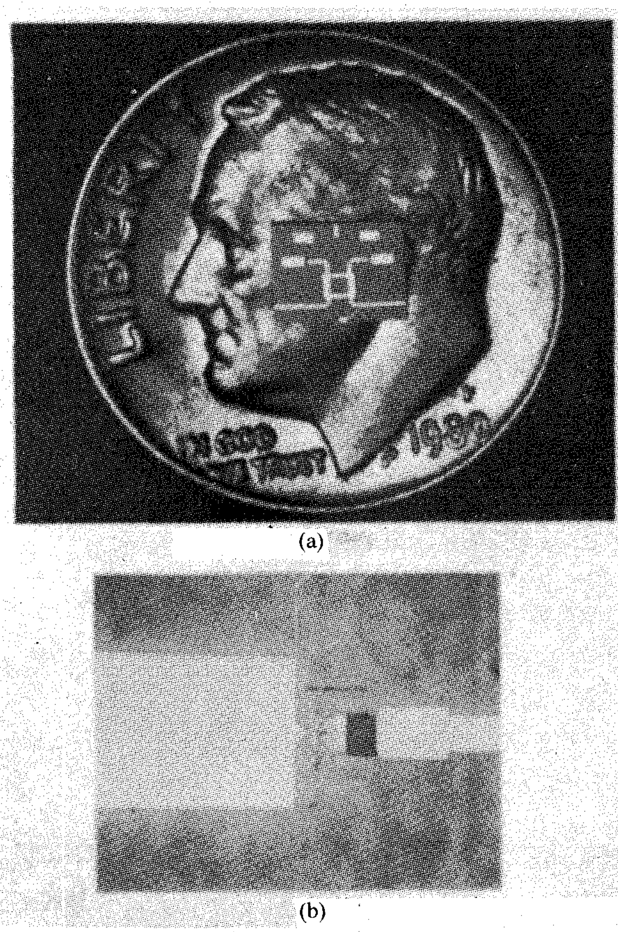


Fig. 2. Monolithic *Ka*-band mixer. (a) Entire circuit. (b) Enlarged view.

180 mil, and includes a single-section branch-line coupler, diode-matching networks, and an IF output filter. Each of these circuit elements was independently optimized, in a precision test fixture, prior to the mixer integration.

The test fixture, shown in Fig. 3, allows accurate measurements to be made of the microstrip components with standard waveguide instrumentation. The test housing contains parallel WR-28 waveguides that are linked by an *E*-plane channel. The channel accommodates a carrier containing microstrip substrates, which are fabricated from 5-mil Duroid and semi-insulating GaAs. Although this multisubstrate approach requires extra assembly operations, it proved to be particularly useful in the early development work. The advantages of this approach include the following.

1) Unlike GaAs, the Duroid substrates are not brittle; although they are supported only at the edges of the waveguide, they are not subject to breakage.

2) The size of the GaAs circuit can be minimized; this reduces the risk of breakage and allows many circuits to be processed on a single wafer.

3) The waveguides can be widely spaced; this avoids spurious coupling between the input and output ports via higher mode propagation.

Referring to Fig. 3, a signal entering one of the WR-28 ports will be coupled into the microstrip probe that is printed on one side of the 5-mil Duroid board. The probe is reactively terminated by a noncontacting back-short whose location can be varied to optimize the impedance match. The signal continues through the GaAs microstrip and is launched into the output waveguide by another probe transition. Measurements show that each transition has a return loss of 16 dB or better and an insertion loss of 0.35–0.5 dB across the band of 32–35 GHz.

With the aid of the waveguide fixture, the dimensions of the hybrid coupler and diode-matching networks were optimized. (The coupler was tested as a two-port network, with internal terminations at the remaining ports.) As a further step in the optimization, the complete mixer was tested as a hybrid circuit [3] prior to the monolithic realization. This circuit, shown in Fig. 4, contains beam-lead diodes that were bonded to the GaAs substrate. Measurements in the waveguide test fixture showed a minimum conversion loss of 6.2 dB, with a useful instantaneous bandwidth of over 5 GHz.

After completing the hybrid tests, some refinements were incorporated in the circuit elements, and a fully monolithic mixer was constructed. The monolithic diode (Fig. 2(b)) is a high-cutoff mesa device, similar in construction to our earlier discrete devices [4]. The processing features tantalum–gold metallization and plasma dry-etch techniques. These techniques result in excellent uniformity and high yield over large wafer areas (up to 6.5 cm^2).

