On-Wafer Photoconductive Sampling of MMICs

Sheng-Lung L. Huang, *Student Member, IEEE,* Eve A. Chauchard, Chi H. Lee, *Fellow, IEEE,* Hing-Loi A. Hung, *Senior Member, IEEE,* Timothy T. Lee, *Member, IEEE,* and Thomas Joseph

Abstract—**Photoconductive (PC) sampling has been shown to be a very powerful technique for characterizing the high-frequency response of monolithic microwave integrated circuits (MMICs). It also has higher signal sensitivity than other optical sampling techniques. On-wafer PC sampling could significantly reduce the cost of MMIC evaluation and give better accuracy, especially in the millimeter-wave regime. This is the first report of PC test structures being fabricated monolithically with MMIC amplifiers for microwave characterization using PC sampling. Good agreement was obtained between the measured results and those obtained from a conventional network analyzer. The special requirements for achieving on-wafer PC sampling are also discussed.**

I. Introduction

PHOTOCONDUCTIVE (PC) sampling has been demonstrated as a useful technique for the characterization of microwave/millimeter-wave integrated circuits [1]–[4]. This technique is needed to test devices with a frequency bandwidth larger than that of conventional electronic network analyzers. One of the main advantages of this measurement technique is that the electrical pulse signal containing the microwave spectrum is generated on-wafer, alleviating the need for microwave/millimeter-wave probe contacts. Only low-frequency sampled signals must be extracted from the device under test (DUT). In addition, this technique allows broadband characterization from a single measurement. Subpicosecond electrical pulse generation by a PC switch has been reported [5]; this pulse width corresponds to Terahertz measurement bandwidth.

On-wafer PC sampling refers to PC sampling on the DUT before it is diced from the wafer and packaged. With this constraint added to conventional PC sampling, two requirements must be met. First, fabrication of the PC switches must be compatible with the gallium arsenide (GaAs) monolithic microwave integrated circuit (MMIC) production process. As previously demonstrated for the hybrid case, PC sampling can be performed with switches fabricated to these specifications [6]. This compatibility allows monolithic integration of the PC switches with the MMIC. Second, only dc probes should be used to generate and extract the signal from the wafer. This rules out the need for complicated microwave/millimeter-wave probes and their associated problems such as reproducibility and invasiveness. In addition to the reduced cost of MMIC production, on-wafer characterization also alleviates the possibility of accidental oscillation of the DUT due to improper transition from the microstrip line to other guiding structures.

On-wafer one-port testing of passive elements has been reported [7]. This is the first report of monolithic integration of optical test structures to MMIC amplifiers, and on-wafer two-port PC sampling. This paper also discusses some issues on the limit of the dynamic range (DR) of optoelectronic sampling, which is over-looked in the literature. Optoelectronic sampling includes all the time-domain optical sampling techniques. Additionally, it has been demonstrated that PC sampling can be used to measure the frequency response of a nonlinear device.

II. Dynamic Range Limitation

The DR is normally defined as the ratio of the maximum to the minimum measurable signal level with a certain measurement time. The maximum measurable signal is limited by the linearity of the system, and the minimum measurable signal is limited by the noise level. In an optoelectronic sampling system, the length of the time-domain sampled waveform may also limit the DR. Depending on the characteristic of the DUT, the optical sampling system, and the optical test structure, the DR may be limited by any of the three factors.

A. System Linearity

Although the DUT can be nonlinear, the sampling system should be linear to provide meaningful measurement. The linearity of the PC sampling system depends mainly on the linear dependence between the current through the PC switch to the bias voltage at a fixed laser power.

The PC switch referred to herein is the sampling switch instead of the switch for generating the short pulse. The generating switch could operate at the nonlinear region, giving better switch responsivity. To maintain the linearity of the sampling system, the sampling switch must operate in the linear region. Different mechanisms such as Schottky contacts [8], impact ionization [6], and velocity overshoot could lead to nonlinear responsivity. All

Manuscript received March 31, 1992; revised July 28, 1992 This work was supported by the Defense Advanced Projects Agency (DARPA) MIMIC phase III program, monitored by the U.S. Army Labcom.

S.-L. Huang, E. A. Chauchard, and C. H. Lee, are with the Electrical Engineering Department, University of Maryland, College Park, MD 20742.

H.-L. A. Hung and T. T. Lee are with COMSAT Laboratories, Clarksburg, MD 20871.

T. Joseph is with TRW Electronic Systems Group, Redondo Beach, CA 90278.

IEEE Log Number 9203702.

