MONOLITHIC 40GHz, 4dB Noise Figure HEMT Amplifier

This amplifier, designed to accommodate the needs of the MILSTAR program, uses a single 0.25-um HEMT to produce gain up to 10 dB at 43 GHz with noise figure as low as 4 dB – the best results to date for a single-stage MMIC amplifier at this frequency.

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Much of the interest at 44 GHz has been generated by the MILSTAR program. With both a 20-GHz downlink and a 44-GHz uplink, MILSTAR will be the first U.S. military communications satellite to operate in the EHF region. Jamming these links will be difficult because the spacecraft utilizes fast frequency-hopping over a 1-GHz bandwidth and other spread-spectrum techniques.

A monolithic, single-stage low-noise amplifier has been developed to satisfy the requirements of MILSTAR. This amplifier is based on a HEMT active device with a 0.25-um gate length that includes matching and biasing circuits within dimensions of 1.1 X 1.1 mm. When fabricated using a "triangular gate" cross- sectional profile this amplifier delivered gain of 6.5 dB and a noise figure of 5 dB from 38 to 44 GHz.

By replacing the triangular gate with a "mushroom" gate profile, the amplifier achieved 8-dB gain and 4-dB noise figure from 36 to 42 GHz. Using a triangular gate profile device with a lower gate-to-drain feedback capacitance, the amplifier achieved 10-dB peak gain at 43 GHz. Currently,

this is the best reported result for a single-stage MMIC amplifier at these frequencies.

The HEMT layers (Figure 1) were grown by MBE at 580 C on GaAs which was doped N- type at about 1 X 10 exp (14)/cc. A five-period AlAs/GaAs superlattice was grown midway into the buffer layer in an attempt to reduce dislocations, as well as to improve surface morphology and noise performance. The discrete 0.25-um X 150-um HEMT showed sharp-kneed I-V characteristics. The gate is Pi-configured with a triangular gate profile and source-drain spacing of 2.5 um.

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The device has a typical Idss of 170 mA/mm, a gm of 520 mS/mm at maximum gain bias and 380 mS/mm at minimum noise bias, a pinch-off voltage of 0.8 V, and a breakdown voltage of 5 V. The sheet density of the two-dimensional electron gas is about 2 X 10 exp (12)/cc.

The device was first characterized by the S-parameter measurements in the common-gate, common-source, and common-drain configurations from 2 to 18 GHz. An equivalent circuit model was deduced to fit the three sets of data. The HEMT showed a measured minimum noise figure of 1.35 dB and associated gain of 12 dB at 18 GHz. The predicted Fmin was 2.74 dB at 40 GHz using Fukui's expression. The maximum available gain of 8 dB was measured at 38 GHz, which extrapolates to an Fmax of about 101 GHz.

Circuit Design

Using the derived device model, a reactively-matched amplifier was designed for a peak frequency of 44 GHz. The amplifier utilized open stubs, shunt-shorted stubs and transmission lines as the input and output matching elements (Figure 2). The electrical lengths of the transmission lines apply to 40 GHz. Nineteen design parameters, including the matching and biasing circuit elements along with the gate periphery, were optimized using Super-Compact[TM] for the flattest gain from 42 to 46 GHz. The impedance of the matching elements was constrained to be within the range of 30 to 90 ohms for the purpose of practical realization and acceptable transmission line loss. Simulated gain of 7.5 dB was obtained from 40 to 46 GHz. The simulation indicates that the amplifier is unconditionally stable from 35 to 50 GHz.

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Amplifier Fabrication

Standard processing techniques were used for most areas of fabrication. Isolation was achieved with a 2500 A mesa etch, and the 0.25-um gate was written with a Cambridge EBMF 10.5 electron-beam machine using PMMA resist. A sputtered SiO2 layer of 2000 A was used as the capacitor dielectric material. In order to achieve good RF grounding, 60 X 60-um backside via-holes were incorporated using reactive ion etching. All other

