An MMIC VCO Design and Fabrication for PCS Applications

Young-Gi Kim and Jin-Ho Choi

Abstract

Design and fabrication issues for an L-band GaAs Monolithic Microwave Integrated Circuit(MMIC) Voltage Controlled Oscillator(VCO) as a component of Personal Communications Systems(PCS) Radio Frequency(RF) transceiver are discussed. An ion-implanted GaAs MESFET tailored toward low current and low noise with 0.5 mm gate length and 300 mm gate width has been used as an active device, while an FET with the drain shorted to the source has been used as the voltage variable capacitor. The principal design was based on a self-biased FET with capacitive feedback. A tuning range of 140 MHz and 58 MHz has been obtained by 3 V change for a 600 mm and a 300 mm devices, respectively. The oscillator output power was 6.5 dBm with 14 mA DC current supply at 3.6 V. The phase noise without any buffer or PLL was 93 dB/1Hz at 100 KHz offset. Harmonic balance analysis was used for the non-linear simulation after a linear simulation. All layout induced parasitics were incorporated into the simulation with EEFET2 non-linear FET model. The fabricated circuits were measured using a coplanar-type probe for bare chips and test jigs with ceramic packages.

I. Introduction

GaAs's high dielectric constant make it a good substrate material for Monolithic Microwave Integrated Circuit (MMIC). Otherwise, it would require additional processes such as etch, oxidation, masks, etc. The GaAs Field Effect Transistor(FET) is an excellent candidate for a low-power and low noise operation in microwave frequency, including S-band frequency, due to high mobility of the semiconductor material.

An ion-implanted GaAs Metal Semiconductor(MES) FET is proven to be suitable for the Monolithic Integrated Circuit, due to the easy control of uniform doping, which makes it as a good choice for mass production. There are hands waving arguments between Silicon Bipolar Junction Transistor(BJT) and GaAs MESFET as an active device for the Microwave Voltage Controlled Oscillator(VCO) due to phase noise characteristics. Traditionally a lot of discrete microwave oscillators are designed by using Silicon BJT. Many people insist that this is due to the superior phase noise characteristics of the Silicon BJT to that of the GaAs FET. Recently, Bark Maoz and Aharon Adar[1] suggested that the phase noise available from silicon IC process is inferior to the phase noise customarily achievable from Silicon BJT devices. Most production Silicon IC processes feature higher phase noise levels than low noise GaAs processes. It has also been reported that *1/f* converted noise in GaAs FET oscillator can be reduced by optimization of low-frequency loading. In addition, an appropriate low-frequency feedback between drain and gate gives improvement over this phase noise[2]. An improvement about 6~12 dB/Hz by feedback circuitry for 1 GHz VCO was reported. It was also reported that DC bias condition also can be adjusted to improve phase noise of the oscillator[3]. Moreover, the phase noise can be improved by Phase Locked Loop(PLL) when the VCO is integrated into the frequency synthesizer. The phase noise requirement for the Personal Communications Systems (PCS) Radio Frequency handset is not so rigorous that the GaAs FET can be used as an active device.

A varactor is required as a frequency tuning element in this system. The varactor normally needs a special doping profile for the linear relationship between the capacitance and the control voltage. In MMIC process, it takes too much cost to consider another doping profile. So the varactor is externally connected in most hybrid MMIC, which consequently produces inaccuracy due to the connection error such as bond wiring and soldering error. Since the FET has a long low doping area for the channel modulation, the FET with its gate shorted to source can be used for this purpose. But, the commercial BJTs are not appropriate for the varcator due to the high doping concentration, which is unavoidable for high gain. Fortunately, a linear relationship between the

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control voltage and capacity is not so stringent in this application because the PLL will take care of the deviation from the linearity when it is inserted into the frequency synthesizer system or module.

Even with this internal varactor, only 13 pieces of masks are needed for the ion implanted GaAs MESFET MMIC VCO process. When the FET is developed as an MMIC component, its data for the MMIC design should be very accurate. Otherwise, we must depend on a trial and error method, which means too much cost.

In this paper an S-band MMIC VCO using GaAs MESFET as an active and tuning element device is successfully designed, fabricated and measured for the PCS applications with these considerations.