The monolithic mixer is fabricated on an epitaxial GaAs wafer that has an n-layer carrier concentration of $3–5\times10^{16}$ cm^{-3} and a thickness of 0.1 μm after processing. The underlying n^+-layer has a thickness of 1.0–1.5 μm, with a carrier concentration of 2×10^{18} cm^{-3}. High reliability is assured by double passivation (sputtered SiO_2 and Si_3N_4 layers), which also serves as the base for the distributed-circuit metallization. Windows were opened through the passivation layer to evaporate ohmic contacts consisting of AuGe–Au. Finally, the circuit was completed by pulse-plating a gold airbridge connection between the ohmic contact and the distributed circuit.

A typical forward voltage–current ($V–I$) characteristic for the monolithic device is shown in Fig. 5. From this plot, it can be determined that the ideality factor is 1.05 and the series resistance is 2.4 Ω.

To measure the RF performance of the mixer, the chip was mounted in a three-port fixture, with special (40-GHz)

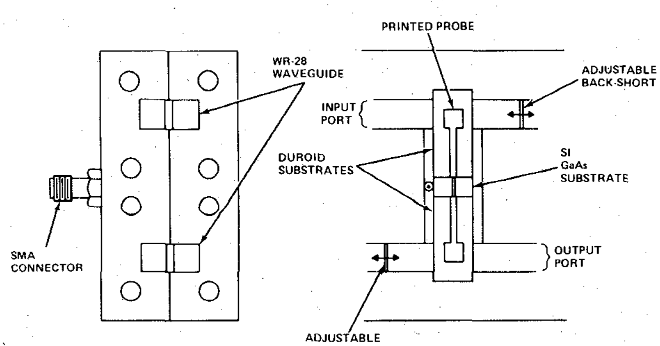


Fig. 3. Waveguide/IC test fixture.

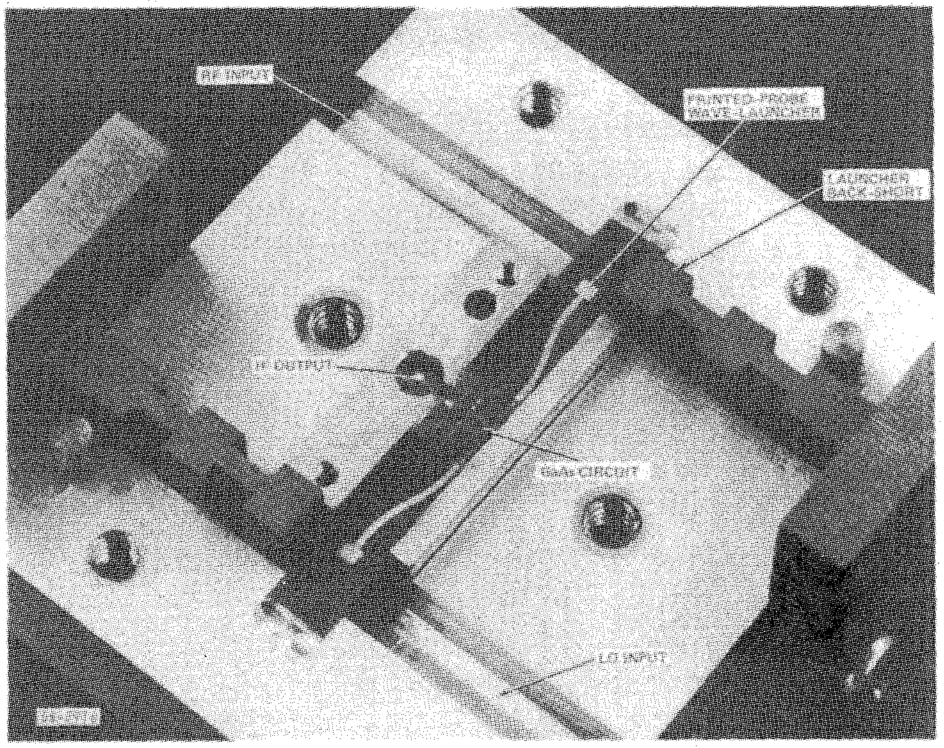


Fig. 4. Mixer in waveguide test fixture.

