Millimeter-Wave Diode-Grid Phase Shifters

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Abstract —**Monolithic diode grids have been fabricated on 2 cm square gallium-arsenide wafers with 1600 Schottky-barrier varactor diodes. Shorted diodes are detected with a liquid-crystal technique, and the bad diodes are removed with an ultrasonic probe. A small-aperture reflectometer that uses wavefront division interference was developed to measure the reflection coefficient of the grids. A phase shift of 70° with a 7 dB loss was obtained at 93 GHz when the bias on the diode grid was changed from −3 V to 1 V. A simple transmission-line grid model, together with the measured low-frequency parameters for the diodes, was shown to predict the measured performance over the entire capacitive bias range of the diodes, as well as over the complete reactive tuning range provided by a reflector behind the grid, and over a wide range of frequencies from 33 GHz to 141 GHz. This shows that the transmission-line model and the measured low-frequency diode parameters can be used to design an electronic beam-steering array and to predict its performance. An electronic beam-steering array made of a pair of grids using state-of-the-art diodes with 5 Ω series resistances would have a loss of 1.4 dB at 90 GHz.**

I. INTRODUCTION

INTERESTING millimeter-wave circuits become possible when solid-state devices are added to periodic structures. Lee and Fong made a pioneering study of the effect of embedding negative-resistance diodes in a corrugated grating [1]. Later, Alexopoulos *et al.* proposed using these active surfaces for scanning a beam electronically [2], and Chekroun *et al.* proposed *Radant*, a three-dimensional grid of diodes for steering a beam [3]. Rutledge and Schwarz demonstrated a multimode microbolometer array [4], and we proposed designs for a periodic grid loaded with diodes for electronic beam steering and frequency multiplication [5], [6]. In the beam-steering array (Fig. 1), the incident beam reflects off a pair of varactor diode grids, and the diode bias controls the phase of the reflected wave. The idea is to program a progressive phase shift across the aperture to steer the reflected beam. Diode grids are attractive because they are suitable for monolithic integration. No transmission lines or waveguides are required, and this simplifies the design and fabrication. Since the power is distributed among many diodes over a large area, the power-handling capability can be quite high.

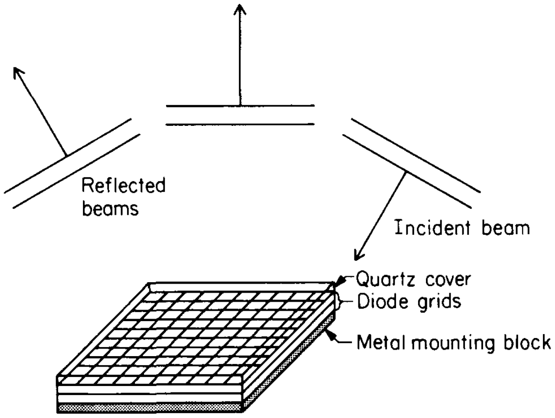

Fig. 1. Proposed millimeter-wave diode-grid electronic beam-steering array [5], [6].

Fig. 2 shows the grid design and the equivalent transmission-line model, and a micrograph of one of the grids. The grid period is chosen to be about half the dielectric wavelength to avoid exciting substrate modes [5]. The vertical metal strips are inductive leads for the diodes, while the horizontal strips are for biasing the diodes by rows. The electric field is vertically polarized. In the circuit model (Fig. 2(b)), the grid is represented by an inductor in series with a diode, and the substrate is represented by a section of transmission line with a characteristic impedance equal to the wave impedance in the dielectric. The horizontal bias leads are neglected because they are perpendicular to the incident electric field. This design only allows the reflection phase to be varied from row to row, so that we would only be able to scan in the E plane. To scan in both planes, we would need to bias diodes individually, or add additional grids with diodes connected in series rather than in parallel. The grid inductance is given by the quasi-static formula [5]

$$L = \left(\frac{\mu_0 a}{2\pi}\right) \ln\left[\csc\left(\frac{\pi w}{2a}\right)\right] \tag{1}$$

Manuscript received July 16, 1987; revised December 11, 1987. This work was supported by the Army Research Office, by the U.S. Army Harry Diamond Laboratory, by the Jet Propulsion Laboratory, and by TRW under the University of California MICRO program.