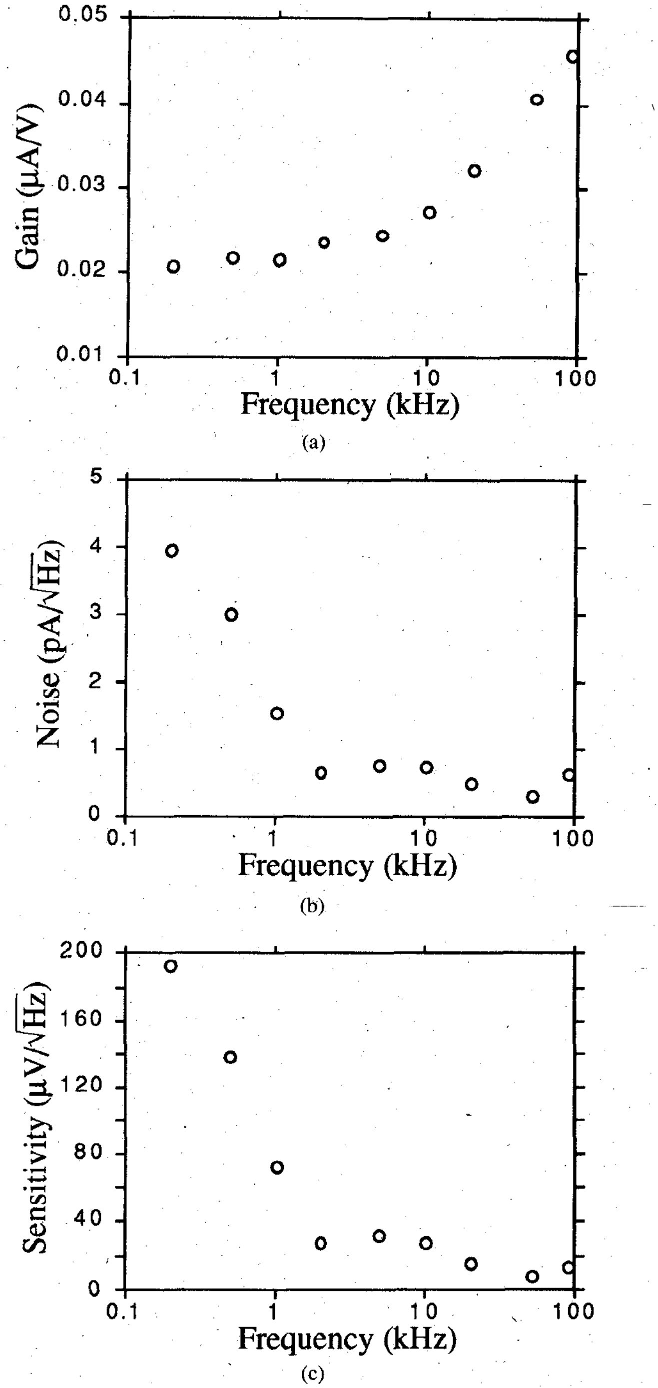


Fig. 1. The noise and system sensitivity measurement. (a) Gain, (b) noise, and (c) sensitivity.

of these mechanisms are highly process-dependent. With the proper process, it is possible to have 10 V on a 10-μm gap without suffering nonlinearity.

B. Sensitivity

The sensitivity of the PC sampling system can be determined experimentally as the ratio of the noise magnitude at the output of the sampling switch to the gain of the sampling switch. The gain of the PC switch, which is defined as the measured current divided by the voltage on

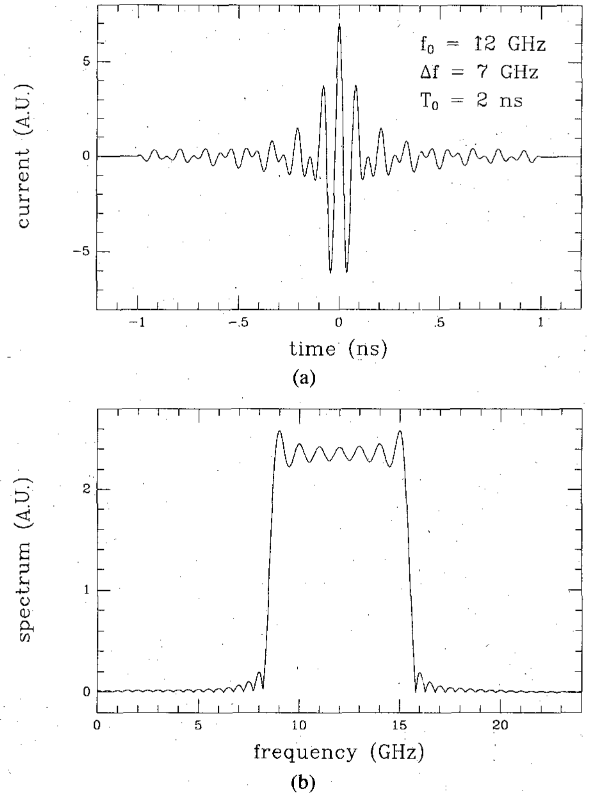


Fig. 2. Sampled (a) time-domain waveform and (b) spectrum.

the main microstrip line, for one of the oxygen ion (O^+)-implanted switches is shown in Fig. 1(a). The frequency dependency is due to the capacitance of the gap. The noise measurement is shown in Fig. 1(b), and the major source of the noise is from the laser intensity fluctuation. In PC sampling, there is no shot noise because the sampled signal is delivered to the lock-in amplifier directly. This is part of the reason that PC sampling has better sensitivity than electro-optic sampling [9]. Fig. 1(c) depicts the sensitivity of the measurement system.

Normally, the signal on the microstrip line is about 100 mV and the typical sensitivity is 10 $\mu V_{rms}/\sqrt{Hz}$. The measurement bandwidth of the lock-in amplifier is 200 Hz. Consequently, there should be more than 55-dB DR in the S-parameter measurement if the DR is limited by the system linearity and sensitivity.

C. Length of the Time-Domain Sampled Waveform

Another possible limitation on DR in the optoelectronic sampling system is the length of the time-domain sampled waveform. To study this effect, consider an impulse delivered to an amplifier with a center frequency f_0 and bandwidth Δf. The output of the amplifier is then sampled by optoelectronic sampling with T_0 sampling length. The sampled waveform and spectrum are shown in Fig. 2. It is clear from Fig. 2(b) that the DR depends on frequency. The envelope of the spectrum can be used to define the frequency-dependent DR. Away from the center frequency, the DR become larger. Assuming an impulse in-

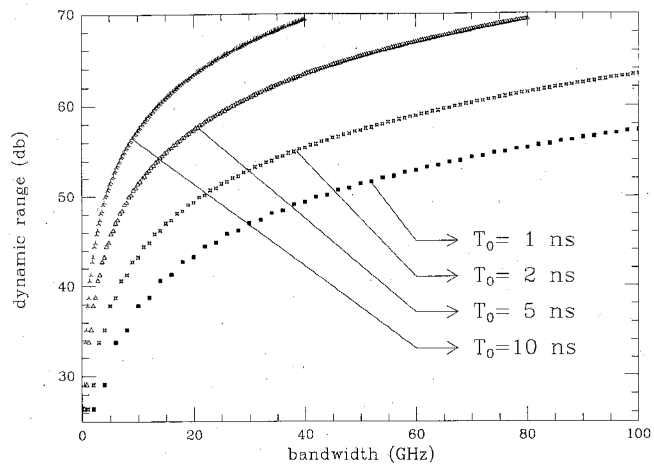


Fig. 3. Dynamic range versus bandwidth of the DUT with different sampling lengths.