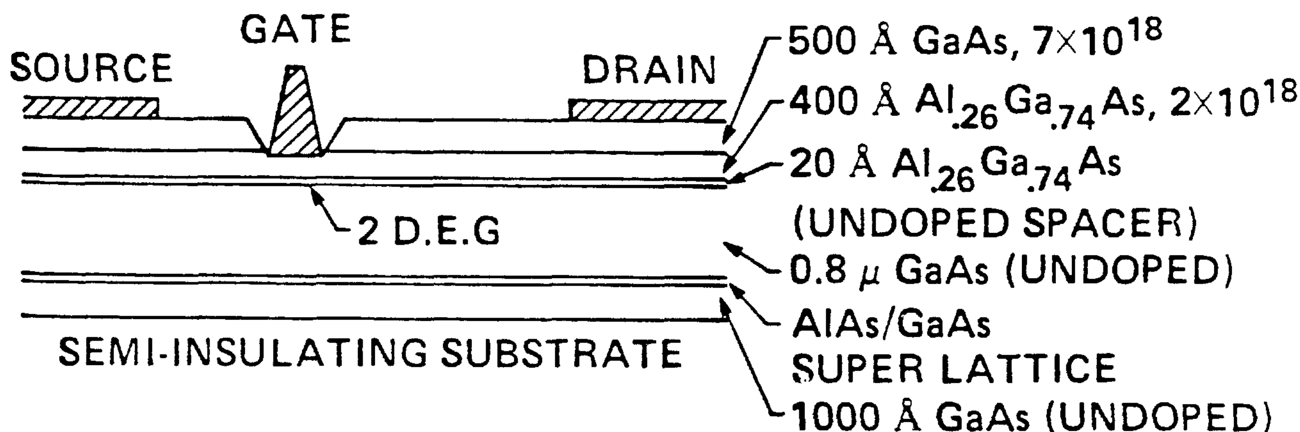

Figure 1. Cross sectional plan of the HEMT device.

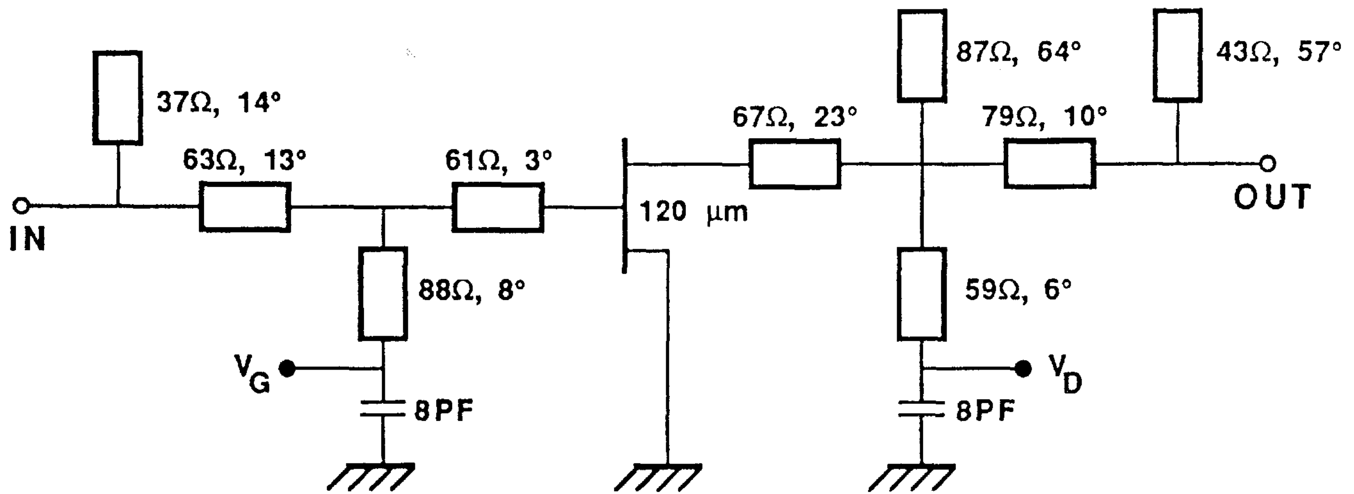

Figure 2. Schematic diagram for the amplifier at 40 GHz.

process steps used conventional metallization, liftoff and pulse-plating techniques. The layout of the circuit is compatible with requirements of the Cascade Microtech RF wafer- prober (Figure 3).

