H-6

ON-WAFER CHARACTERIZATION OF MONOLITHIC MILLIMETER-WAVE INTEGRATED CIRCUITS BY A PICOSECOND OPTICAL ELECTRONIC TECHNIQUE

P. Polak-Dingels†, H-L. A. Hung‡, T. Smith‡, H. C. Huang‡, K. J. Webb*, and C. H. Lee*

† The Laboratory for Physical Sciences, College Park, MD 20740

‡ COMSAT Laboratories, Clarksburg, MD 20871

* Department of Electrical Engineering, University of Maryland, College Park, MD 20742

ABSTRACT

A new picosecond optical electronic sampling technique for the characterization of monolithic microwave integrated circuits (MMICs) has been developed. The measured time domain response allows the spectral transfer function of the MMIC to be obtained. This technique was applied to characterize the frequency response of a two-stage Ka-band MMIC amplifier. The broadband results agree well with those obtained by conventional network analyzer measurements.

1. INTRODUCTION

In the development of new monolithic microwave integrated circuit (MMIC) technology, the testing of MMIC chips usually constitutes one of the major costs of the program. It is desirable to have a new low cost testing technique which allows on-wafer characterization of MMICs before dicing the wafer into individual chips. This is especially true for MMICs operating in the millimeter-wave range. In addition, as the operating frequencies of discrete devices and MMICs have been extended into the millimeter-wave range, the evaluation of these devices has become more difficult. The current commercially available on-chip characterization systems for MMICs have provided valuable performance data and their frequency of operation is being extended. However, several limitations still exist. With these systems, which use special coplanar waveguide (CPW) probes [1], it is more difficult to achieve a low-loss impedance-matched probe at millimeter-wave frequencies. The operating life of such a mechanical direct-contact probe is usually quite limited and a customized probe card is required for each set of microwave circuits on the wafer. The circuits also require coplanar waveguide patterns incorporated at various test locations.

This paper describes a new approach using picosecond optoelectronic techniques which can be used to characterize GaAs MMICs operating at millimeter-wave frequencies. Improved accuracy and new results, compared to those reported from a preliminary experiment [2], have been achieved with a new photoconductive switch design. The method was verified by measurement, resulting in the frequency response of a two-stage MMIC operating in the 28 GHz band. This non-contact optoelectronic technique can be readily incorporated into the on-wafer testing scheme.

Picosecond laser pulses with a repetition rate of 100 MHz are used to generate a short electrical pulse in an input transmission line. The pulse approximates a delta function in the time domain, resulting in a very broad spectrum. This pulse can be precisely sampled by time-delaying the same laser pulses and illuminating a second picosecond photoconductive switch on the input side of the MMIC under test. The output of the MMIC can be sampled by the same procedure with a photoconductive switch at the output of the MMIC. By comparing the Fourier transforms of the transmitted and reflected waveforms to that of the incident waveform, the two-port scattering parameters can be determined without using CPW probes. Since the sampled signals are collected at the 80 Hz chopper frequency, only low-frequency signal probes are needed to pick-up the sampled signal, eliminating the need for expensive microwave probes.

2. MEASUREMENT AND ANALYSIS

The proposed technique was adapted from picosecond photoconductivity correlation measurements developed by Auston [3], which assume that the small signal photoconductor response is linear. The laser system delivers green pulses at a repetition rate of 100 MHz with a pulse duration of 5 ps. The laser output is split into two beams, one illuminating the pulse generator and the other the sampling gate. The optical delay line, shown schematically in Fig. 1, provides a variable time delay between the two beams with a resolution of 0.8μm.

The photoconductive switches, which act as pulse generators and waveform samplers, were fabricated in a microstrip line circuit on a 0.010 inch GaAs substrate which was proton implanted at a dose of $10^{14}/cm^2$ to yield a picosecond gating time. A conductor thickness of 3 μm was used. Effort was made to design switches which present a minimal discontinuity to signals on the through line. A 5 μm photoconductive gap was used throughout. In the experiment, the GaAs circuit to be tested is mounted between two wafers each containing two photoconductive switches. The experimental data was obtained in the time domain and transferred to the frequency domain by a fast Fourier transform (FFT) algorithm. Two circuits were tested, one being the reference and the other the MMIC to be characterized. The reference circuit consisted of a sample 50 Ω line for the overall system calibration. The other was a two-stage power MMIC with a nominal gain of 4 dB and an output power close to 0.5 W at 28 GHz [4]. Figure 2 shows a photograph of the switch/MMIC assembly.