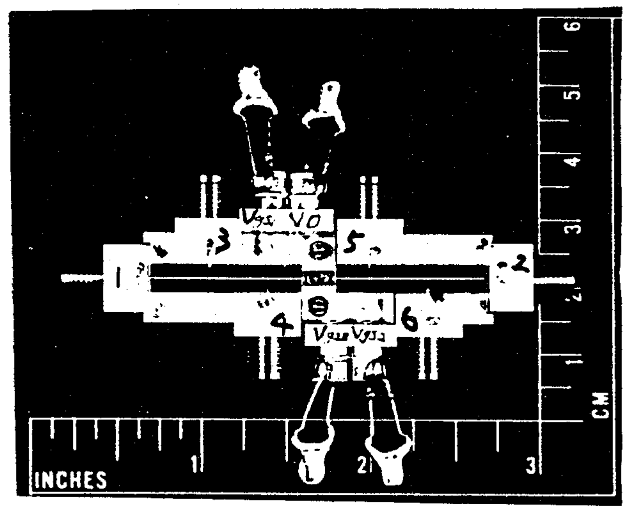


Fig. 4. The hybrid testing structure.

put for the amplifier, the DR at $f = f_0 \pm \Delta f$ can be obtained.

$$\mathrm{DR} \cong 20 \log \left| \frac{\displaystyle\int_0^{T_0/2} \frac{\sin(\pi t \Delta f)}{t}\, dt}{\displaystyle\int_0^{T_0/2} \frac{\sin(\pi t \Delta f)}{t} \cos\left[2\pi t(\Delta f + \delta)\right] dt} \right| \, db$$

where

$$\delta = \frac{-1}{\pi T_0} \frac{2 \sin^2\theta \tan\theta}{3 - 2\cos^2\theta}, \qquad \theta = \frac{\pi T_0 \Delta f}{2}$$

It is well-known that the above integrals have no analytic expressions. Fig. 3 shows the calculated DR versus bandwidth of the DUT for different sampling lengths. It is easier to achieve a higher DR with a wideband circuit than a narrowband circuit.

III. Hybrid Testing Configuration

Hybrid testing configuration means that the GaAs optical test structures are wire-bonded to the MMIC which were fabricated using an O^+-implant process rather than proton bombardment. This configuration is tried first to prove the validity of the PC switches.

As mentioned earlier, the first requirement for achieving on-wafer PC sampling is the compatibility of PC switch fabrication to that of the MMIC. O^+ is one of the typical ion species used for the isolation process by implantation during MMIC fabrication. The same energy and dose as used in the isolation process were used to implant the PC switches. Therefore, these switches can be fabricated with the MMIC, without adding a new process step.

A. Experiment

The O^+ implantation was performed at two energies, 140 keV with a dose of 5×10^{11} cm^{-2} and 360 keV with a dose of 1.3×10^{12} cm^{-2}, which are the same as the regular oxygen isolation process for the TRW MMICs. It was then annealed at 410°C for 10 minutes after implantation to reduce defects generated by the ion implantation. The O^+ is midgap hole trap that serves as an efficient recombination center. All of this was done before the formation of the metal contact to allow on-wafer optical probing to be included in the TRW MMIC fabrication process.

The laser system is a Coherent CW Mode-locked Nd:YLF laser which generates 50-ps pulses at 1.054 μm with a 76-MHz repetition rate. The output was compressed to approximately 3 to 5 ps by a fiber pulse compressor then frequency doubled to 0.527 μm by a potassium titanyl phosphate (KTP) crystal. The data are then collected using the standard pump-probe PC sampling technique. Typical electrical auto correlation full width at half maximum of the O^+ switch is about 19.5 ps. Fig. 4 shows the assembly of the optical testing structure and the DUT, which is a three-stage 12-GHz automatic gain control (AGC) MMIC amplifier with a 7-GHz bandwidth.

The output sampling time is deliberately extended to 2 ns to study the effect of time windowing [10]. Due to dark current, photovoltaic effect, and difference of responsivity inherent to the switches, calibration of the acquired data is necessary. The measured results of the PC switch response in terms of detected current vs bias are shown in Fig. 5. Both switches show good linear response at low bias voltage. The responsivity gives a 17-percent difference for the two sampling switches, which is equivalent to a 1.34 dB in $|S_{21}|$ calibration.

B. Results

S_{21} parameter measured by network analyzer and PC sampling with different time window length is shown in Fig. 6. Good agreement with the network analyzer measurement is obtained up to a 40-dB DR in the case of the 2-ns time window length. Two distinct features of the PC sampling measurements are evident. First, the separation of the peaks of the ripples is approximately equal to the inverse of the length of the time window. Second, the DR

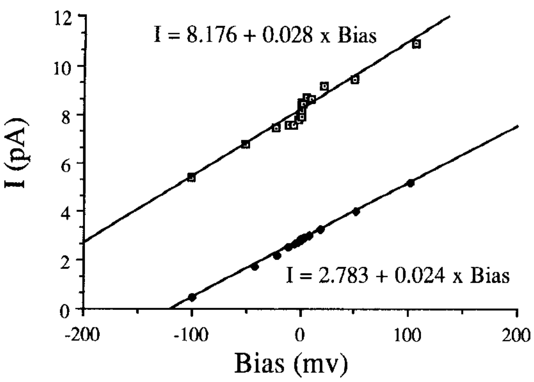


Fig. 5. Switch responsivity and linearity measurement for the hybrid case. The lower and upper curves are measured at the input and output ports, respectively.

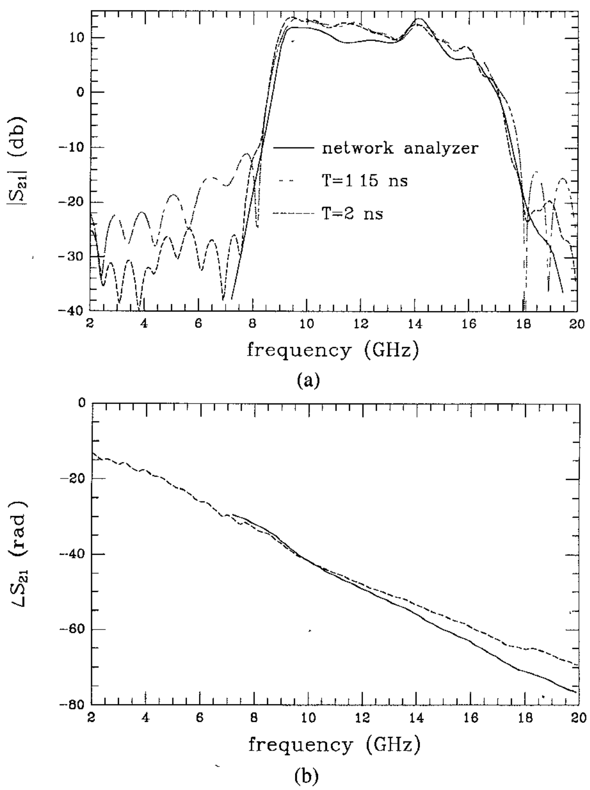


Fig. 6. The comparison between (a) magnitude (b) phase of S_{21} measured by network analyzer and PC sampling with 2 ns and 1.15 ns time window lengths.

increases as the time window increases. At 7 GHz from the center frequency, the DRs are 31 and 39 dB for the 1.15- and 2-ns time window lengths, respectively. The quantitative calculation shown in Fig. 3 gives very good agreement compared to this experimental result. The calculated DRs of 35 and 40 dB correspond to the two time window lengths. The conclusion is that the DR is limited primarily by the time window length. The 40-dB DR is the highest DR experimentally measured by optoelectronic techniques.