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Measured Performance

Gain of approximately 6.5 dB from 38 to 44 GHz (biased at a Vds of 3 V and Ids of 15 mA) and

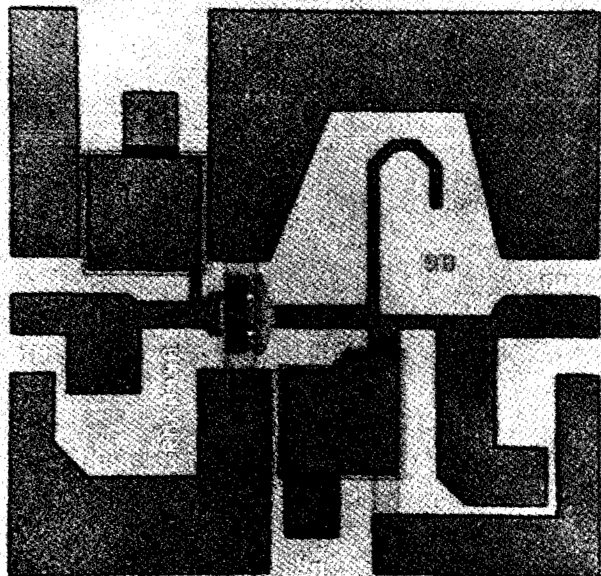

Figure 3. The 1.1 x 1.1 mm monolithic 40 GHz amplifier chip.

input/output return loss of better than 10 dB from 39 to 43 GHz were measured (Figure 4). Measurements were made with the waveguide-based HP-8510 network analyzer with full error correction and the 50-GHz Cascade Microtech wafer probes. Measured peak gain (7 dB) agreed well with the simulated results, but the peak frequency was shifted from 44 GHz to 41 GHz. This was attributable to the higher gate capacitance of the actual device compared with that of the equivalent circuit model. As predicted, the amplifier was unconditionally stable from 36 to 50 GHz.

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The noise figure was 5-dB from 38 to 44 GHz when the device was biased at minimum noise bias conditions (Figure 5). The amplifier's noise figure below 40 GHz was measured with an HP-R347B noise source and a HP noise measurement system using the waveguide test setup and the Cascade

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Microtech wafer prober. Above 40 GHz, the measurement was performed using a gas-tube noise source with the amplifier bonded onto a finline fixture. When biased at maximum power (Vds = 3 V, Ids = 21 mA), the 1-dB compression power for the HEMT amplifier was 10 dBm at 40 GHz.

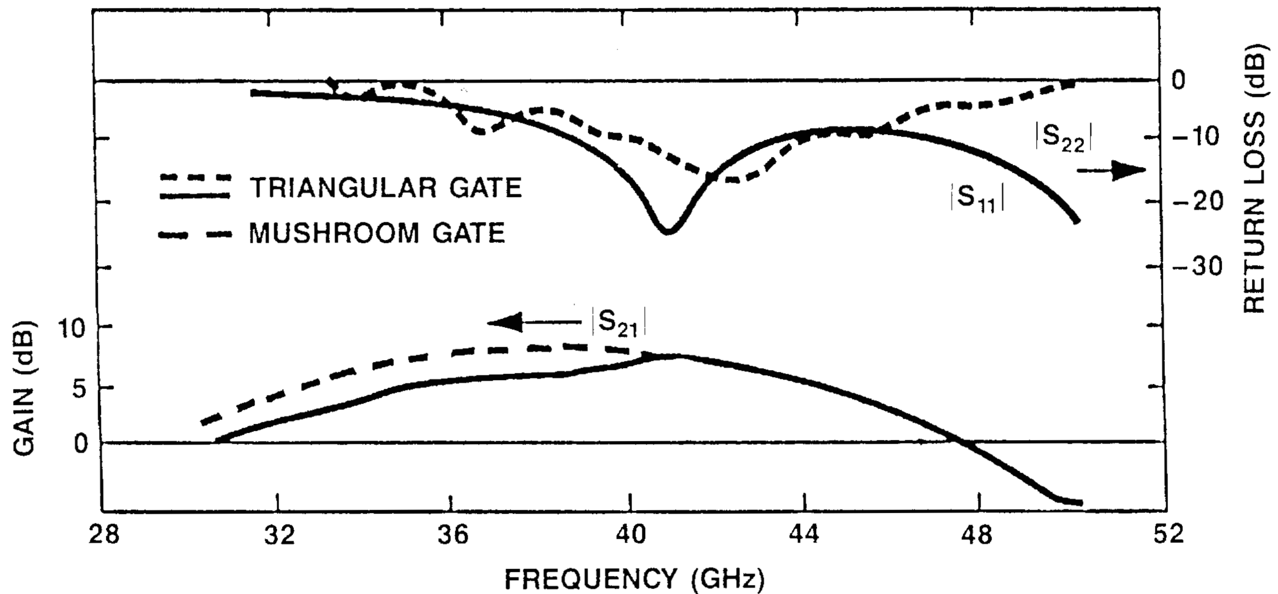

Figure 4. Measured gain and return loss performance of the monolithic 40 GHz amplifier.