Ⅱ. Computer Aided Design

The principal design is based on a self-biased FET with capacitive feedback. The target of DC power supply is 3.6 V and control voltage range is from 0 V to 3.0 V, which are to be supplied by commercial portable battery and Phase Locking Loop(PLL) IC. The voltage variable capacitor is realized using a 300 mm FET with the drain shorted to the source. In this way, the gate source capacitance of the device provids the necessary tuning element.

A simplified schematics of the VCO is shown in Fig. 1. DC gate bias is established by the voltage drop across the source resistor and thus eliminates the need for a negative supply voltage. Negative input resistance, an essential condition for oscillation, is achieved through the use of feedback capacitors C_1 and C_2[4]. Inductor L_2 resonates with the varactor to establish the frequency of oscillation, and L_2 also provides DC ground for the gate of the FET. The varactor is realized by shorting the drain and source of a 300 mm FET and the gate source capacitance of the FET can then be varied by applying a voltage across the gate source junction of the FET.

As an initial numerical approach, a rough estimation of the oscillation frequency could be obtained from Fig. 2. Major reactive contribution from the FET is the capacitance between gate and source (C_{gs}). With this C_{gs}, a roughly estimated oscillation frequency is given by

$$f_{osc} = \frac{1}{2\pi LC}$$

Where

$$C = C_3 + \frac{(C_1 + C_{gs}) \times C_2}{C_1 + C_{gs} + C_s}$$

The oscillation condition starts with the simulation at which the open loop gain magnitude becomes larger than one and the phase angle of the open loop gain becomes zero degree as shown in Fig. 3. The Accuracy of the resonant capacitance value is very crucial for the successful design of the circuits. Therefore, the very accurately measured zero-biased FET data are used for the FET as a varactor element in stead of normal nonlinear model in order to increase the accuracy. All layout component effects such as microstrip line, microstrip step discontinuity, and microstrip tee junction are incorporated into the simulation, which enables re-analysis with the layout being subsequently modified in order to eliminate any unwanted effects.

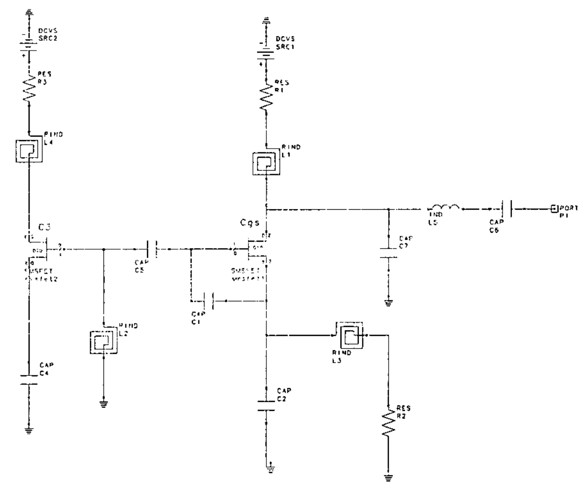

Fig. 1. A simplified schematic circuit of the MMIC VCO for PCS RF transceiver.

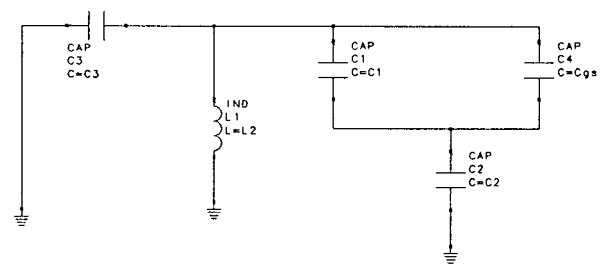

Fig. 2. A simplified VCO circuitry for a rough estimation of the oscillation frequency.

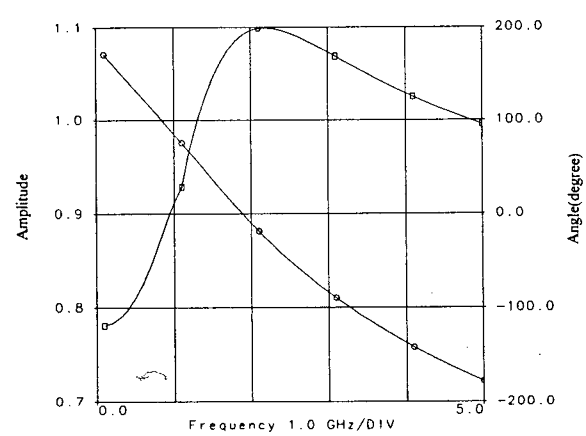

Fig. 3. The computer simulated loop gain curves for the oscillation condition of the oscillator.