IV. Monolithic Testing Configuration

With the success of the characterization of an MMIC by the hybrid testing configuration using O^+ implanted PC switches, the optical test structures were monolithically integrated with the MMIC. This is the first report of a PC testing structure having been fabricated monolithically with the MMIC. Different testing structure designs were implemented in an effort to reduce the real estate required for the optical test structures.

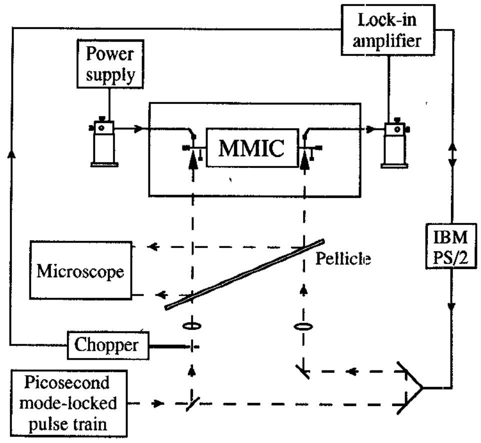


Fig. 7. The schematic diagram of the on-wafer sampling system.

A. Experiment

The optical system is the same as that used in the hybrid case. To facilitate on-wafer testing, a probe station using only dc tungsten probe needles was developed. The gold plated probes were used to bias the MMIC, and the generation gap switch, as well as to extract the cross-correlated signal from the sampling ports. A high-resistivity probe is required to bias the generation switch gap. The dc probes provide the only electrical contacts to the MMIC. A microscope was also implemented to assist in placing the dc tungsten probes at the 100-μm^2 pads. The schematic diagram of the on-wafer sampling system is shown in Fig. 7. With the exception of this probe station, the standard optical generating and sampling method was used for the measurement.

One important consideration limiting the commercial viability of on-wafer optical measurement techniques is the size of the GaAs real estate required for the built-in optical test structure. Two different methods were used in an attempt to reduce the size of these structures. One utilized a bent microstrip line, while the other used a test structure whose size is comparable to that used in a conventional coplanar waveguide (CPW) probe, referred to here as the de-embedding structure. De-embedding is a computational procedure devised to extract S-parameters from a DUT in the presence of other scattering sites.

The test structures are shown in Fig. 8. Fig. 8(a) shows the bent microstrip with generating and sampling gates monolithically fabricated with the DUT. In this configuration, mitered corners for the microstrip line are used. Figure 8(b) depicts the DUT measured using the second method. Data obtained from measurements of this device were compared to reference through-line measurements to compute the true input signal to the MMIC. Figure 8(c), which shows the test structure required for the CPW

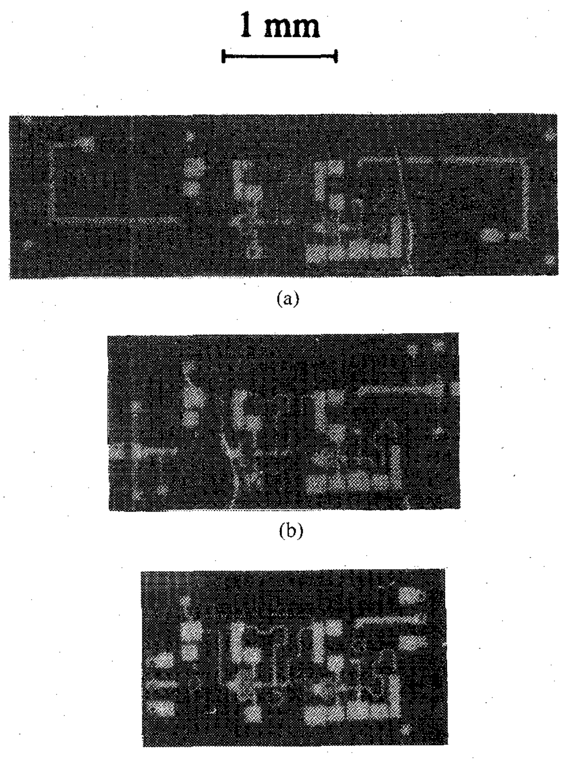


Fig. 8. MMIC broadband amplifiers with (a) bent structure (b) de-embedding structure (c) CPW test structure.

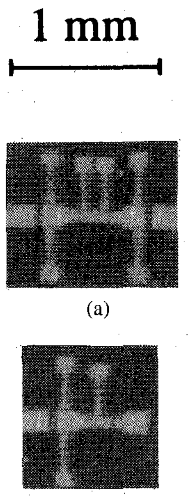


Fig. 9. (a) Through line and (b) 50 Ω termination designed the de-embedding structure.

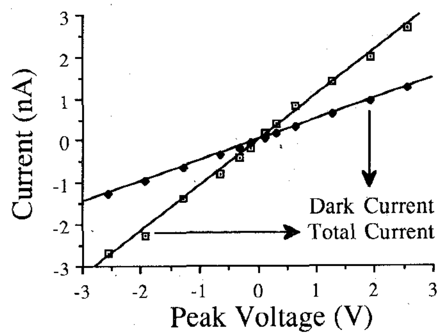


Fig. 10. Switch responsivity and linearity measurement for the monolithic case.