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IEEE Log Number 8819961.

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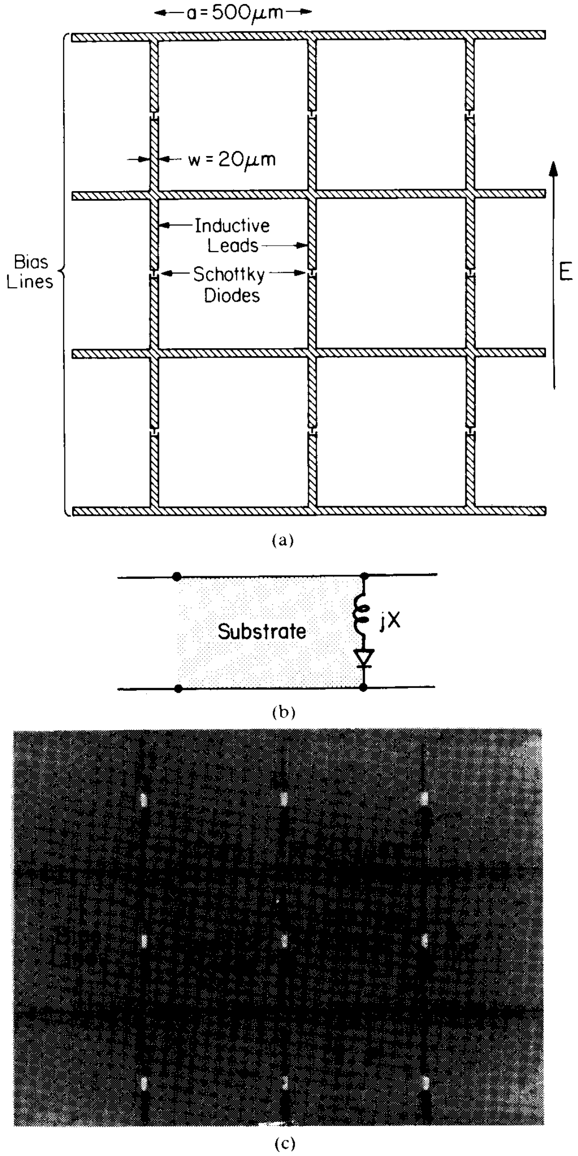


(a)

(b)

(c)

Fig. 2. (a) Diode-grid dimensions, (b) the equivalent transmission-line model, and (c) a micrograph of a section of a diode grid fabricated on a gallium-arsenide wafer.

where a is the grid period and w is the lead width. For our grid, with $a = 500$ μm and $w = 20$ μm, the inductance is 277 pH, which gives a reactance of 157 Ω at 90 GHz. This inductance is in series with the diode capacitance, and it allows the total reactance to be tuned over a range of both positive and negative reactances.

II. FABRICATION

Four grids were made. The wafer area ranged from 4 cm^2 to 6 cm^2, and the wafers were lapped to a thickness of 230 ± 25 μm, which is a quarter of a dielectric wavelength at 90 GHz. The varactor diodes were fabricated with a self-aligning process similar to that developed by Zah *et al.* [7]. Details are given in [6]. The epitaxial layers were grown on a semi-insulating gallium arsenide substrate by molecular beam epitaxy, and a truncated hyperabrupt x^{-1} doping profile was used. The x^{-1} doping profile causes the reactance to tune linearly with the applied bias voltage. The diode area was 18 μm^2. The best fabrication yield for individual diodes in an array was 98 percent. The remaining shorted diodes were identified with a liquid crystal detection technique, and these were removed with an ultrasonic probe. The measured diode series resistances ranged from 20 Ω to 100 Ω. The zero-bias capacitance of the individual diodes at 1 MHz ranged from 20 fF to 40 fF, and the breakdown voltage of the diode grid ranged from −1 V to −3 V. The low breakdown voltage is partly attributed to the fact that aluminum was evaporated in an oil diffusion-pumped vacuum system rather than grown *in situ* by molecular beam epitaxy [8].