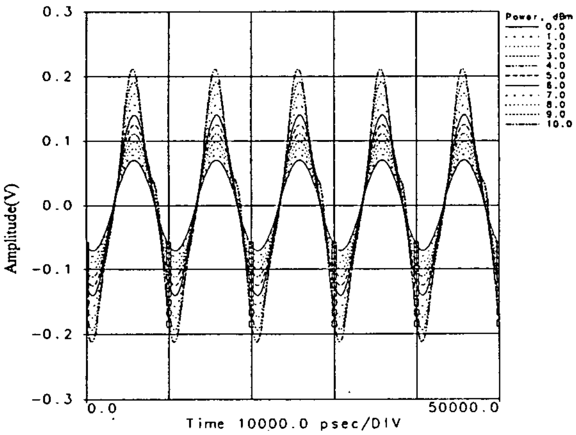

Fig. 4. The simulated time domain oscillation curve shapes for different powers.

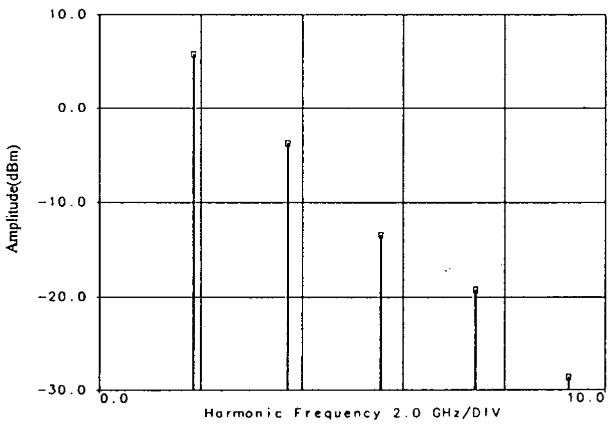

Fig. 5. The simulated spectrum responses for control voltage with 50% of the FET pinch-off voltage.

Harmonic balance analysis is used for the non-linear simulation. This iterative analysis is based on the assumption that for a given sinusoidal excitation there exists a steady-state solution that can be approximated to satisfactory accuracy using a finite Fourier series[5, 6]. EEFET2 model is used for the non-linear FET device modeling. Simulated time domain oscillation shapes for different powers are depicted in Fig. 4. The simulated spectrum responses from harmonic balanced analysis for control voltage with 50% of the FET pinch-off voltage are shown in Fig. 5. Several harmonic powers are shown in this figure. The second harmonic power is less than that of the first by 10 dB.

A 600 mm FET is also used as the varactor for 200 MHz frequency tuning by changing the same control voltage[7]. The designed oscillator output power is 6 dBm with 14 mA DC current supply at 3.6 V. The simulated phase noise without any buffer or PLL was -105 dBc / 1 Hz at 100 KHz offset.

The production tolerance estimation for the device variations is performed. Specially, capacitors and resistors are expected to vary

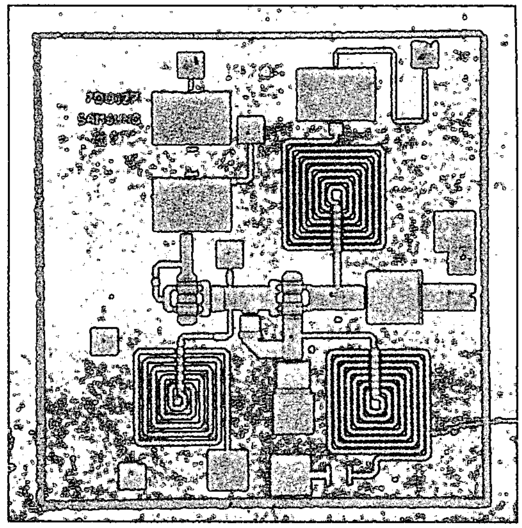

Fig. 6. A photograph of the MMIC VCO bare chip.