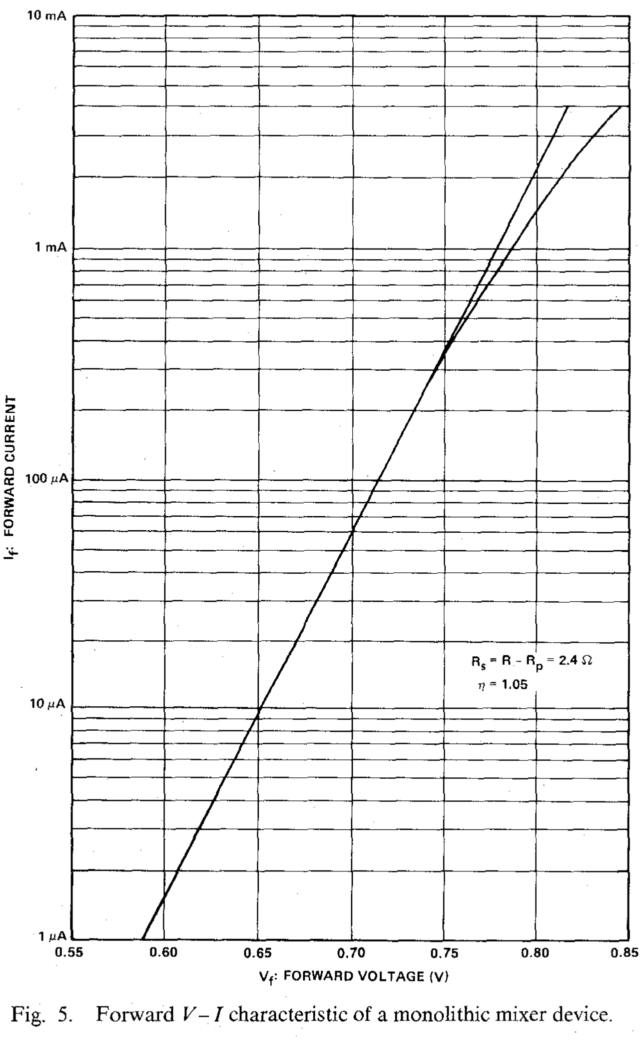


Fig. 5. Forward $V-I$ characteristic of a monolithic mixer device.

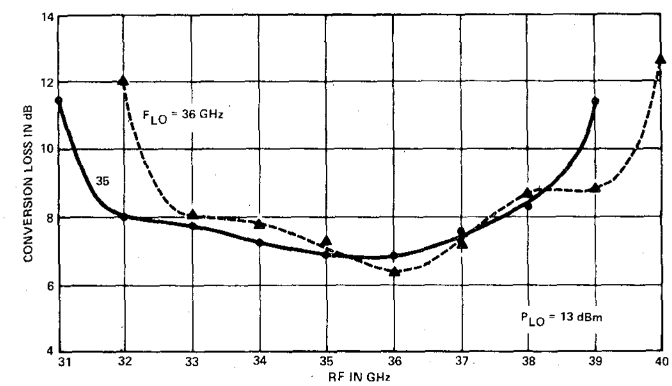


Fig. 6. Conversion loss of a monolithic mixer.

SSMA connectors and low-loss coax/waveguide transitions. Fig. 6 shows the conversion loss of the mixer, as measured at the optimum LO drive level of 13 dBm. With the LO fixed at 36 GHz, the minimum conversion loss is 6.3 dB and the 3-dB bandwidth is 7 GHz. Correcting for the connector and transition loss, the minimum conversion loss of the mixer is estimated to be 5.3 dB. This performance compares favorably with the best reported results for *Ka*-band monolithic mixers [5], [6].

IV. IF Amplifier

Another key component in the front end is the two-stage IF amplifier. Each stage is realized as a hybrid IC on a 5-mil semi-insulating GaAs substrate. This approach allows for compatibility in the processing of the mixer and IF chips. Moreover, the IF chip can be upgraded to a fully monolithic circuit, when desired, with further work. (A long-range goal of this program is to produce an entire receiver on a single chip.)

Each stage is a lumped-element lossy feedback amplifier, with a commercially available GaAs device (Mitsubishi MGFC 1402). The circuit layout and schematic diagram of one stage are shown in Figs. 7 and 8. Parallel feedback is used for gain flatness and reduced input–output VSWR.