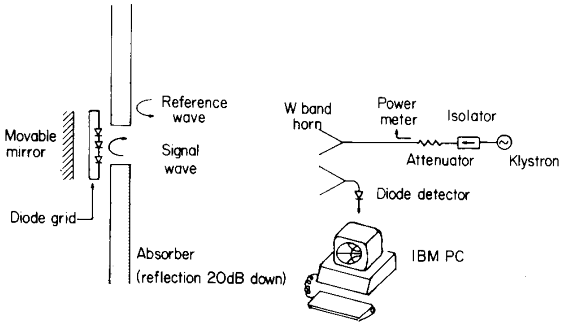


Fig. 3. Computer-controlled reflectometer for measuring reflection coefficients of small irregular samples at millimeter-wave frequencies.

III. REFLECTION MEASUREMENTS

Fig. 3 shows a computer-controlled small-aperture reflectometer we developed to measure the reflection coefficient of the diode grid. The idea is to use an absorbing foam screen (Eccosorb AN-72, manufactured by Emerson and Cuming) with a hole in the center to divide an incident wavefront into two parts. At millimeter-wave frequencies, this foam is not a perfect absorber, and it reflects about 1 percent of the incident power. The portion that reflects off the absorber is the reference, while the other part, which reflects off the sample, is the signal. The interference between these waves is measured as the sample is translated relative to the absorber. The phase and the amplitude of the reflection coefficient were calculated by a simple four-point method [9]. This method of measurement is attractive for small and irregular samples, because the absorber hole can be cut to the shape of the sample, and the supporting apparatus is shielded from the incident waves. In addition, there are no lenses to contribute stray reflections. The initial distance between the sample and the mirror is measured by a small hand-held microscope to an accuracy of 25 μm. The scanning mirror serves as a tuning parameter as well as a standard load for calibration. The mirror was a good reference for reflectance, but in the phase measurements there were offsets of about 10°, pre-

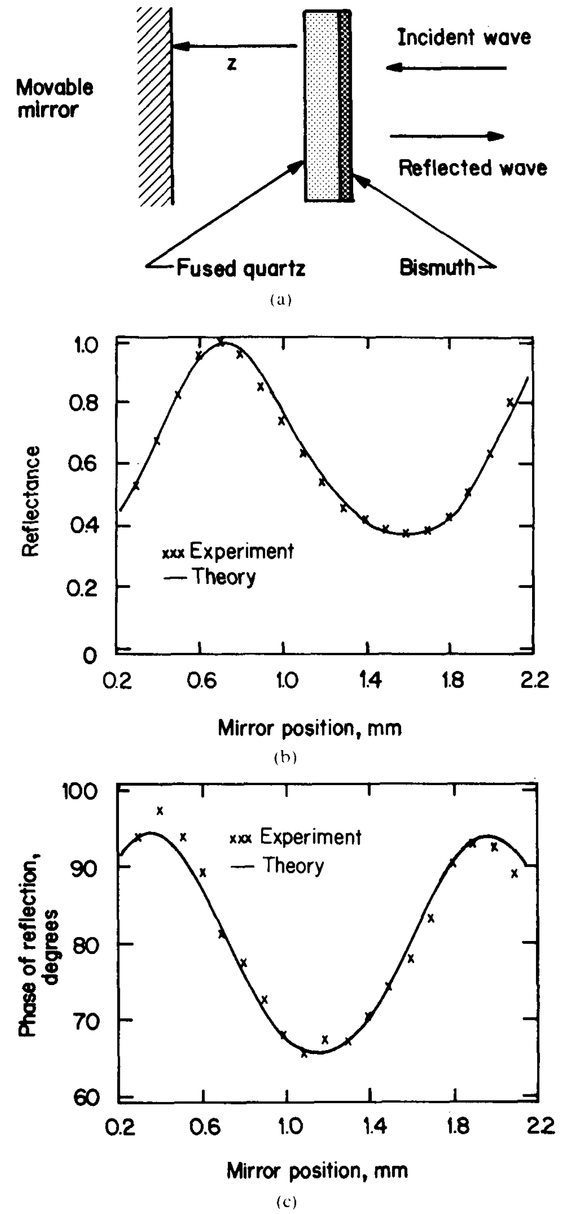


Fig. 4. (a) Bismuth-on-quartz test structure for small-aperture reflectometer. (b) Reflectance and (c) phase as a function of mirror position at 93 GHz. The theory uses the transmission-line model and dc four-point probe measurements of the bismuth resistance.