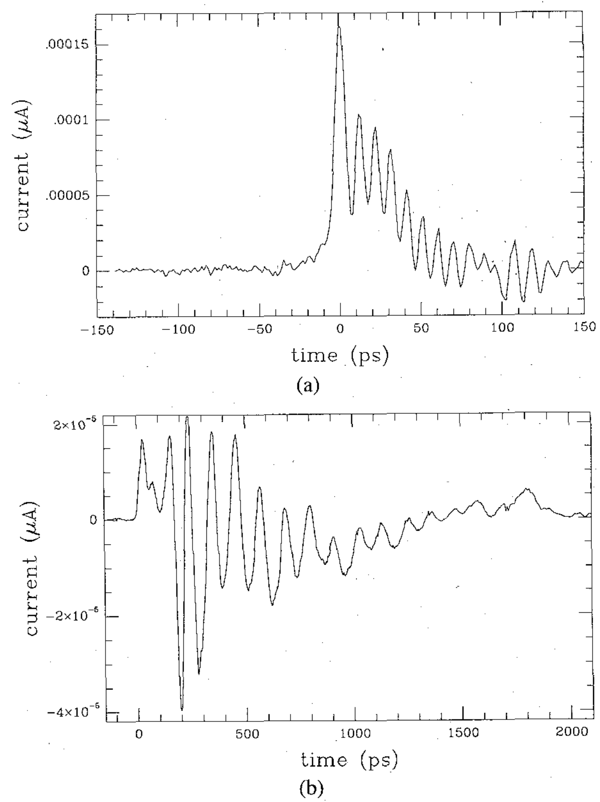


Fig. 11. (a) Input and (b) output waveforms for the bent structure.

probe, is included as a comparison of the wafer sizes required for the various methods. Fig. 9 shows the reference through-line and 50-Ω termination structures for the de-embedding structure. All these MMIC chips are mounted on gold-plated kovar slabs and attached to a small metal block having a tapped hole on the bottom for securing the block to the optical station.

Accurate characterization of the MMIC using the PC sampling techniques requires careful calibration of the PC switches. A dc signal is usually applied to the microstrip, and the on-state and off-state resistances are measured. In the case of the monolithic test structure, the microstrip is terminated in a 50-Ω integrated resistor. This prevents the application of a large dc signal on the line to calibrate the switch responsivity. However, a small dc voltage (a few hundred millivolts) on the line can not be resolved by the lock-in amplifier because both photoconductive and photovoltaic signals exist at the same chopper frequency. Instead, a needle probe is used to deliver 4-V, 80-μs electrical pulses with a 1.2-kHz repetition rate on the line, detected after the sampling switch by a lock-in amplifier. This measurement, shown in Fig. 10, serves as the reference for calibration. The relatively large dark current is through capacitive coupling.

Finally, the use of PC sampling as a tool for characterizing nonlinear devices was investigated. Due to its broadband nature, PC sampling allows the characteriza-

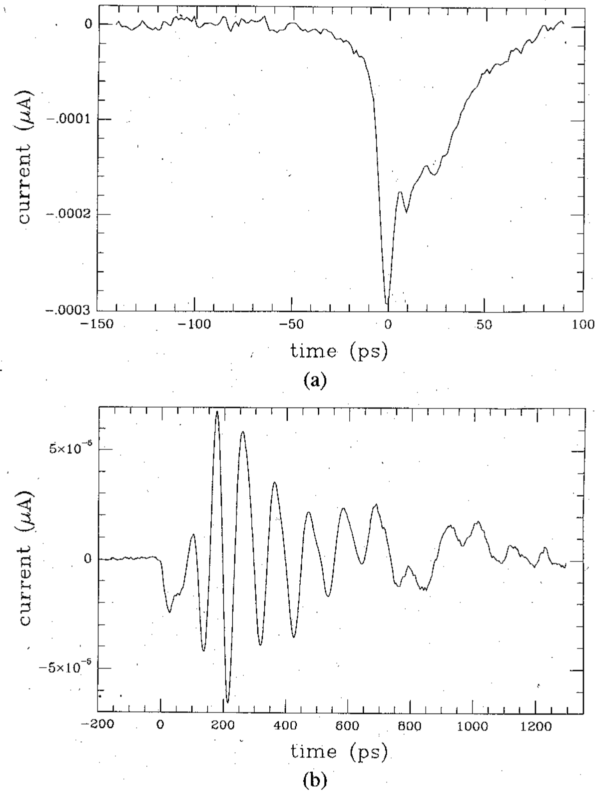


Fig. 12. (a) Input and (b) output waveforms for the de-embedding structure.

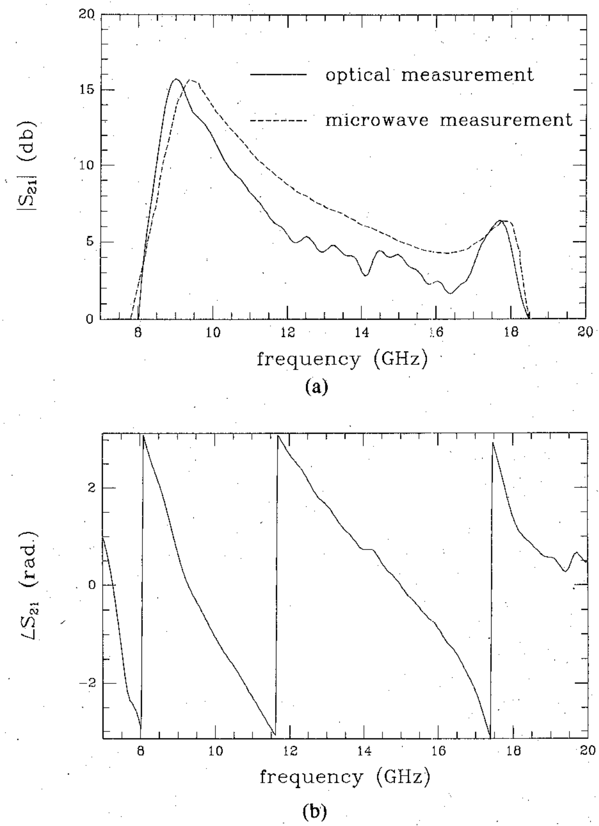


Fig. 13. (a) Comparison of measurement of $|S_{21}|$ by the microwave network analyzer to the optical bent structure. (b) $\angle S_{21}$ measured by the bent structure.

tion of S-parameters of nonlinear devices which cannot be characterized by conventional network analyzers. The conventional network analyzer can extract only the harmonic frequencies due to the nonlinear response from the device. In this paper, the S-parameter characterization of a nonlinear device, particularly a nonlinear transmission line, will be demonstrated.

