100 GHz On-Wafer S-parameter Measurements by Electrooptic Sampling

R. Majidi-Ahy, B. A. Auld and D.M. Bloom

Edward L. Ginzton Laboratory, Stanford University
Stanford, CA 94305.

(Invited Paper)

Abstract

We describe the electrooptic sampling system at Stanford configured for millimeter-wave measurements. An active wafer probe frequency-multiplier, developed for supplying the stimulus signal for these measurements is also described. 100 GHz on-wafer S-parameter measurements of linear circuits, time waveforms of nonlinear circuits and propagation characteristics of uniplanar waveguides on GaAs are discussed.

Introduction

On-wafer measurements of millimeter-wave devices and IC's using conventional techniques are presently limited to 40 GHz. The conventional wafer probes also present 50 ohm impedances to the device under test, and therefore can not be used for internal node probing of the IC's. For higher frequency analysis and circuit design with these devices, equivalent circuit models derived from measurements below 40 GHz are typically used. However due to frequency-dependent elements in the equivalent circuit models of the devices , these extrapolations to higher frequencies are not accurate. Therefore direct measurements at the operating frequencies above 40 GHz are essential to accurate characterization and understanding of millimeter-wave devices.

Waveguide sources and harmonic mixers are commercially available, which extend the frequency range of automatic network analyzers such as HP 8510 to 100 GHz. However due to their waveguide configuration, they are incompatible with on-wafer testing.

Electrooptic sampling is an optical probing scheme, for characterization of high-frequency devices and circuits[1]. One configuration using an external electrooptic modulator which is compatible with on-wafer testing, is the electrooptic needle probe[2]. Direct electrooptic sampling uses the substrate of the GaAs circuit under test as the electrooptic modulator, eliminating electrical parasitics associated with external electrooptic elements and providing internal node probing of the IC's with picosecond time resolution and micron spatial resolution[3].

We have used direct electrooptic sampling in GaAs, for 100 GHz on-wafer S-parameter measurements, nonlinear circuit characterization and potential mapping. The stimulus signal to the device under test was provided by a new device which we call an active probe frequency-multiplier.

Electrooptic Sampling System

Figure 1 shows the cross section of the probing geometry for coplanar waveguide (CPW) on GaAs. The optical beam is focused through the backside of the substrate and is reflected by the signal conductor. Since GaAs is electrooptic, the CPW millimeter-wave signal induces optical birefringence. The optical beam polarization is therefore changed by the longitudinal electric field components for standard [100] cut GaAs substrate. The reflected light is passed through a polarizer and its intensity is deteced by a photodiode. By appropriate adjustment of the probe beam polarization, the intensity of the reflected beam is directly proportional to the voltage across the substrate. For well-designed millimeter-wave CPW's the fields are highly confined to the frontside and the backside potential is approximately zero

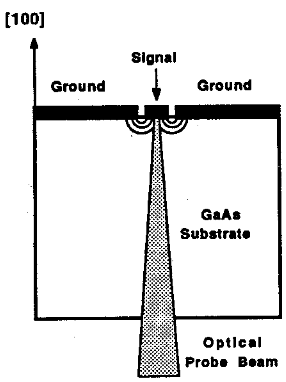

Figure 1. Backside probing for CPW.

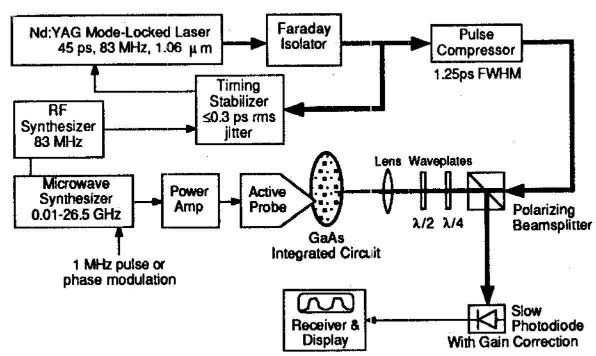

Figure 2. The millimimeter-wave electrooptic sampling system.