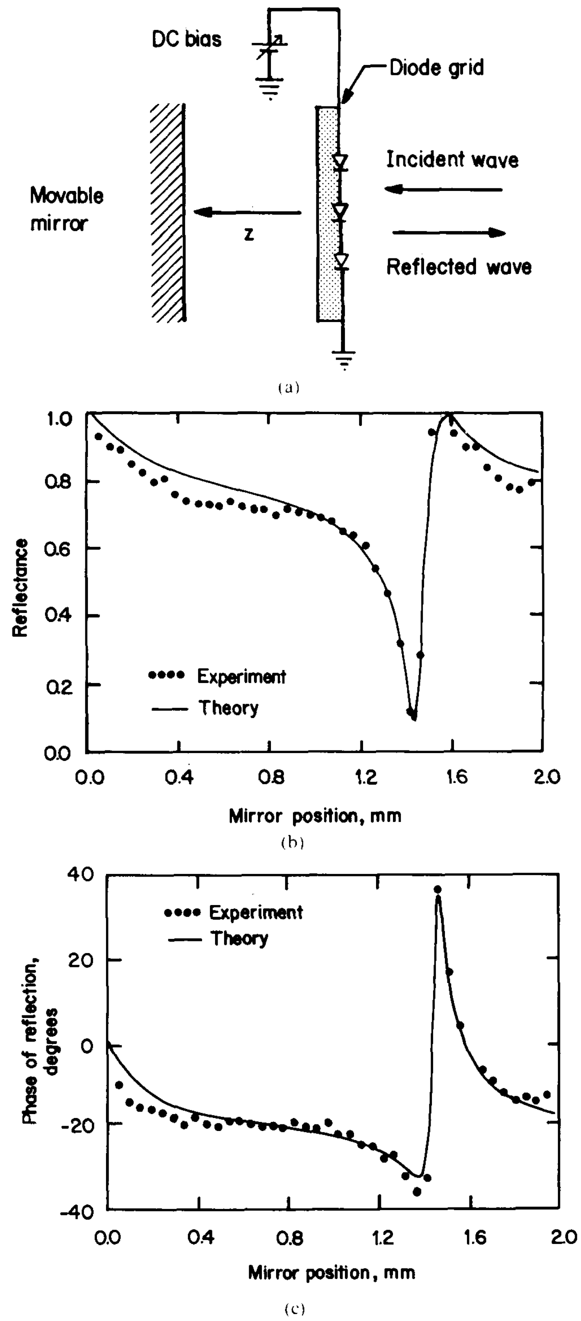


Fig. 5. (a) Testing the diode grid. (b) Reflectance and (c) phase as a function of mirror position at zero bias and 93 GHz. The theory is based on the transmission-line model and low-frequency measurements on the diodes.

sumably due to errors in measuring distances. For this reason, a phase offset was included as a free parameter to be determined by curve fitting. Effectively the tuning curves are used to calibrate the phase. The slab samples and the scanning mirror are aligned with a helium–neon laser, and are translated by stepper motors with a resolution of 1 μm per step.

To test the reflectometer, the reflection coefficient of a 2.5 cm square fused-quartz plate coated with a 600 Å thick bismuth film was measured and compared with transmission line theory (Fig. 4). The theoretical curves are plotted using the dc four-point-probe measurement of the bismuth sheet resistance (92.2 Ω) and the measured plate thickness (434 ± 5 μm). The refractive index of fused quartz, 1.96, was taken from the work of Afsar and Button [10]. We also used the curve-fitting routine to work backward and predict the sheet resistance from the millimeter-wave experi-