The Mushroom Gate Profile

The mushroom gate profile has lower gate resistance than the triangular gate profile due to the increased cross-sectional area. Consequently, noise figure of a mushroom-gate device should be lower and gain higher than that of a triangular-gate device. To determine the performance of the mush-

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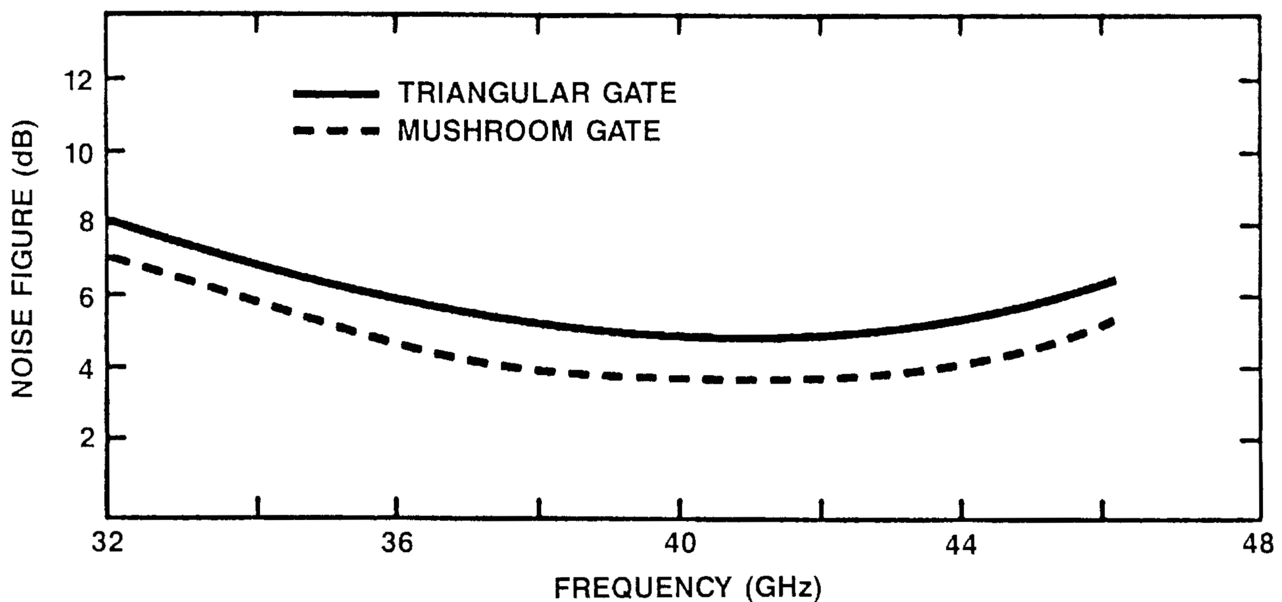

Figure 5. Measured amplifier noise figure.

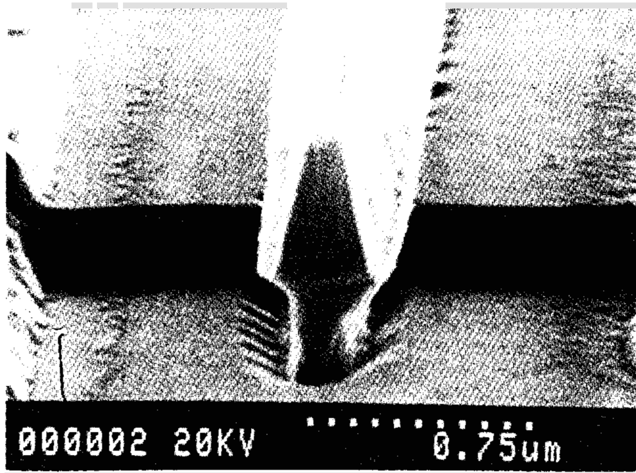

Figure 6. Scanning electron microscope photograph of a typical mushroom gate profile.

room gate in this application, a 0.25-um gate with a mushroom profile was fabricated with three-level resist and E-beam lithography (Figure 6). The DC gate resistance of a 0.25-um gate with a mushroom gate profile (70 ohm/mm) was only one-seventh of that of a similar 0.25-um gate with a triangular profile (470 ohms/mm).