CH2725-0/89/0000-0299$01.00 © 1989 IEEE

The block diagram of the electrooptic sampling system is shown in Figure 2. The three major sections of the system are the short optical pulse generation, millimeter-wave stimulus signal generation and the receiver system for data acquisition and signal processing. The optical pulse train is generated by a commercially available Nd:YAG laser which produces 45 ps pulses at 1.06 micron with 83 MHz pulse repetition frequency. A fiber-grating pulse-compressor reduces the pulsewidth to 1.25 ps.

The millimeter-wave stimulus signal is generated by an active probe frequency-multiplier driven by a power amplifier connected to a commercially available microwave synthesizer. The receiver section consists of a 1 MHz gain-correcting photodiode detector, an IF-converter for second stage down-conversion from 1 MHz to 50 KHz and a lock-in amplifier.

Harmonic mixing is used for vector measurements, with the millimeter-wave signal frequency set to an exact multiple of laser pulse repetition frequency plus 1 MHz frequency offset, and the receiver configured as a synchronous detector to measure the magnitude and phase of the recieved signal at the offset frequency. Equivalent-time sampling is used to view the time-waveforms, with an offset frequency of 1-100 Hz. Pulse or phase modulation at 1 MHz is used to suppress laser intensity noise. The resulting signal varies at the slow offset rate in proportion to the detected signal.

System Bandwidth

The electrooptic sampling system bandwidth is primarily determined by the optical pulsewidth, the interaction time of the optical beam and the electrical signal, and the timing jitter of the laser pulses. The estimated compressed optical pulsewidth from its measured autocorrelation is 1.25ps FWHM assuming a Gaussian pulseshape. The spectral content of the pulse obtained by direct numerical Fourier transform of the autocorrelation typically has a measured 3 dB bandwidth in excess of 200 GHz.

The interaction time of the optical beam and the electrical signal consists of the electrooptic effect response time, the electrical transit time and the optical transit time. The time constant of the electrooptic effect in GaAs is very short and is of the order of 10 fs. The electrical transit time is defined as the time it takes the electrical signal to traverse the optical beam. For well-focused beams the electrical transit time is less than 100 fs. The optical transit time is defined as the effective time the optical beam interacts with the electric fields in the substrate and is a function of the CPW geometry. For well-designed millimeter-wave CPW's the ground-to ground spacing is typically much smaller than the substrate thickness and the fields are tightly confined to the frontside of the substrate. To a first order approximation the effective field peneteration depth is of the order of the ground-to-ground spacing (typically a factor of 5 smaller than the substrate thickness). For a CPW on a 100 micron thick GaAs substrate the effective optical transit time is less than 0.5 ps with a 3 dB bandwidth in excess of 600 GHz. Since the timing jitter of the laser pulses affects both bandwidth and sensitivity of the system, it is essential to reduce it to a level below the optical pulsewidth. A timing stabilizer phase-lock-loop system reduces the free-running 4 ps pulse-to-pulse rms timing jitter of the laser to less than 300 fs[4]. With this improvement currently the worst case uncertainty in the phase of a measured 100 GHz signal due to the timing jitter is less than 10 degrees.

System Sensitivity

The fundamental limiting noise source in the electrooptic sampling system is the shot noise of the probe beam observed as the shot noise of the photodiode detector quiescent current. Although the signal detection is translated to 1 MHz where 1/f low-frequency laser noise is below the shot noise limit, typically the noise floor is 10-15 dB above shot noise level. The excess noise arises from stimulated Raman scattering (SRS) and polarization noise in the pulse compressor. The SRS noise is minimized by keeping the input power to the pulse compressor below the fiber Raman threshold. The polarization noise is kept low by temperature stabilizing the fiber. With a narrowband 1 MHz receiver data acquisition rates of 10-100 Hz with typical voltage sensitivies less than 500 microVolts per root Hz are acheivable. Faster data acquisition are obtained by trading off sensitivity.

Active Probe Frequency-Multiplier

The active probe frequency-multiplier generates the stimulus signal and supplies it to the device under test for millimeter-wave S-parameter measurements by electrooptic sampling[5]. The active probe frequency-multiplier has a coaxial input, and a coplanar waveguide output tip which contacts the device pads on wafer.