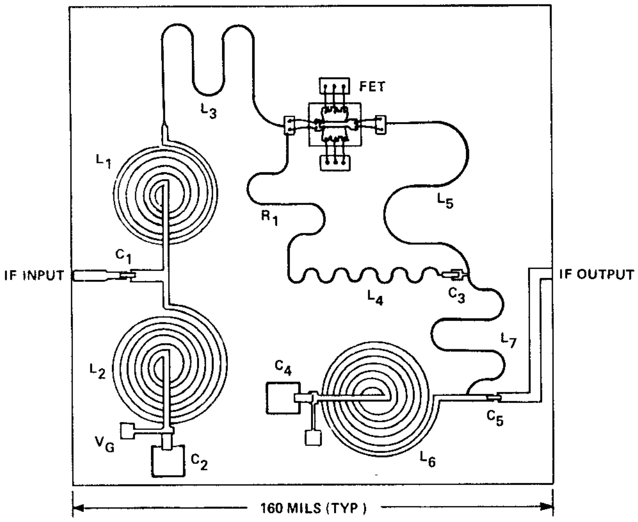


Fig. 7. Circuit layout for a one-stage IF amplifier

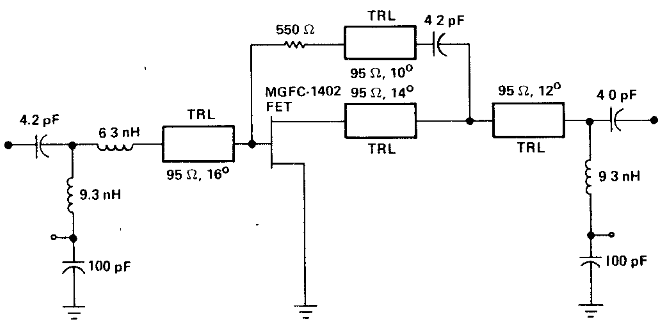


Fig. 8. Schematic diagram of a one-stage IF amplifier.

Reactive input and output networks are included for further VSWR reduction, and to provide convenient bias-injection points. The feedback resistor R_1 is achieved with a tantalum-film meander line, whose width is 25 μm. All capacitors are overlay types, with a tantalum-oxide dielectric and an airbridge connection to the adjacent element. The bypass capacitors (C_2 and C_4) include via-holes which connect the bottom plate to the microstrip ground plane.

The processing steps for fabricating the lumped elements are shown in Fig. 9. The process begins with the *in situ* deposition of seven layers of Ta, Au, and Ta_2O_5 (Fig. 9(a)). Next, the layers are selectively etched to form the lumped elements of Fig. 9(b). The resistors are defined by a combination of wet- and dry-etch techniques. All the other elements are defined entirely with plasma dry-etch techniques.

After this, via holes are added to form a low-inductance ground to the rear-surface metallization (Fig. 9(c)). Finally, airbridges are added, as shown in Fig. 9(d).

The elements that were processed and evaluated include:

interdigital capacitors (0.1–1.2 pF),
overlay capacitors (0.5–160 pF),
meander inductors (0.5–2.5 nH),
spiral inductors (3.4–9.3 nH), and
meander resistors (300–1000 Ω).

Some examples of typical lumped elements are shown in Fig. 10. After the processing, RF testing was performed to determine the equivalent circuit and useful frequency range for each element. Examples of typical equivalent circuits, unloaded Q's, and self-resonant frequencies (SRF's) are presented in Fig. 11.

Following the characterization of isolated elements, a one-stage amplifier was designed and tested. Fig. 12 summarizes the key performance features of the amplifier. Across the design band of 1–2 GHz, the measured gain was 10.5 ±0.4 dB and the noise figure was 2.5 ±0.2 dB. Additional measurements showed that the input/output

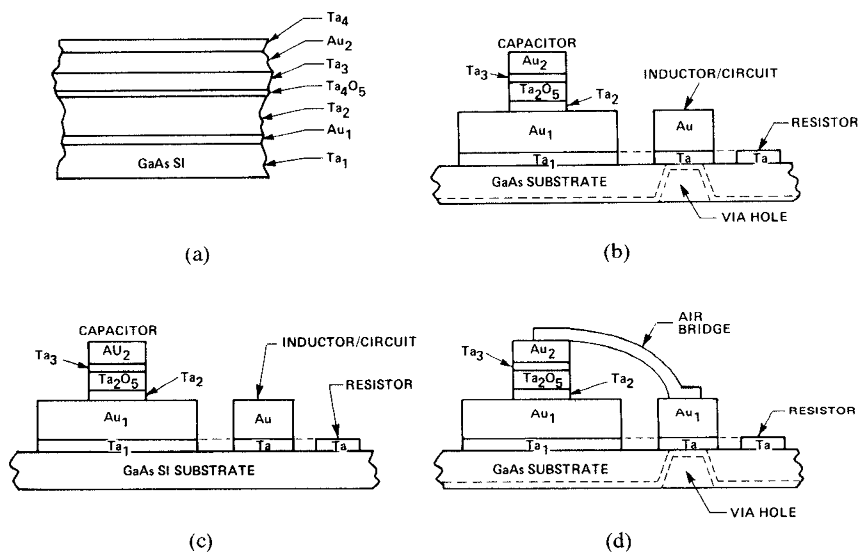


Fig. 9. Processing steps for fabricating lumped elements.