Figure 3 gives a schematic diagram of the switch characterization system and the monolithic circuit. The output at Port 2 corresponds to an autocorrelation of the voltage pulse $X(t)$ created at Port 1 and is obtained by the illumination of the gaps associated with Ports 1 and 2 with picosecond light pulses. This assumes identical photoconductor gaps at Ports 1 and 2. Therefore, the time dependent sampled signal at Port 2 is

$$R_{xx}(t) = X(-t) * X(t), \quad (1)$$

where $R_{xx}(t)$ is the autocorrelation of $X(t)$ and $*$ represents the convolution operation. At the output of the MMIC, the voltage pulse is the convolution of the impulse response of the device, $H(t)$, and the voltage input to the device, $X(t)$. The photoconductive gaps used for sampling at the output are the same as those used for generation and sampling in the input network. The output at Port 3 or 4 is the cross-correlation of $X(t)$ and the MMIC output signal $Y(t)$, so the signal is given by

$$R_{xy}(t) = X(-t) * Y(t), \quad (2)$$

where $R_{xy}(t)$ is the cross-correlation of $X(t)$ and $Y(t)$. Therefore, the frequency domain transfer function $H(f)$ of the MMIC, being the Fourier transform of the two-port impulse response $H(t)$, is equal to the ratio of the Fourier transform of the signals measured at Ports 2 and 3 or 4:

$$H(f) = R_{xy}(f)/R_{xx}(f). \quad (3)$$

The transfer function magnitude and phase, or the complex scattering parameters, can thus be obtained. The numerical algorithm was implemented on a Hewlett Packard minicomputer connected to the experimental setup, so that the frequency response is directly obtained using the FFT.

3. RESULTS AND DISCUSSION

The accuracy of the optical electronic sampling technique has been evaluated by a comparison with measurements performed with a network analyzer for a sample MMIC amplifier designed for Ka-band (28 GHz). The autocorrelation of the input signal measured at Port 2 is shown in Fig. 4. The signal measured at Port 4, which corresponds to the cross-correlation of the input signal to, and the output signal from, the MMIC is shown in Fig. 5. Figure 6 gives the normalized (accounting for conductor loss) Fourier transform of the impulse response obtained by this optoelectronic technique. It is interesting to note that the response in Fig. 6 is relatively insensitive to the time domain window of the correlation responses, which is an indication of the robustness of this technique. The measured data presented here consisted of 800 points taken at 0.5 ps time intervals, and the spectral domain data was then obtained using a 4000 point FFT (with zero padding). A photoconductor bias voltage of 40 V was used for these measurements. A comparison with the network analyzer measurement of the magnitude of the transfer function, which is given in Fig. 7, shows close agreement over the measured frequency range of 2 to 32 GHz.

As presently implemented, auxiliary test structures are needed to use the optoelectronic technique described in this paper. For application to on-wafer characterization, the maskset must be designed with microstrip test structures connected to the MMICs to be characterized. If these lines are made short, more chips can be sampled and the wafer can have a higher chip density. Unfortunately, there are restrictions on the minimum length of these test microstrip lines in order to resolve the time domain signals.

Electro-optic sampling could be used instead of built-in optical switches along a transmission line. This has the advantage that any point on the line can be selected for sampling, or even a point within the MMIC itself. The advantage of this technique is that only generation switches are required, which is important because the switches themselves cause some reflection. The disadvantage is that it can only be used with materials which exhibit the electro-optic effect, such as GaAs. This approach is currently being investigated.

4. CONCLUSION

An optical electronic characterization technique has been demonstrated to achieve the broadband frequency response of a Ka-band MMIC. The measurement system has been calibrated, with measurements being performed on both the input and output signals. The results obtained show close agreement with data obtained from network analyzer measurements. This technique offers significant potential for on-wafer characterization of high speed/frequency components.

REFERENCES

[1] E. W. Strid, "26-GHz wafer probing for MMIC development and manufacture," *Microwave Journal*, pp. 71-82, Aug., 1986.

[2] P. Polak-Dingels, H-L. A. Hung, T. Smith, H. C. Huang, K. J. Webb, and C. H. Lee, "Optical electronic characterization of monolithic millimeter-wave integrated circuits," Proc. of Int. Conf. on Infrared and Millimeter Waves, Orlando, FL, Dec. 14-18, 1987.

[3] D. A. Auston, "Impulse response of photoconductor in transmission lines," *IEEE J. Quantum Electron.*, vol. QE-19, pp. 639-648, Apr., 1983.

[4] H-L. A. Hung et. al., "Ka-band monolithic power amplifiers," IEEE Microwave and Millimeter-Wave Monolithic Circuit Symposium Digest, June 1987, pp. 97-100.

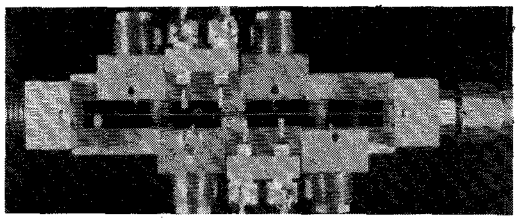

Figure 2. Switch/MMIC assembly

OPTICAL DELAY LINE AND SWITCH

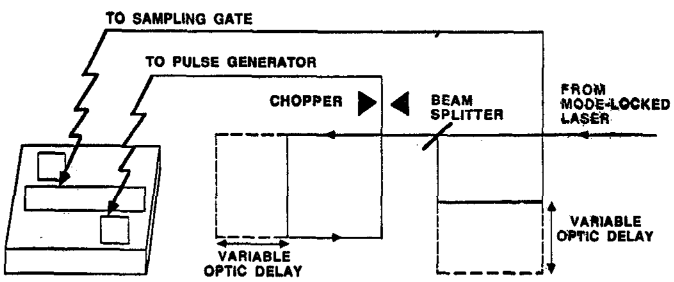

Figure 1. Schematic diagram of the optical arrangement for sampling.