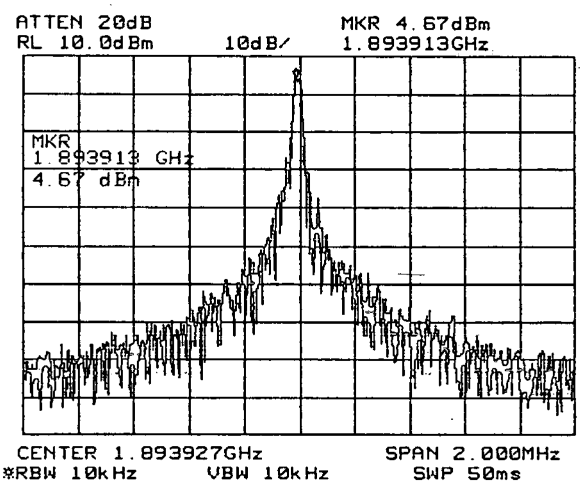

Fig. 7. The power spectrum of 300 mm FET varactor VCO with the tuning voltage of 0V from the bare chip measurement.

+/-5% and +/-15% respectively from their normal design values. Variations in circuit resistors have minimal effect on oscillation frequency but do cause the output power to vary by as much as +/-1 dB. On the other hand, changes in capacitance have minimal effect on output power but the frequency to change by +/-30 MHz.

Ⅲ. Fabrication and Measurement

Samsung Microwave Semiconductor GaAs foundry G30 process is used. In this process, an ion-implanted process tailored toward low current and low noise is used for the GaAs MESFET with a gate length of 0.5 mm. Air-bridge interconnections and via holes are used for the device connections. The size of the fabricated bare chip is 1.6 × 1.5 mm and its photograph is shown in Fig. 6. The fabricated bare chip circuits are measured using a microwave

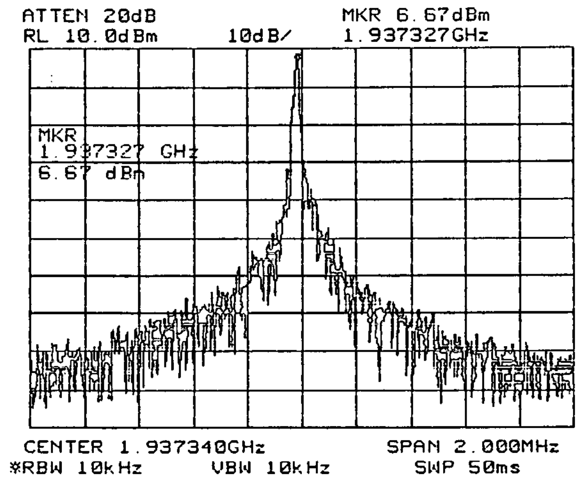

Fig. 8. The power spectrum of 300 mm FET varactor VCO with the tuning voltage of 1.5V from the bare chip measurement.

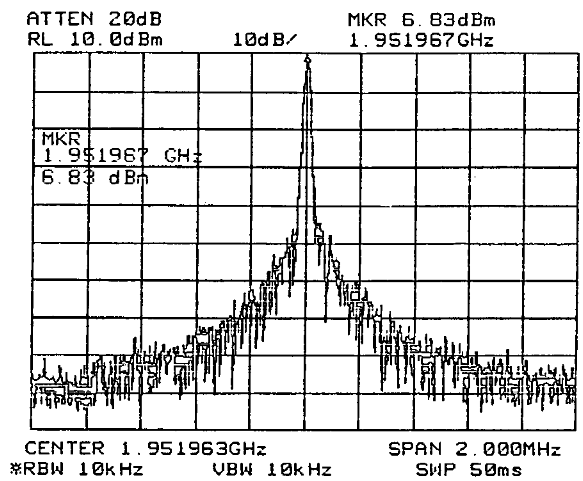

Fig. 9. The power spectrum of 300 mm FET varactor VCO with the tuning voltage of 3V from the bare chip measurement.