A wafer . . . processed . . . utilizing a new gate etchant (ammonia), . . . had . . . lower gate-to-drain capacitance (0.011 pF) . . . higher peak gain (10 dB) and . . . frequency (43 GHz)

The predicted device performance was realized. The 0.25 X 150-um Pi-configured HEMT with a mushroom gate profile had noise figure of 0.9 dB and associated gain of 13 dB at 18 GHz. A 40-GHz reactively-matched amplifier with a mushroom gate profile was also fabricated on HEMT material. This amplifier delivered 8- dB of gain and a 4-dB noise figure over the 36-to-42-GHz band. The amplifier using the mushroom gate had 2-dB higher gain and 1-dB lower noise than the amplifier with a triangular gate profile.

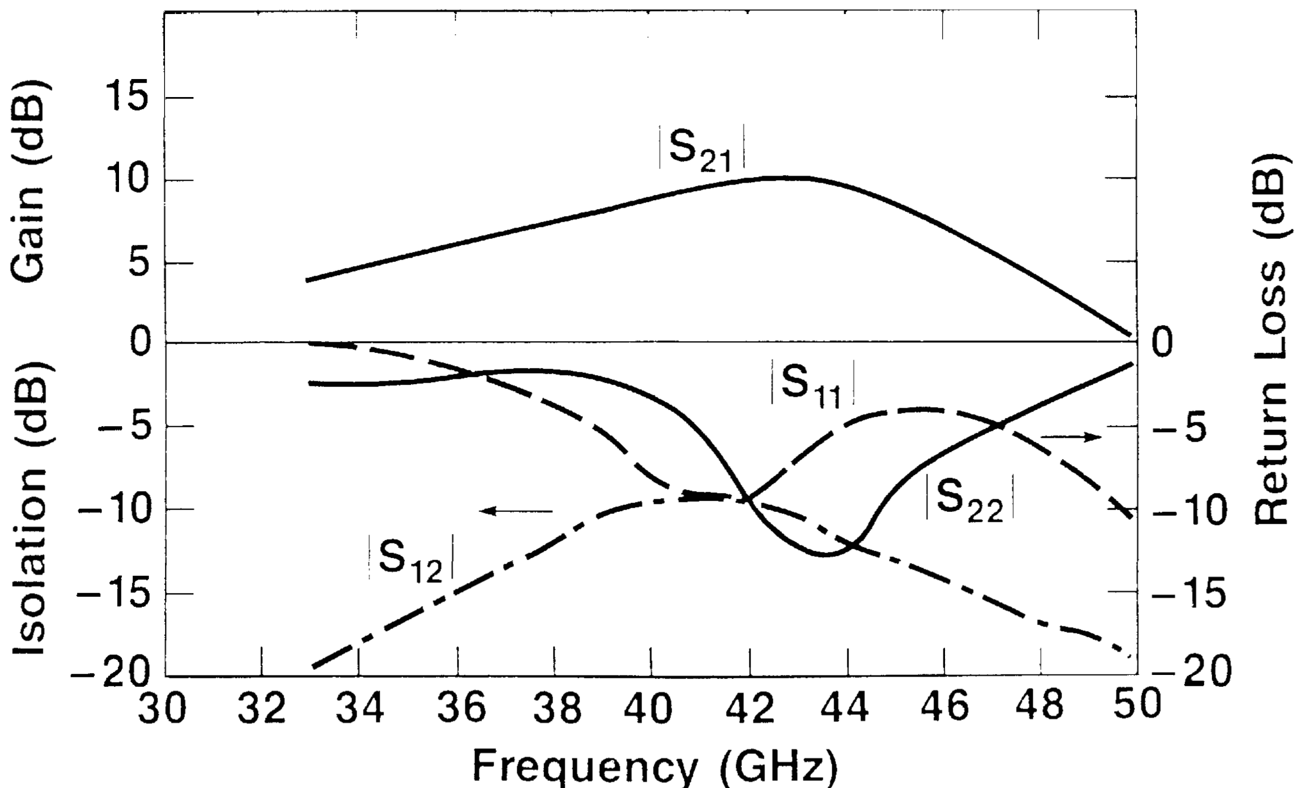

Figure 7. Measured gain, return loss and isolation of the monolithic 40-GHz amplifier on a recent wafer.