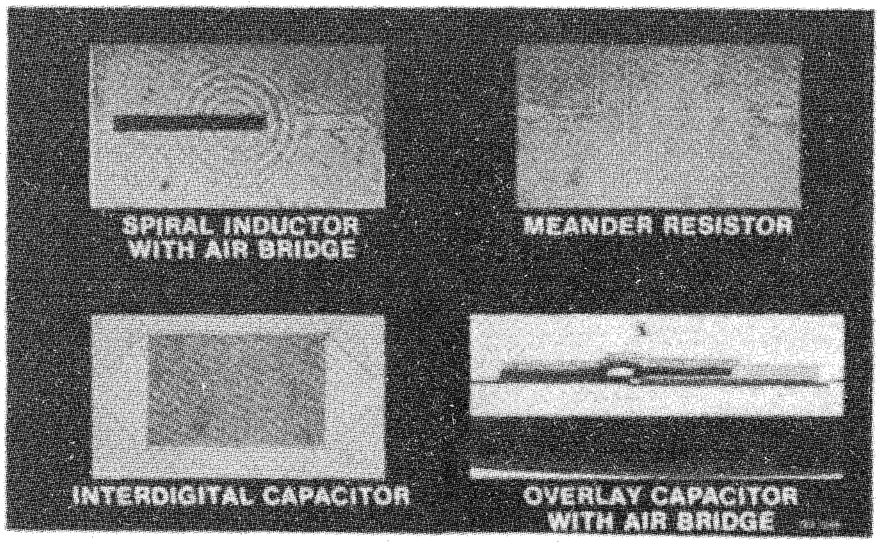
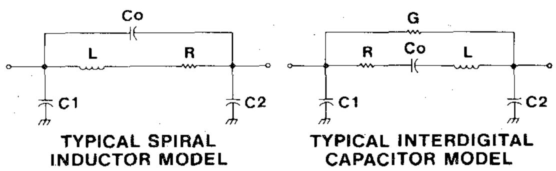


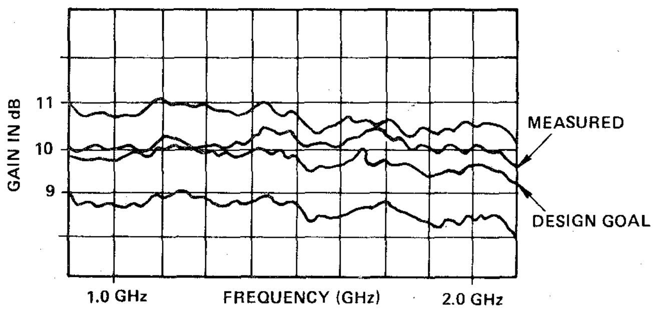
Fig. 10. Lumped elements on semi-insulating GaAs.



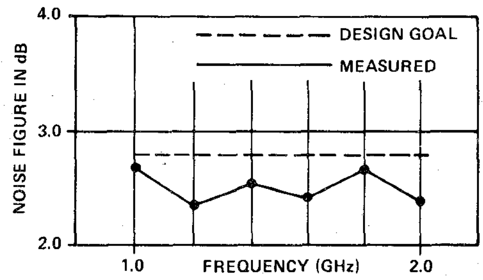
TYPICAL FIGURES OF MERIT

ELEMENT TYPE	VALUE	Qa/GHz	SRF
INTERDIGITAL CAPACITOR	0.6 pF	270	55 GHz
SPIRAL INDUCTOR	6.0 nH	30	3.2 GHz
OVERLAY CAPACITOR	0.6 pF	300	21 GHz
MEANDERED RESISTOR	500 Ω	-	-

Fig. 11. Lumped-element characterization.



(a)



(b)

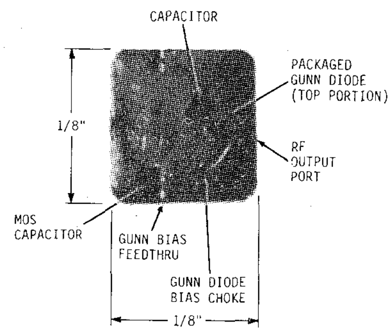
Fig. 12. IF amplifier performance. (a) Gain. (b) Noise figure.

SWR was less than 1.9:1 and the output power for 1-dB gain compression was +10.8 dBm. This performance is in good agreement with the computer-aided design analysis.

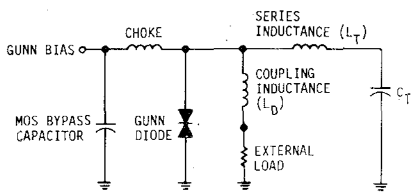
V. Local Oscillator

Module A contains a 7-dB pad, which ensures a good LO input SWR during unpumped (start-up) conditions. A coax connector can be attached to the input of the pad, for external LO operation. Alternatively, a lumped-element Gunn oscillator (in Module B) can be substituted for the LO connector.

As in an earlier design [7], the lumped-element oscillator features small-size (0.1 cubic in) and minimum parts count. The construction features and the equivalent circuit of the oscillator are shown in Fig. 13(a) and (b), respectively. The



(a)



(b)

Fig. 13. Lumped-element oscillator. (a) Photograph of an oscillator circuit. (b) Circuit diagram.