SCHEMATIC DIAGRAM OF THE CIRCUIT

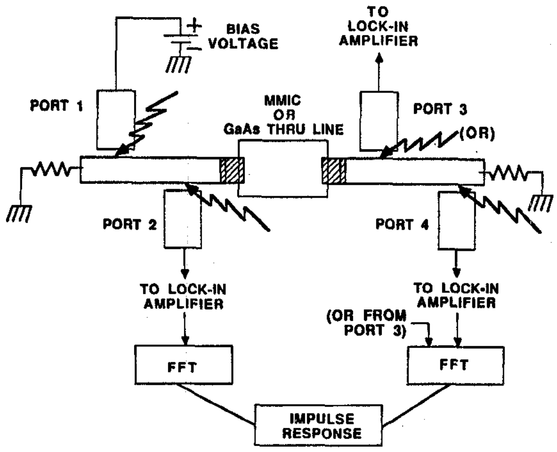

Figure 3. Schematic diagram of the switch characterization system and MMIC.

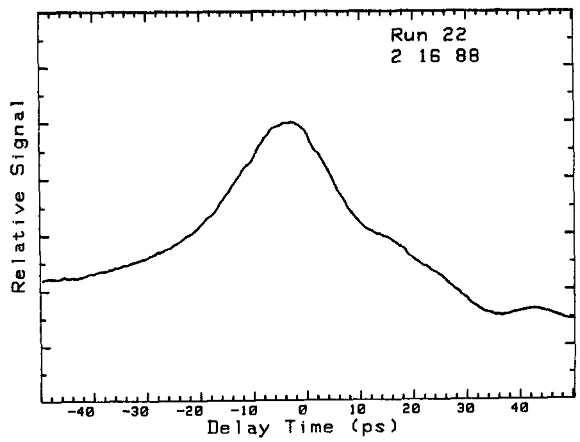

Figure 4. Measured correlation response at Port 2.

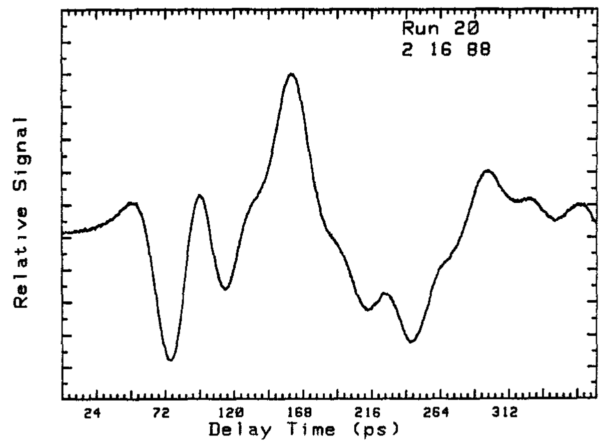

Figure 5. Measured correlation response at Port 4.

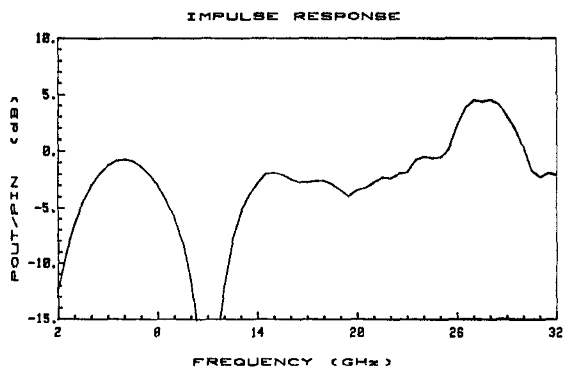

Figure 6. Computed MMIC transfer function based on the measured time domain data.

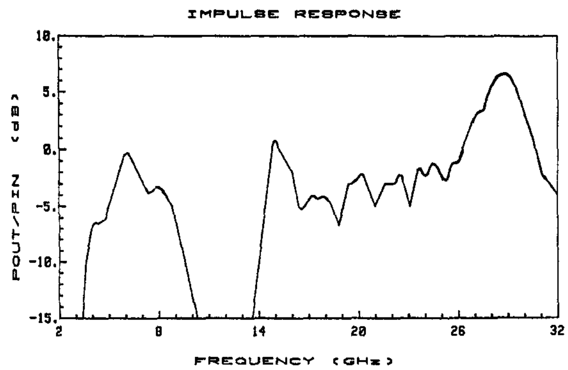

Figure 7. Transfer function of the MMIC from network analyzer measurements.