Achieving 10-dB Gain at 43 GHz

A wafer was processed with a triangular gate profile utilizing a new gate etchant (ammonia), which created a different gate recessed-channel profile than that of the previous wafers on which HF was used as the etchant. The device on this new wafer had a significantly lower gate-to-drain capacitance (0.011 pF) than the device on the previous wafers (0.02 pF). The measured gain, input/output return loss, and isolation for the amplifier on this wafer were indicative of the change in device processing. The amplifier had a higher peak gain (10 dB) and higher peak frequency (43 GHz) than amplifiers from previous wafers which delivered 7-dB peak gain at 41 GHz (Figure 7). The higher gain and peak frequency are related to the lower gate-to-drain capacitance, which in turn produced increased gain.

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References

1. P. M. Smith, P. C. Chao, K. H. G. Duh, L. F. Lester, B. R. Lee and J. M. Ballingall, "Advances in HEMT Technology and Applications," 1987 IEEE MTT-S International Microwave Symposium Digest, p. 749.
2. S. Bandy, C. Nishimoto, C. Yuen, R. LaRue, M. Day, J. Eckstein, Z. Tan, C. Webb and G. Zdasiuk, "A 2-20 GHz High-Gain Monolithic HEMT Distributed Amplifier," IEEE Trans. Microwave Theory and Tech., MTT-35(12), 1494 (1987).
3. S. Bandia, G. Dawe, C. Bedard, R. Tayvani, D. Shaw, L. Raffaelli and R. Goldwasser, "A 35 GHz Monolithic MESFET LNA," 1988 IEEE MTT Microwave and mm- Wave Monolithic Circuits Symposium, p. 151.
4. H-LA. Hung, T. T. Lee, F. R. Phelleps, J. F. Singer, J. F. Bass, T. F. Noble and H. C. Huang, "60 GHz MMIC Low Noise Amplifiers," IEEE MTT 1987 Microwave and mm-Wave Monolithic Circuits Symposium Digest, pg. 87.
5. J. Berenz, H. C. Yen, R. Esfandiari, K. Nakano, T. Sato, J. Velebir and K. Ip, "44 GHz Monolithic Low Noise Amplifier," IEEE MTT 1987 Microwave and Millimeter-Wave Monolithic Circuits Symposium Digest, pg. 15.
6. C. Yuen, C. Nishimoto, M. Glenn, Y. C. Pao, S. Bandy and G. Zdasiuk, "A Monolithic Ka-Band HEMT Low Noise Amplifier," 1988 IEEE MTT Microwave and mm- Wave Monolithic Circuits Symposium Digest, pg. 139.
7. C. Yuen, C. Nishimoto, S. Bandy and G. Zdsiuk, portions of this paper were presented at the 1989 MTT-S Symposium in a paper entittled "A Monolithic 40-GHz HEMT Low-Noise Amplifier," see pg. 205 of the Symposium Digest.

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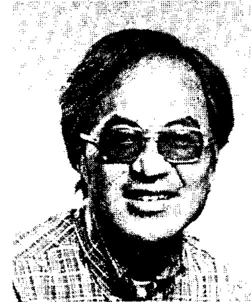

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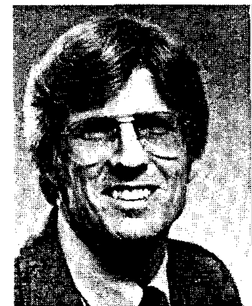

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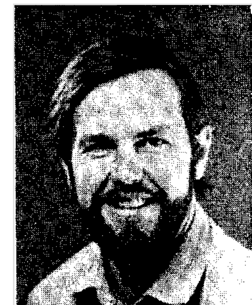

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