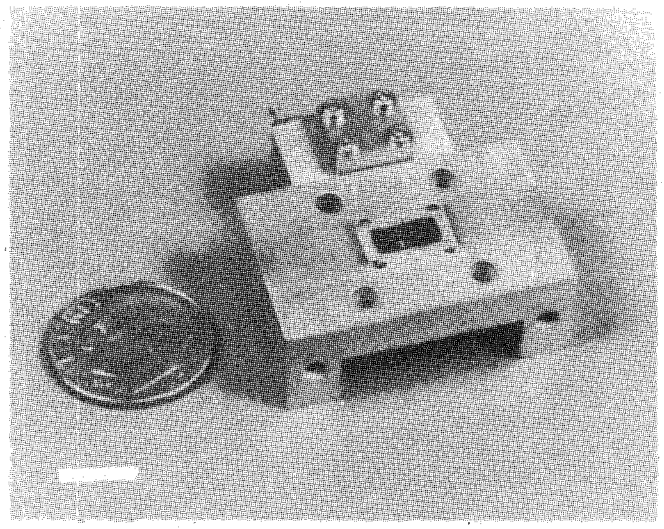


Fig. 14. Oscillator with a waveguide test fixture.

output of the oscillator is a subminiature coax cable (UT-34), which can interface with a waveguide test fixture (Fig. 14) or Module A. The oscillator requires 4.9 Vdc at 1.1 A, and provides a power output of +18.7 dBm at 35 GHz.

VI. Integrated Front End

The previously described components have been integrated to form a microminiature *Ka*-band front end. Fig. 15 shows Module A, which includes the monolithic mixer, LO pad, mode barrier, and two-stage IF amplifier. In addition to the RF, LO, and IF connectors, the housing contains bias pins for dc inputs to the amplifier.

Fig. 16 shows the measured RF–IF gain of Module A, with external LO drive. For each of the indicated LO frequencies, the drive level was held at +12.5 dBm, referenced at the mixer input (i.e., +19.5 dBm at the input to the 7-dB pad). As expected, upper and lower sideband responses appear symmetrically about the LO frequency. An RF–LO gain of 11 dB or better can be achieved across a wide (7.5-GHz) band by step tuning the LO from 33.5 to 36.5 GHz.

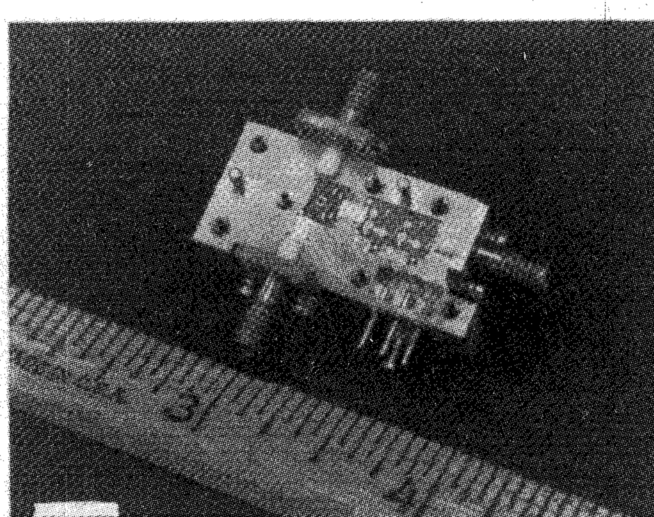


Fig. 15. Module A of integrated *Ka*-band front end.

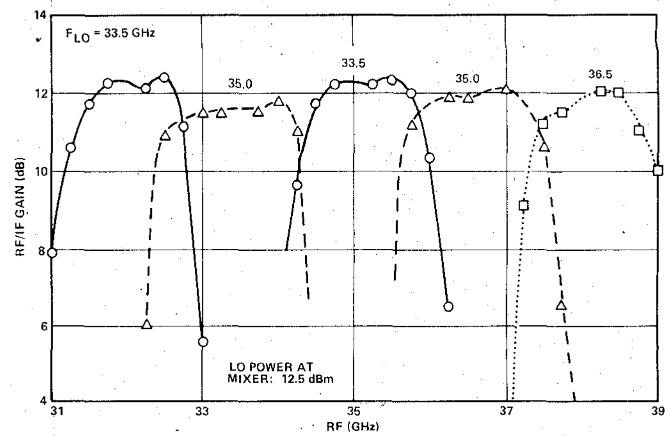


Fig. 16. Conversion gain of front end.