B. Results

The typical input and output waveforms from the built-in optical test structure configurations are shown in Figs. 11 and 12. The multiple peaks of the input waveforms are a result of reflections from the end of the biasing side line, which is a shunt microstrip line designed to minimize the discontinuity seen by the electric pulse on the main microstrip line. Both methods give reasonable results compared to the conventional scalar network analyzer measurement, as shown in Figs. 13 and 14. Some discrepancies can be attributed to the nonuniform nature of the specific circuits tested. Fig. 15 shows the S_{11} measured by the de-embedding structure compared to the conventional scalar network analyzer measurement.

Since the reflection at the end of biasing side line depends on the exact position of the probe on the contact pad, different probe positioning can slightly alter the shape and timing of the reflection. This effect is more pronounced in the case of a de-embedding structure because the needle probe may not be at the corresponding position when measuring the responses of the MMIC and the

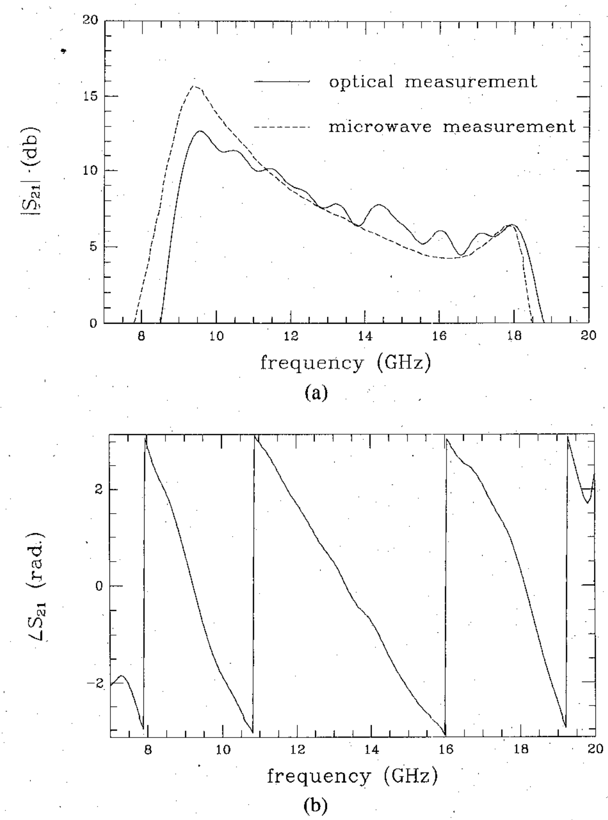


Fig. 14. (a) Comparison of measurement of $|S_{21}|$ by the microwave network analyzer to the optical de-embedding structure. (b) $\angle S_{21}$ measured by the de-embedding structure.

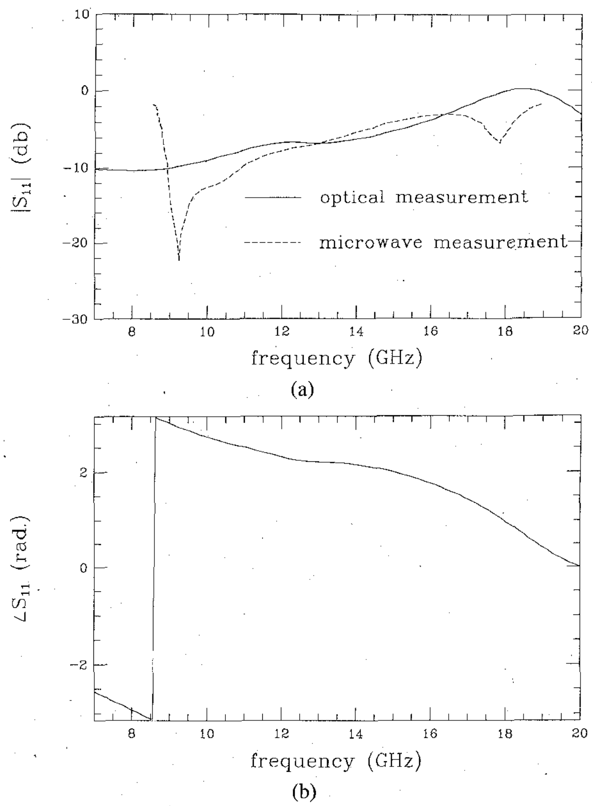


Fig. 15. (a) Comparison of measurement of $|S_{11}|$ by the microwave network analyzer to the optical de-embedding structure. (b) $\angle S_{11}$ measured by the de-embedding structure.

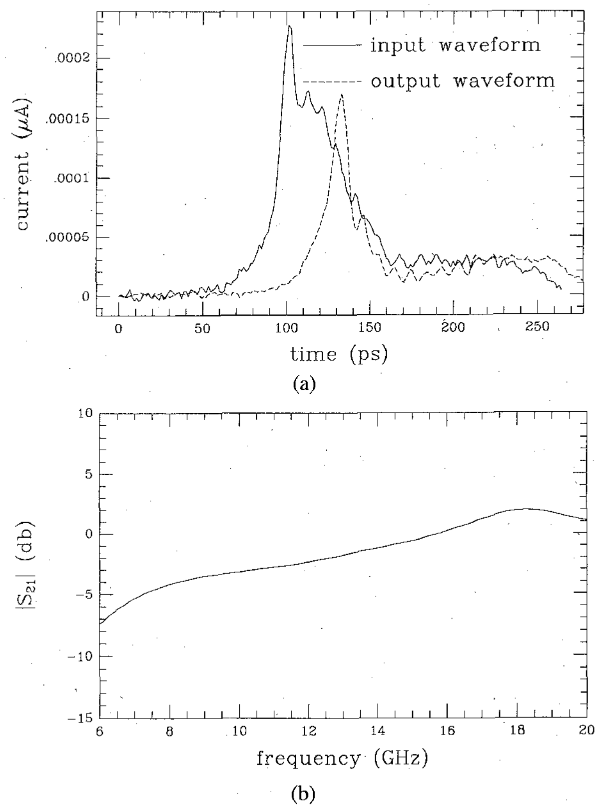


Fig. 16. (a) Input and output waveforms and (b) $|S_{21}|$ of the nonlinear transmission line.

through-line calibration structure. The exact position of the generation gap biasing probe cannot be duplicated from device to device, or from measurement or measurement. With the implementation of a dc probe, which has a built-in chip resistor, the mechanical constraints in positioning the probes on the contact is not critical. It was found that a ~50- to 100-Ω chip resistor gives the best attenuation. Larger resistance may cause more radiation coupling across the chip resistor, resulting in less attenuation. This also suggests that it is possible to use a lossy biasing side line to reduce the reflection from probe/side line contact.