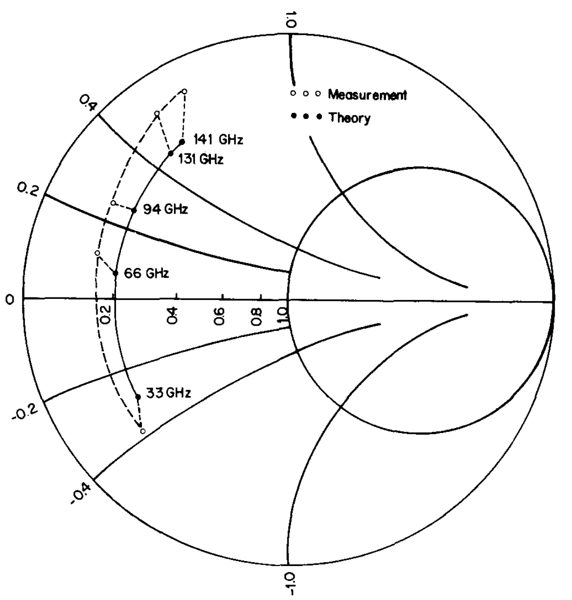
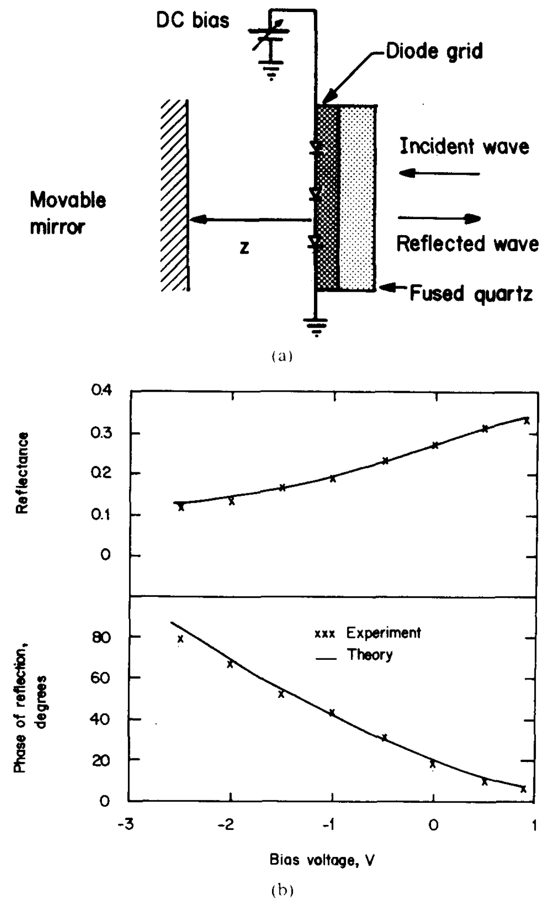


Fig. 6. Diode-grid impedance as a function of frequency, plotted on a Smith chart with a normalizing impedance of 377 Ω. The theoretical curve uses the measured average dc series resistance, 78 Ω, the measured average 1 MHz capacitance, 30 fF, and the quasi-static inductance, 277 pH. The plot shows a characteristic clockwise spiral as the frequency increases.

mental curves. The RF result was 91.6 Ω, which compares well with the dc value of 92.2 Ω.

IV. Characterizing the Diode Grids

These measurements gave us the confidence to use the reflectometer to characterize the diode grids. We measured the reflection coefficient of a grid as a function of mirror distance at 93 GHz, and the reflectance and the phase are plotted in Fig. 5. Also plotted are theoretical curves based on the transmission-line model of the grid, with the Afsar and Button values for the refractive index of gallium arsenide, 3.6 [10]. One complicating factor is that the thickness of the gallium-arsenide wafers was not uniform. The wafers were lapped by hand, and the thickness at different parts of the wafer varied by ±25 μm. This thickness and the separation between the wafer and the mirror were left as free parameters, and determined by curve fitting. For the diode parameters we used 1 MHz capacitance measurements on individual diodes in the grid (mean value, 30 fF) and dc series resistance measurements on individual diodes (mean value, 78 Ω; standard deviation, 19 Ω). In addition, we used the reflectance and phase curves in Fig. 5 and transmission line theory to de-embed the grid impedance from the wafer and the mirror. For this grid, the impedance at 93 GHz is $58 + j94$ Ω. The real part compares reasonably well with the dc series resistance measurements quoted above. We extended these measurements with several different oscillators to measure the grid impedance at frequencies from 33 GHz to 140 GHz. The results are plotted on a Smith chart in Fig. 6.



(a)

(b)

Fig. 7. (a) The phase shift measurement at 93 GHz. The back side of the gallium-arsenide wafer faces away from the mirror, and a quarter-wave layer of fused quartz has been added. The mirror was placed 1.49 mm from the diode grid. (b) Phase shift and loss of a diode grid at 93 GHz.