The frequency-multiplier hybrid circuit consists of an input low-pass filter and matching network, an anti-parallel beam-lead GaAs Schottky diode pair in shunt, and an output bandpass filter and matching network.In this circuit, a 16-25 GHz input signal is multiplied by five to 80-125 GHz. The schematic circuit diagram of the quintupler is shown in Figure 1. The input filtering and matching was performed by a five-section direct-coupled coplanar waveguide low-pass circuit. Output filtering and matching was implemented by a six-section edge-coupled coplanar waveguide bandpass circuit.

The quintupler bandwidth, shown in Figure 2, was from 80 to 125 GHz. The maximum output power was -11 dBm, corresponding to 180 mV peak-to-peak at 95 GHz. The average conversion loss was 38 dB.

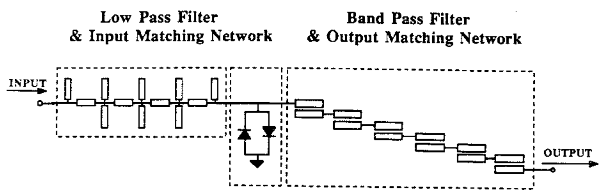

Figure 3. Active probe frequency-multiplier schematic

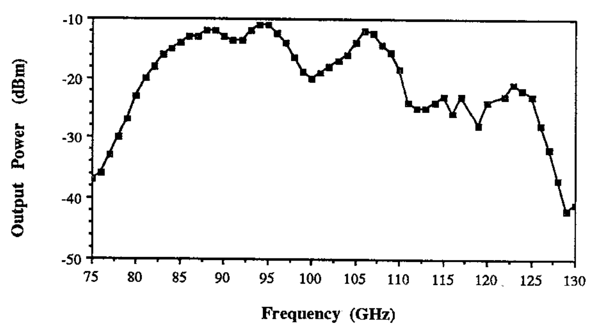

Figure 4. Active probe frequency-multiplier output

Millimeter-Wave On-Wafer Measurements

The electrooptic sampling system in conjunction with the active probe frequency-multiplier are used for on-wafer millimeter-wave characterization of GaAs devices and IC's. Since the electrooptic sampler can noninvasively probe internal nodes of a circuit, it can measure device performance under realistic loading conditions.

S-parameter Measurements

The electrooptic sampler directly measures voltages on the probed transmission line. Measuring the voltages as a function of position with the optical probe, similar to a slotted-line measurement, permits calculation of the incident and the reflected waves on the trasnsmission lines, from which the S-parameters are calculated by a linear estimation algorithm. Figure 4 shows the 100 GHz standing wave measured by electrooptic sampling on a 50 ohm CPW terminated in a short circuit, with the input signal supplied by the active probe quintupler. The reflection coefficient of the 1.0 millimeter long 50 ohm CPW terminated in a short circuit in Figure 4, was calculated to be 0.93 at -94 degrees. Figure 5 shows the measured and modeled input reflection coefficient of this test structure from 60 to 100 GHz.

For two-port S-parameter measurements the electrooptic probe is scanned along the input and output transmission lines and the travelling-wave coefficients are determined. Figure 6 shows measured 50 to 95 GHz S-parameters of a 500 microns long 25 ohm CPW, compared to a CPW model which includes the parasitics.