Using the same built-in structures, the nonlinear circuits were characterized. Fig. 16(a) shows the input and output waveforms measured from a nonlinear transmission line. The pulses become narrower after propagating along the line. Due to this nonlinearity, new frequencies are generated; therefore, some frequencies experience gain. The magnitude of S_{21} of this nonlinear transmission line is shown in Fig. 16(b). The propagation of the pulses in both directions was measured, both cases experiences pulse compression, as shown in Fig. 17. This rules out the possibility that the narrowing is due to the nonuniform nature between the generating and sampling switches. This nonlinearity may be the result of the voltage-dependent capacitance of the Schottky junction between the microstrip line and the wafer. Fig. 18 shows the dependence of the magnitude of S_{21} on the input signal amplitude. With a larger signal on the line, the loss becomes

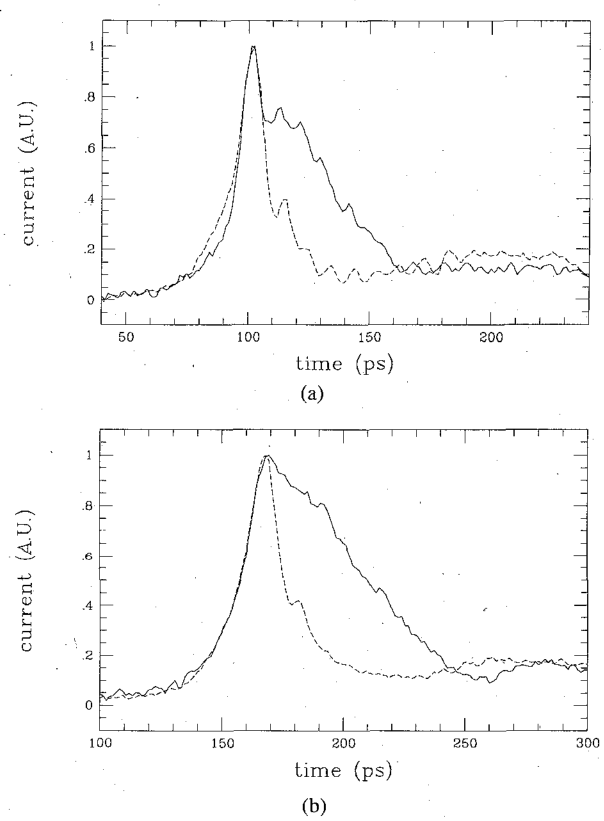


Fig. 17. Input and output waveforms of the nonlinear transmission line with (a) forward (b) reverse propagation direction. Solid lines are the input waveform and dotted lines are the output waveforms. The input and output waveforms are normalized in time.

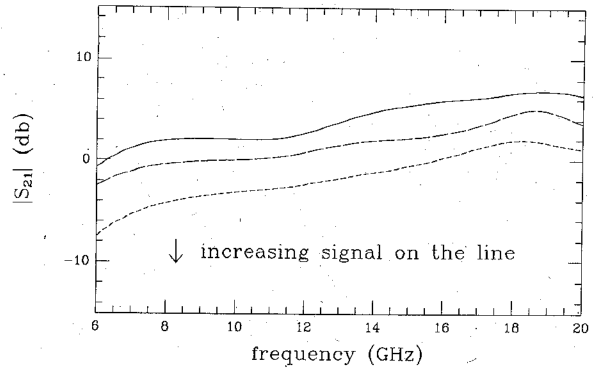


Fig. 18. Signal dependence of the $|S_{21}|$ of the nonlinear transmission line.

larger. This might be due to the increase of shunting conductance by a greater forward bias of the Schottky junction.

V. Conclusion

The objective of this study is to develop a practical technique for the on-wafer characterization of the high-frequency response of a MMIC. PC sampling provides *S*-parameter measurement with broadband, high sensitivity, and accurate calibration. In addition, due to its inherent broadband signal generation on the wafer, high-frequency information of the circuits can be extracted merely by using dc probes.

Step by step, the on-wafer PC sampling technique has been developed. Starting from a hybrid testing configuration, the compatibility of PC switch fabrication to the MMIC production process was demonstrated. In this phase, 40-dB DR in the *S*-parameter measurement—the highest DR measured by optoelectronic techniques—was achieved. The success motivated the monolithic integration of the PC switches onto the MMIC. Efforts were also made toward reducing the size of the optical test structure. Good agreement between a conventional network analyzer measurement and two optical testing results was achieved. This shows that built in optical test structures can be designed to have comparable overall size with existing CPW test structures. Increased measurement accuracy has been demonstrated by designing the biasing circuit to suppress unwanted reflections.

One of the capabilities of PC sampling which is often overlooked is the characterization of nonlinear devices. In this paper, the *S*-parameter characterization of a nonlinear transmission line was also demonstrated.

References

[1] P. R. Smith, D. H. Auston, and W. M. Augustyniak, "Measurement of GaAs field-effect transistor electronic impulse response by picosecond optical electronics," *Appl. Phys. Lett.*, vol. 39, pp. 739–741, Nov. 1981.

[2] H-L. A. Hung, P. Polak-Dingels, K. J. Webb, T. Smith, H. C. Huang, and C. H. Lee, "Millimeter-wave monolithic integrated circuit characterization by a picosecond optoelectronic technique," *IEEE Trans. Microwave Theory Tech.*, vol. 37, pp. 1223–1231, Aug. 1989.

[3] H-L. A. Hung, T. T. Lee, P. Polak-Dingels, E. A. Chauchard, K. J. Webb, C. H. Lee, and H. C. Huang, "Characterization of GaAs monolithic circuits by optical techniques," *SPIE Proc. Optical Technology for Microwave Application*, vol. 1102, pp. 98–106, Mar. 1989.

[4] C. H. Lee, "Picosecond optics and microwave technology," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 596–607, May 1990.

[5] J. A. Valdmanis and G. Mourou, "Subpicosecond electrooptic sampling: Principles and applications," *IEEE J. Quantum Elec.*, vol. QE-22, pp. 69–78, Jan. 1986.