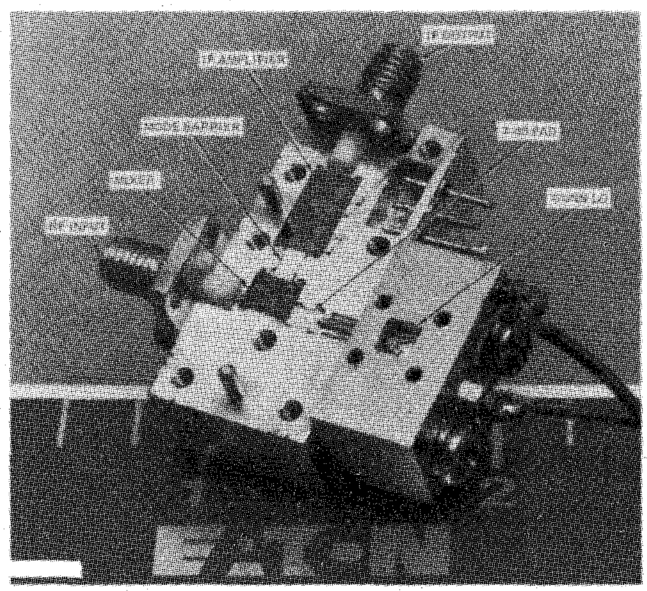


Fig. 17. Entire front end (Modules A and B).

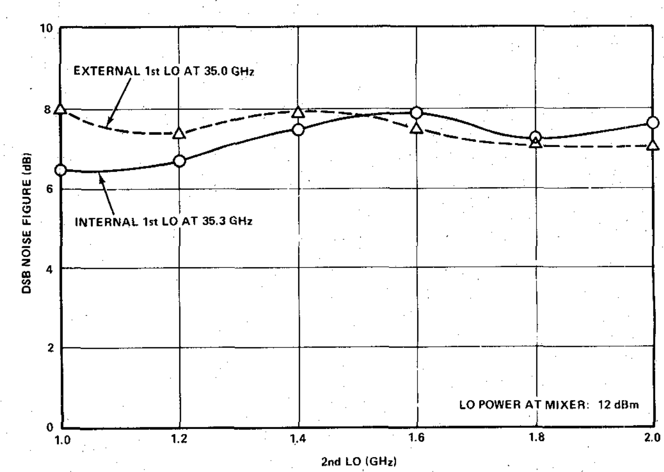


Fig. 18. DSB noise figure of front end.

The noise figure of Module A was also measured. With the LO fixed at 35 GHz, the double sideband (DSB) noise figure was 7 dB for power levels of 11–13 dBm at the mixer input. From this measurement and the known conversion loss of the mixer and the gain of the IF amplifier, it can be shown that the excess noise ratio of the mixer diodes is unity.

After completing the tests of Module A with an external LO, the module was integrated with Module B (Fig. 17). As shown in Fig. 18, good agreement was obtained between the noise-figure measurements with internal and external LO's. Additional measurements, including RF–IF gain, confirm that the mixer integration has been successfully completed.

VII. Conclusions

A *Ka*-band front end has been developed which integrates a low-loss wide-band monolithic mixer, a two-stage hybrid IF amplifier, and a lumped-element Gunn LO. Small size (0.5 cubic in) and high performance (11-dB gain over a 7.5-GHz RF band) have been obtained by applying synergistic IC construction techniques. This type of front end is applicable to a wide range of system applications, including EW frequency-extension programs, radiometric seekers, and phased-array radars.

Acknowledgment

Technical assistance was provided by D. Elliott, E. Dolphy, R. Hans, W. Hrabie, L. Gorney, R. Loveland, and P. Nichols.

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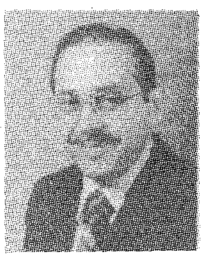


Paul J. Meier (S'55–M'59–SM'69–F'85) was born in New York, NY, in 1936. He received the B.E.E. degree from Manhattan College, New York, NY, in 1958, and the M.S. degree from Long Island University, Greenvale, NY, in 1969.

From 1958 to 1965, he was a Development Engineer, and later a Senior Development Engineer at Wheeler Laboratories, which is now part of the Hazeltine Corporation. There, his work included the study of dielectric-lined and periodically-loaded circular waveguides and their application to phased-array radiators and polarization converters. In 1966, he joined AIL, which is now a division of Eaton Corporation. There, as a Project Engineer in the Radar Techniques Department, he was responsible for the development of phased-array antenna elements and ferrite phase shifters. Later at AIL, he served as a Project Engineer in the Applied Electronics Division on programs resulting in the development of a high-power solid-state switch, an *X*-band MIC sweeping receiver, and a multibeam quasi-optical millimeter receiver. He is currently a Staff Consultant in the Receiver Systems & Technology Department engaged in the development of millimeter-wave hybrid and monolithic integrated circuits. He holds the U.S. Patent for Integrated Fin-Line and has published over 35 papers concerning microwave and millimeter-wave components.

