A TIME-DOMAIN NETWORK ANALYZER WHICH USES OPTOELECTRONIC TECHNIQUES

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ABSTRACT

The performance of characterization measurements using time domain optoelectronic techniques offers many advantages and is especially suited for the on-wafer probing of GaAs integrated circuits. A single measurement can provide broadband scattering parameters. Signal generation is achieved by the illumination of a biased picosecond photoconductor with a short optical pulse and sampling by either a photoconductive or electro-optic technique. A comparison of results using both optical sampling techniques and frequency domain measurements is made.

INTRODUCTION

Microwave measurements are traditionally performed in the frequency domain, where desired results are typically expressed in the form of scattering parameters. If results are required over a broad frequency range, then more than one waveguide system may be necessary. Each new measurement network requires calibration and at the end all the data must be assembled in broadband form. Circuit components are usually mounted in a 50 Ohm microstrip network and the measurements performed with a Network Analyzer, such as the HP 8510, which uses a coaxial system for microwave frequencies. High performance coaxial to microstrip transitions are therefore necessary. In the millimeter-wave range a rectangular waveguide measurement system is usually used. In GaAs monolithic microwave and millimeter-wave integrated circuit (MMIC) manufacture, it is desirable to be able to characterize the devices before the wafer is diced, ie. to perform on-wafer measurements. This is possible using an external source with coplanar waveguide probes, which are customized to fit the particular integrated circuit being tested. Such mechanical contacting probes have a fairly short lifetime and deteriorating electrical performance at the higher frequencies.

In an effort to reduce the cost of large scale on-wafer measurements and to achieve a more diverse technique, the use of optoelectronic techniques has been proposed. Several approaches for making these measurements have been studied. Frequency domain measurements have been performed by electro-optic probing of the electrical signal on a microstrip line [1]. This work used a coplanar waveguide probe to launch the microwave signal. An alternative is to generate a very short electrical signal on-wafer by illuminating a biased photoconductor with a picosecond optical pulse [2], [3]. The electrical signal on a line can then be sampled by electro-optic (EO) or photoconductive (PC) sampling. Some results for a GaAs FET mounted in a silicon-on-sapphire test circuit have been presented using this approach with PC sampling [4]. A comparison of this technique with frequency domain measurements performed on a Ka-band integrated circuit have been made with an on-wafer characterization emphasis [5].

In the optoelectronic characterization of MMICs, it is clearly advantageous to be able to generate the characterization signal on the wafer, thereby avoiding the difficult problem of launching the microwave or millimeter-wave signal. Whether one should use PC or EO sampling is an issue which warrants further consideration. Factors involved in making this choice are versatility (EO sampling can be performed anywhere), speed, sensitivity, ease of making the measurement, dynamic range and accuracy.

Upon a comparison of optoelectronic time domain measurements with frequency domain measurements, a number of tradeoffs are evident. When measurements are performed in the time domain, broadband information can be obtained with a single measurement. The bandwidth of the electrical signal generated using optoelectronic techniques can be tailored to a desired shape, which may be advantageous for some applications. Frequency domain measurements can have dynamic ranges on the order of 70 dB, a tall order for optoelectronic techniques to match. The time domain approach can be used to characterize non-linear effects and the current optical technique can be simply extended for multi-port measurements. The amplitude of the generated signal can be adjusted by varying the bias voltage, with perhaps a modification in the photoconductor geometry for widely varying voltages. For low-power device measurement, small signal levels are necessary and therefore relatively narrow band signals may be required. It is clear that there are a number of issues which must be investigated to obtain a clear picture of the potential and application of optoelectronic time domain techniques. Such techniques offer the possibility of measurement diversity, low-cost on-wafer probing, and broadband characterization.

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MEASUREMENT TECHNIQUE

The measurement system for obtaining two-port scattering parameters using PC sampling is shown in Fig. 1. The pulse generation occurs at ports a or d, with the pulse traveling away from the device under test (DUT) either being terminated in the matched load or being windowed out by the sampling time duration. Photoconductive sampling is based on the small signal operation of the photoconductor whereby the time dependent portion of the sampled signal (as a function of the delay between the sampling and generation optical pulses) has been shown to correspond to the cross-correlation between the electrical signal on the line and the PC response of the sampling gap, which is assumed to be identical to the generation gap [2]. If the DUT is assumed linear, then the broadband scattering parameters can be reconstructed from the measured time domain response by appropriately windowing the measured data at the sampling ports and using the fast Fourier transform. For example, with generation at port a resulting in an incident signal $f_i(t)$, a reflected signal $f_r(t)$ from the DUT and a transmitted signal $f_t(t)$, the Fourier transform of the sampled signal at port b is