probe station and spectrum analyzer. The RF output port is connected to the spectrum analyzer by the calibrated coplanar-type probe tip and the frequency tuning port is connected to variable voltage source by DC probe tip. The obtained spectrum responses of the 300 mm FET varactor device with different control voltages, i.e. for 0 V, 1.5 V and 3 V, are shown in Fig. 7, 8, and 9, respectively. The measured tuning range of 58 MHz with 3 V control voltage change for 300 mm FET varactor device can be observed in these figures. The computer simulation result is relatively in a good agreement with the measured data. The operating frequency is centered at 1925 MHz in bare chip measurement. However, this center frequency is shifted to 1850 MHz due to package parasitics when chip is packaged. A 600 mm FET is also used as the varactor for 140 MHz frequency tuning by changing the same voltage control. The measured spectrum responses of the 600 mm FET varactor device with different control

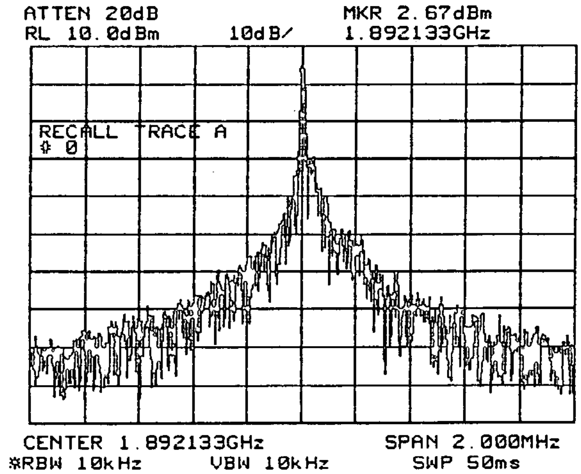

Fig. 10. The power spectrum of 600 mm FET varactor VCO with the tuning voltage of 0 V from the bare chip measurement.

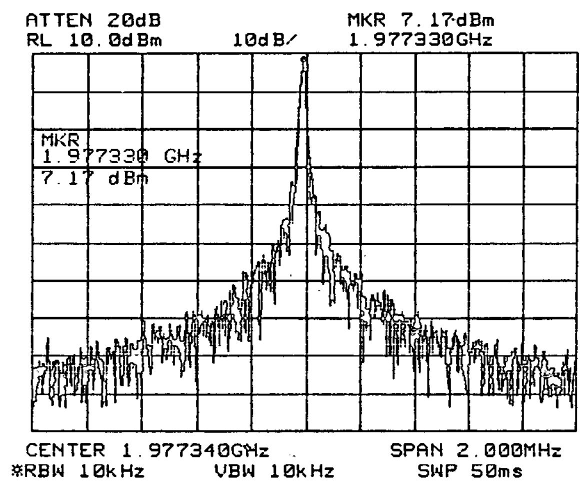

Fig. 11. The power spectrum of 600 mm FET varactor VCO with the tuning voltage of 1.5 V from the bare chip measurement.

voltages, i.e. for 0 V, 1.5 V and 3 V, are shown in Fig. 10, 11, and 12, respectively.

The test jig measurement is also performed with ceramic package of the circuit. The package effect mainly caused by wire bonding is considered as 0.8 nH / 1 mm. This package effect has been predicted in the simulation stage and is confirmed with packaged device measurement. The oscillator output power is 6.5 dBm with 14 mA DC current supply at 3.6 volt. The phase noise without any buffer or PLL is measured to be -93 dBc / 1 Hz at 100 KHz offset as shown in Fig. 13. The second harmonic suppression is 20 dB as shown in Fig. 14.

Ⅳ. Conclusion

In this paper, a GaAs MMIC VCO with internal varactor for

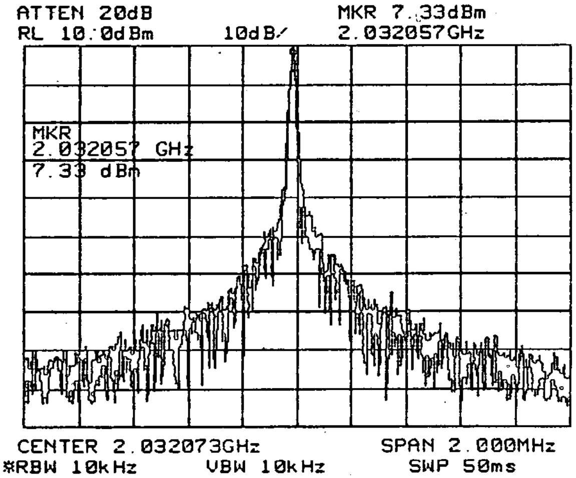

Fig. 12. The power spectrum of 600 mm FET varactor VCO with the tuning voltage of 3 V from the bare chip measurement.