Mr. Meier is a member of Eta Kappa Nu and is a Past-Chairman of the New York/Long Island Chapter of the MTT Committee. In 1984, he received the MTT-S Microwave Applications Award.

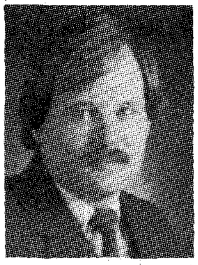
Joseph A. Calviello (M'65–SM'77) was born in Genzano, Italy, in 1933. He received the B.S. degree in electrical engineering and the M.S. degree in electrophysics from the Polytechnic Institute of Brooklyn, Brooklyn, NY, in June 1962 and 1966, respectively. He has successfully completed all course requirements for the Ph.D. degree in electrophysics.

In 1961, he joined the Central Research Group of Eaton Corporation, AIL Division. In June 1973, he was promoted to Research Scientist and, in April 1978, he was promoted to the rank of Senior Research Scientist. Since 1969, he has directed all the semiconductor research and development of state-of-the-art devices such as varactors, beam-lead mixers, hyperabrupt tuning diodes, GaAS MESFET's, as well as studies of epitaxial growth technologies such as molecular beam epitaxy and ion implantation. He has also developed and fabricated high-performance detectors for the submillimeter and optical region. He is presently engaged in the development of high-performance GaAs monolithic microwave integrated circuits. He currently holds 10 patents, and several other patents are pending. He has published over 25 technical papers, and he has made several technical presentations at various conferences and symposiums.

Mr. Calviello is a member of Sigma Xi. He is listed in "Who's Who in the East", "Who's Who in Technology Today", and in the "Directory of World Researchers 1980's." In 1985, he received the Charles Hirsh Award for "contributions to millimeter technology."

Anthony J. Cappello (M'82) received the B.S. and M.S. degrees in electrical engineering from the Polytechnic Institute of New York, in 1980 and 1985, respectively.

He joined the AIL Division of Eaton Corporation in 1980 as a Design Engineer in the Advanced Technology Division. His responsibilities since joining Eaton have been for the design and development of low-noise broad-band amplifiers as well as for the development of microwave filters, attenuators, couplers, and sources. His current technical interests include the development of monolithic microwave integrated circuits and subsystems. He has coauthored several papers and articles on microwave components including monolithic circuits, high-frequency amplifiers, and cryogenically-cooled low-noise FET amplifiers.



Ronald J. Pomian (M'83) was born in Philadelphia, PA, in 1957. He received the B.S. and M.S. degrees in physics from the Pennsylvania State University, College Park, PA, in May 1979 and May 1982, respectively. His graduate thesis work involved the deposition and characterization of amorphous phosphorus thin films and resulted in several publications.

In 1982, he joined the Central Research Laboratory at Eaton Corporation, AIL Division, as an engineer. He has worked on the design and fabrication of microwave devices on gallium arsenide, including mixer diodes, MESFET's, and monolithic circuits.

Mr. Pomian is a member of the American Physical Society.

Leonard D. Cohen (S'48–A'50–M'58) received the B.E.E. degree, cum laude, from the College of the City of New York. He received the M.S.E.E. degree from the Polytechnic Institute of New York, Brooklyn, NY, in 1967.

Prior to 1972, Mr. Cohen was a member of the Technical Staff at General Telephone and Electronics. His work was in the fields of microwave and millimeter-wave solid-state and vacuum electronic devices. He joined AIL in 1972 and is a Consultant in the Receiver Systems and Technology Department, where he is presently engaged in the design and development of solid-state microwave and millimeter-wave components and sources for various system applications. His current responsibilities are with an integrated wide-band millimeter-wave receiver program and a wide-band high-power millimeter-wave VCO program. He has eight patents and 25 publications in the electronics field.

Mr. Cohen is a member of Eta Kappa Nu and is a registered Professional Engineer in New York State.

Paul R. Bie (S'67–M'72) was born in Brooklyn, NY, in 1930. He received the B.S. degree in engineering science from Long Island University, Greenvale, NY, in June 1971.

Since joining the Central Research Laboratories of Eaton Corporation, AIL Division, in 1962, he has worked on the development and fabrication of several *III–V* compound semiconductors. Since 1966, he has worked exclusively on the development of gallium arsenide devices. This includes p-n and Schottky varactor diodes, metalized and beam lead mixer devices. He is currently working on MESFET devices and monolithic circuit applications.