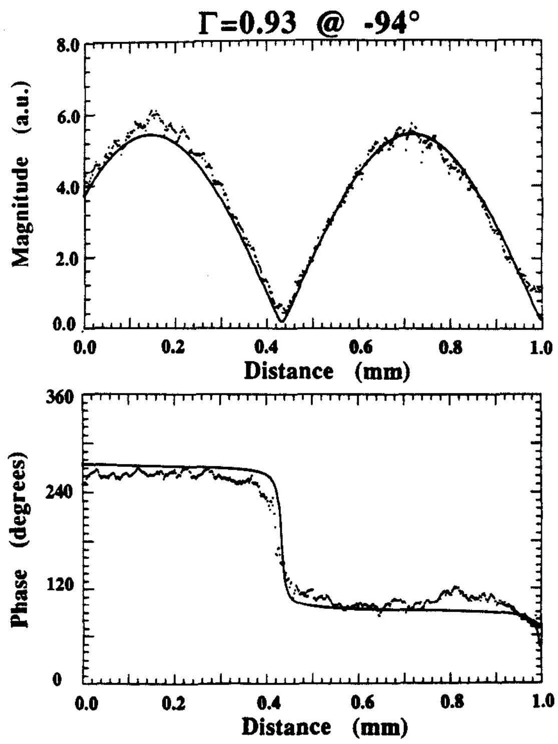

Figure 5. 100 GHz CPW standing wave measured by electrooptic sampling.

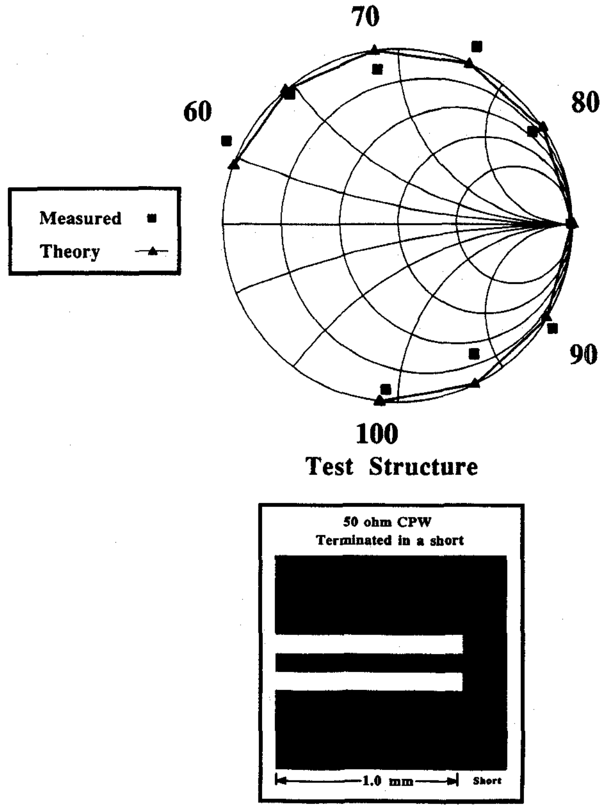

Figure 6. 60-100 GHz S11 measurement by electrooptic sampling.

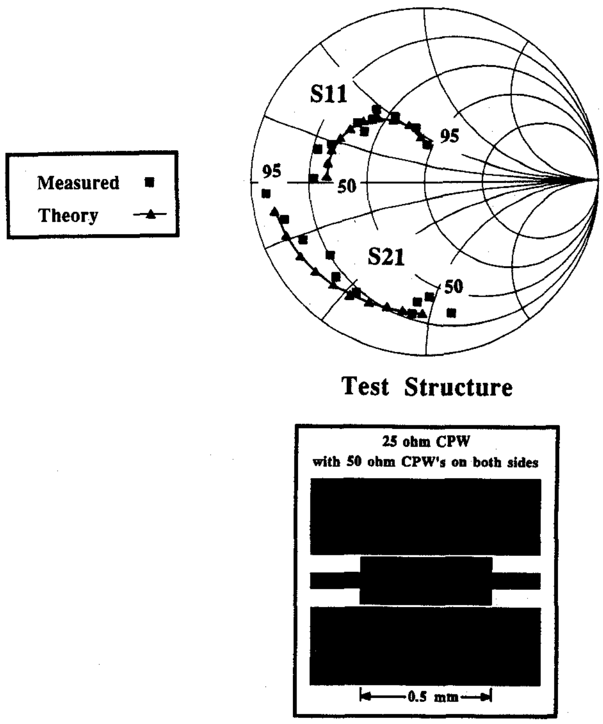

Figure 7. 50-95 GHz 2-port S-parameter measurement by electrooptic sampling.