The phase shift performance was measured at 93 GHz with a different diode grid with a lower dc series resistance, 26 Ω. Fig. 7 shows the configuration and a comparison between experiment and theory based on the measured low-frequency capacitance variation between 27 fF at zero bias, and 20 fF at −3 V. A 70° phase shift with an average loss of 7 dB was measured. The low breakdown voltage limited the phase shift that could be obtained, and the high series resistance accounts for the loss. It should be noted that at this point in the measurements, three out of 35 rows of the diode grid were shorted out and could not be biased.

V. Conclusions

In these plots, theory and experiment agree well over the complete reactive tuning range provided by the mirror, over a wide band of frequencies from 33 GHz to 141 GHz, and over the entire capacitive voltage bias range of the diodes. This shows that we can use the simple transmission line model and the measured low-frequency diode parame-

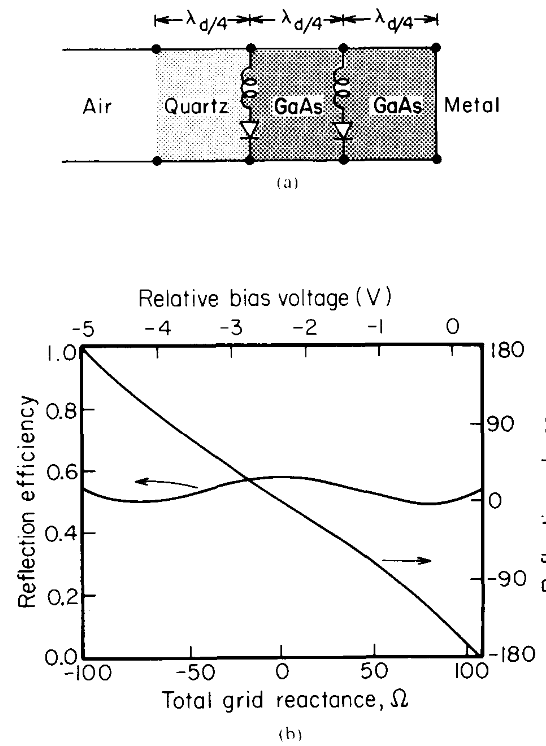


Fig. 8. (a) Beam-steering array with two grids [5], and (b) the simulated reflectance and phase shift for a diode series resistance of 10 Ω. The incident waves are TE polarized at an incident angle of 45°.

ters to design a beam-steering array and to predict its performance. To build a beam-steering array, we need to be able to vary the phase by 360°. This is difficult to do with a single grid, but a design for two grids is shown in Fig. 8. There are two identical grids with a reflecting mirror on the back and a quartz matching layer on the front. It is an analog to an earlier phase shifter developed by Garver [11]. To make a 360° phase shift, the total reactance on each grid must sweep from +107 Ω to −107 Ω, where 107 Ω is the wave impedance of the gallium arsenide substrate. In the simulation, the series resistance is assumed to be 10 Ω. We found that the average loss is 2.7 dB. In addition, the simulations show that the loss in dB varies almost linearly with the series resistance. Since researchers have reported millimeter-wave monolithic diodes with series resistances as low as 5 Ω [12], [13], it is now feasible to make an electronic beam-steering array at 90 GHz with a loss of 1.4 dB.

ACKNOWLEDGMENT

One of the authors (W. Lam) acknowledges the support of an AMOCO Foundation Fellowship and would like to thank Dr. Chung-en Zah at Bell Communication Research for showing him how to fabricate diodes. The authors are indebted to Prof. A. Yariv and Prof. M-A. Nicolet at Caltech for the use of their fabrication facilities, and to Prof. W. Bridges at Caltech for the loan of millimeter-wave equipment. They would also like to thank Dr. T. Kuech at IBM for providing MOCVD wafers, Dr. T. Fong and Dr. John Berenz at TRW and Dr. J. Maserjian and L. Eng at JPL for providing MBE wafers, Dr. H. Yamasaki, Dr. H. Kanber, and B. Rush at Hughes, and Dr. F. So and A. Ghaffari at Caltech for providing proton implantation.

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Wayne W. Lam, photograph and biography not available at the time of publication.

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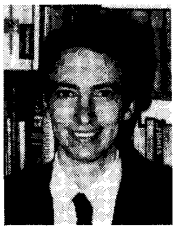

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