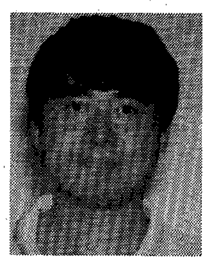
[6] S. L. Huang, E. A. Chauchard, C. H. Lee, T. Smith, T. T. Lee, T. R. Joseph, "Comparison of oxygen ion and proton implanted GaAs photoconductive switches," in *OSA Proc. Picosecond Electronics & Optoelectronics*, vol. 9, pp. 248–252, Mar. 1991.

[7] C. Rauscher, "Optoelectronic approach to on-chip device and circuit characterization at microwave millimeter-wave frequencies," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 1179–1193, July 1991.

[8] S. C. Moss, J. F. Knudsen, and D. D. Smith, "Linearity of response of ultrafast photoconductive switches: Critical dependence upon ion-implantation and fabrication conditions," *J. Modern Optics*, vol. 35, pp. 207–2030, 1988.

[9] B. H. Kolner and D. M. Bloom, "Electrooptic sampling in GaAs integrated circuits," *IEEE J. Quantum Elec.*, vol. QE-22, pp. 79–93, Jan. 1986.

[10] S. L. Huang, L. P. Golob, E. A. Chauchard, C. H. Lee, T. Smith, T. T. Lee, and T. R. Joseph, "Time window limited dynamic range of photoconductive sampling," *Dig. Conf. IEEE/LEOS Summer Topical Meeting on Optical Millimeter-Wave Interaction: Measurements, Generation, Transmission, and Control*, paper WA-3, Newport Beach, CA, July 1991.



Sheng-Lung L. Huang (S'89) was born in Taiwan, Republic of China, in 1964. He received the B.S. degree in electrical engineering from the National Taiwan University, in 1986, and the M.S. degree in electrical engineering from the University of Maryland, College Park, in 1990. He is currently pursuing the Ph.D. degree at the University of Maryland, College Park. His present research interests include ultrafast phenomena and developing novel applications of applying ultrafast optics to microwave/millimeter-wave semiconductor devices and circuits.

Mr. Huang is a member of the Optical Society of America and the Mathematical Association of America.

Eve A. Chauchard, photograph and biography not available at the time of publication.

Chi H. Lee (M'80–SM'86–F'91) received the B.S. degree in electrical engineering from the National Taiwan University in 1989 and the M.S. and Ph.D. degrees from Harvard University in 1962 and 1968, respectively.

He is currently a Professor of Electrical Engineering at the University of Maryland. His research interest includes ultrafast lasers and optoelectronic devices, optical control and characterization of microwave and millimeter-wave devices and circuits.

Dr. Lee is a Fellow of the Optical Society of America. He was the chairman of the technical committee on lightwave technology in IEEE Microwave Theory and Technique (MTT) Society. He also served as Co-chair of the OSA topical meetings on Picosecond Electronics and Optoelectronics.

Hing-Loi A. Hung (S'67–M'75–SM'81) received the S.B.E.E degree from the Massachusetts Institute of Technology in 1968, and the M.S. and Ph.D. degrees from Cornell University in 1970 and 1974, respectively.

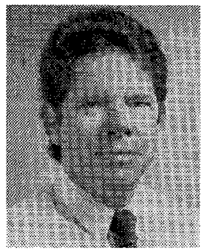
He is currently a Principal Scientist at COMSAT Laboratories, Clarksburg, MD. His present research areas include millimeter-wave monolithic integrated circuits, heterojunction devices, and optical/microwave interactions. He also manages programs in the productions of MMIC T/R and high-efficiency power modules, the development of P-HEMT integrated receiver and optical characterization of MMICs. He has served different managerial and research positions, and developed various MICs and MMICs for communications, EW and radar applications. He participated in satellite transponder designs for various INTELSAT, COMSAT STC and INMARSAT programs, and was responsible for the productions of a *Ku*-band thermoelectrically cooled LNA system for earth stations and the COMSTAR satellite 28-GHz IMPATT beacons. Prior to joining COMSAT in 1974, he worked on microwave components at Micromega Corp., MIT Research Laboratories of Electronics and Chu Associates.

Dr. Hung has been an adjunct professor at the George Washington University since 1978, has served as Session and Panel Chairman for IEEE and AIAA technical conferences, and was the past Chairman of the IEEE Washington Electron Devices Society.

Timothy T. Lee (S'77–M'79) received the S.B.E.E. and S.M.E.E., Electrical Engineering and Computer Science, Massachusetts Institute of Technology, 1980.

He is a Scientist in the Microwave Circuits Department of the Microwave Electronics Division at COMSAT Laboratories. His responsibilities include circuit design of monolithic microwave and millimeter-wave frequency components, device modeling and MMIC module development. His special interests are the applications of computer-aided techniques to both circuit design and the measurement/MMIC evaluation area. He has been involved in the development of advanced MMIC components such as low-noise amplifiers, receivers, and power amplifiers. He designed MMIC L-band and *X*-band AGC amplifiers for a data-link application. He designed *V*-band P-HEMT MMIC LNAs and EHF frequency translators for inter-satellite link applications. Also, for X-band radar applications, he developed the MMIC chip set for a 10-W high efficiency SSPA. In the DARPA MIMIC Phase III program, he was the program manager of a team that investigated optical on-wafer characterization techniques to improve MMIC testing capabilities at millimeter-waves through *W*-band.

Mr. Lee is a member of the IEEE Microwave Theory and Techniques Society and the IEEE Electron Devices Society. He has authored or coauthored several scientific papers in the microwave and millimeter-wave MMIC field.



Thomas R. Joseph was born in Washington, D.C. in 1950. He received a B.S. from the California Institute of Technology in 1971, and the M.S.E.E. and Ph.D. degrees from the University of Southern California in 1973 and 1976, respectively.

From 1976 to 1982 Dr. Joseph worked at the Hughes Aircraft Company in the area of surface acoustic wave devices and acousto-optics. Since 1982 Dr. Joseph has been at TRW, where he is currently a senior staff engineer in the Advanced Microelectronics Laboratory. His research interests at TRW in the electo-optics areas have included, microwave fiber optic links, acousto-optic devices and systems, and integrated optics. More recently, his work at TRW has centered on monolithic microwave integrated circuit development and manufacturing. He was responsible for the development and implementation of on-wafer test methods during the MMIC Phase I program. Currently, he is actively engaged in the development of TRW's GaAs foundry services.