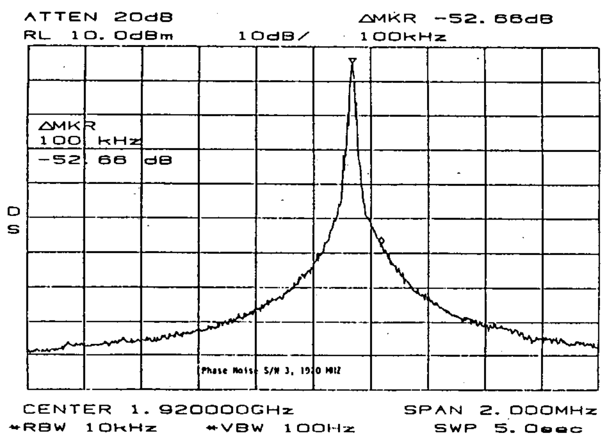

Fig. 13. The power spectrum of 600 mm FET varactor packaged VCO with the tuning voltage of 1.5 V measured with test jig.

the application of personal communication systems in the frequency range of 1.8-1.9 GHz has been designed, fabricated, and characterized. In this study, precisely measured zero-biased FET data has been used to make an accurate design. The designed center frequency and output power are good agreements with those of the fabricated devices as a result. The measured frequency tuning range of the VCO with 300 mm FET varactor is 58 MHz which is 58% of simulated tuning range of 100 MHz. For the other one with 600 mm FET varactor, it is 140 MHz which is 70% of simulated 200 MHz tuning range. From this result, we can conclude that the frequency tuning range of the fabricated VCO is less than simulated range. It also can be concluded that the larger gate width FET varactor is better to make an exact design for the required tuning range of the MMIC VCO. Also, it is very obvious that the VCO with the larger gate width FET varactor produces larger frequency tuning range. Generally, some degree

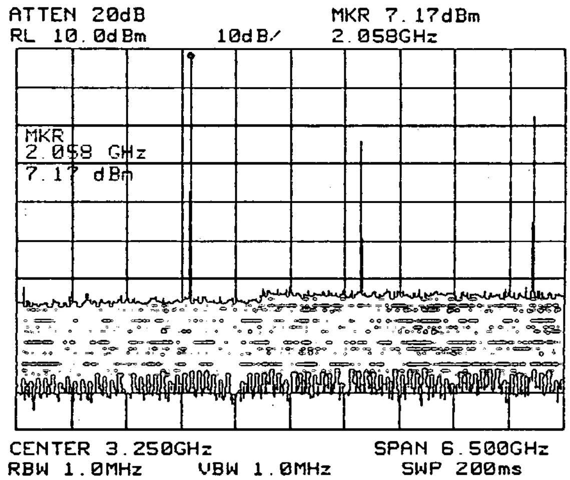

Fig. 14. The harmonics characteristics of the 600 mm FET varactor packaged VCO with tuning voltage of 3.0 V from the bare chip measurement.

of error would be unavoidable in MMIC process. Therefore the FET's gate width should be larger than simulated value to meet the required center frequency and frequency tuning range. However, the FET's gate width is inversely related with phase noise. Therefore the FET's gate width should be compromised between the requirement of frequency and that of phase noise with the consideration of process variation. In commercial PCS hand set application, the required frequency tuning range is 30 MHz, the output power is more than 0 dBm. These requirements were satisfied with process variation margin in the circuit with 300 mm FET. Therefore it can be conclude that the 300 mm FET is a good choice for varactor and active device in the PCS hand set application with respect to frequency tuning range and output power.

The phase noise caused by flicker noise can be improved by using proper feedback circuitry. The phase noise also can be improved by using externally connected high Q varactor.

This work represents a significant advancement of the ion-implanted GaAs MESFET for the commercial PCS applications.

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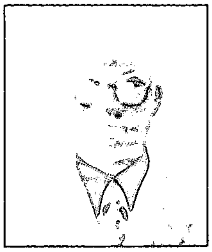

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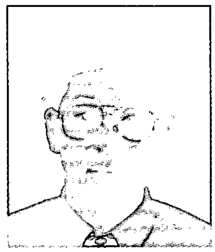

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