Nonlinear Circuit Characterization

The electrooptic probe configured in the equivalent-time sampling mode can be used to directly measure time-waveforms of nonlinear circuits. Figure 7 shows the output time-waveform of the active probe frequency-multiplier , measured using the elctrooptic sampler. In this example, a 15.4 GHz sinusoidal input waveform is distorted and filtered by the multiplier to generate the fifth harmonic at 77 GHz. Due to finite rejection of the quintupler output filter an envelope at the fundamental frequency is present. Other nonlinear GaAs devices and circuits can similarly be characterized by electrooptic sampling measurements of time waveforms and spectral content of their input/output and internal nodes.

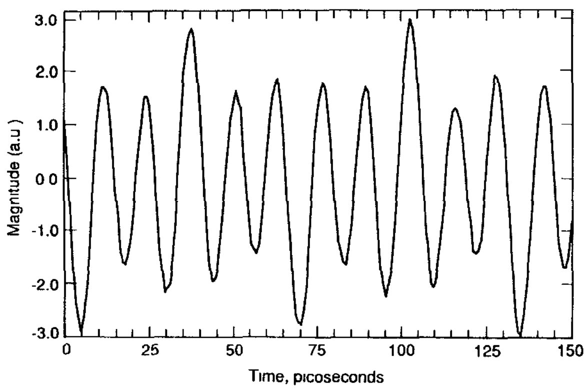

Figure 8. 77 GHz time-waveform measurement by electrooptic sampling.

Potential Mapping

Electrooptic sampling has also been used as a potenial probe to measure millimeter-wave transverse potential distribution, fundamental modes, coupling to surface-wave modes and dispersion characteristics of CPW, CPS and slot-line. These data are helpful for millimeter-wave broadband circuit design using uniplanar waveguides. Figure 8 shows the dispersion characteristics of a 50 ohm CPW on GaAs measured from 15 to 100 GHZ by electrooptic sampling.

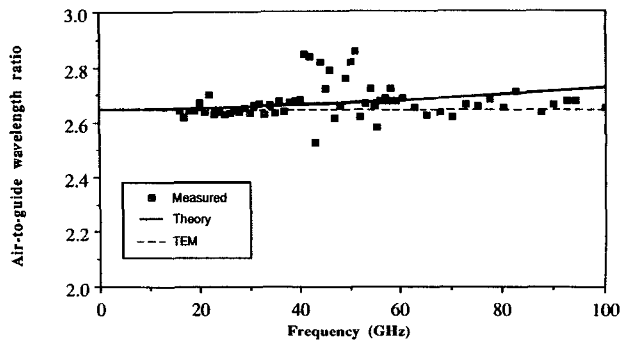

Figure 9. 15-100 GHz CPW dispersion measurement by electrooptic sampling.

Conclusion

We have described an electrooptic sampling system with a measurement bandwidth in excess of 200 GHz for on-wafer millimeter-wave measurements. An active probe frequency-multiplier has been developed to supply the millimeter-wave stimulus signal to the device under test. On-wafer measurements of S-parameters of linear circuits, time-waveforms of nonlinear circuits, and propagation characteristics of uniplanar waveguides on GaAs to 100 GHz, by direct electrooptic sampling have been demonstrated.

Acknowledgements

The authors wish to thank Brian Kolner, Kurt Weingarten, Jim Freeman and Mark Rodwell for their contributions to the electrooptic sampling system at Stanford. We also would like to thank Pauline Prather for her work in assembling the active probes, Mohammad Shakouri and Reed Gleason for their help and suggestions. We acknowledge the generous measurement equipment donations by the Hewlett-Packard Company, Tektronix Inc. and Cascade Microtech Inc. This work was supported in part by Air Force Office of Scientific Research contract F49620-85K-0016. Reza Majidi-Ahy acknowledges a Rockwell Science Center/Stanford Center for Integrated Systems fellowship.

References

[1]- Kolner B. H. et al:IEEE J. Quant. Elec., 22, 79, 1986.

[2]- Valdmanis J. A. et al:IEEE J. Quant. Elect., 22, 69, 1986.

[3]- Weingarten K. J. et al:IEEE J. Quant. Elec., 24, 198, 1988.

[4]- Rodwell M. J. W. et al:Optics Letters, 11, 638, 1986.

[5]- Majidi-Ahy R. et al:Electronics Letters, 25, 6, 1989.