$$G_{bi}(f) = |F_i(f)|^2 \quad (1)$$

for the incident signal and

$$G_{br}(f) = F_i^*(f)F_r(f) \quad (2)$$

for the reflected. The Fourier transform of the sampled signal at port c or d is

$$G_{ct}(f) = |F_i(f)|^2 H(f), \quad (3)$$

where $H(f)$ is the Fourier transform of the impulse response of the DUT. For this excitation, the scattering parameters can then be constructed from

$$S_{11}(f) = \frac{G_{br}(f)}{G_{bi}(f)} \quad (4)$$

$$S_{21}(f) = \frac{G_{ct}(f)}{G_{bi}(f)}. \quad (5)$$

S_{22} and S_{12} can be obtained by a similar procedure with excitation at port d.

If the sampling were to be performed using the EO effect, the probe signal can be located anywhere along the microstrip line, subject to the constraint of resolving the incident and reflected time domain signals. The principle of operation relies on the electric field induced (due to electrical signal on the line) polarization rotation of the optical probe beam [1]. This approach of course relies on the use of either an EO substrate or sampling probe. The detected sampled signal then follows the shape of the time domain electrical signal on the line (except for the optical sampling gate effect), so the scattering parameters can be obtained by simply forming a ratio of the Fourier transform of the windowed sampled time domain waveforms, representing the incident, reflected and transmitted signals.

RESULTS

Results are presented for example tests performed on a 28 GHz MMIC using PC sampling, EO sampling and frequency domain approaches.

Firstly, consider the use of the PC sampling approach. The optical system used is a Quantronix CW mode-locked Nd:YAG laser followed by an optical fiber/grating pulse compressor and a KTP frequency doubler. This resulted in an optical signal with a wavelength of 532 nm, a FWHM pulse duration of 5 psec, a repetition rate of 100 MHz, and an average power of 400 mW. The optical beam is split into two: the generation and sampling beams, resulting in a fluence of 30 $\mu J/cm^2$ at the PC gaps. The test circuit consists of the MMIC (DUT) mounted between two sets of PC switches ($5 \mu m$ simple gap) on a GaAs substrate, which was doped with hydrogen to obtain a surface concentration of 10^{14} cm^{-2} in order to reduce the carrier lifetime, producing a fast decay time for the PC response. The input and output lines are 50Ω with high impedance lines to the sampling gaps. The sampled signal is taken by sampling the charge over many periods as a function of delay time. The sampling is therefore done at low frequency, thereby avoiding concerns with high frequency lines on the wafer and microwave connectors.

In sampling using the EO effect, the same pulse generation is used as for the PC sampling case. The probe beam used had a wavelength of 1.06 μm and a pulse duration of 6 psec. The electrical signal is sampled by a gate whose shape is that of the laser pulse, rather than the photoconductor response, as in PC sampling. This reduces dimensional requirements in oder to resolve a particular pulse profile. The polarization must be carefully aligned to achieve a satisfactory EO effect [1].

First consider a comparison of the results obtained using PC and EO sampling for the example MMIC. The measured time domain signals at the input and output, with excitation at port a, are shown in Figs. 2 and 3, respectively. Both measurements were performed at the same location (the location of ports b and d) with data taken at approximately 0.5 psec intervals. The data obtained from PC sampling is the cross-correlation of the electrical signal on the line and the PC response. The EO data represents the time-delayed average windowed (5 psec pulse) sample value, which is equivalent to a cross-correlation. The distance between the input sampling port and the DUT for the current experiment is not quite long enough, given the decay time of the electrical pulse generated (FWHM of 10-12 psec). A slightly longer line length is necessary to clearly distinguish between the incident and reflected signals. This is more of a problem with PC sampling, since the sampled signal is a correlation of the gap response and the line signal. In this aspect, EO sampling is more accurate. However, with EO sampling, the result is very sensitive to the location of the probe beam with respect to the microstrip line, necessitating careful alignment. This is especially a problem when obtaining the transmission curve as sampling is performed at two locations. In other words, establishing a reference for EO sampling is more difficult.

With PC sampling, the illumination of the gaps can be normalized easily by interchanging the excitation and probe ports. It is relatively easy to align the probe beam over the sampling gap (spot size is approximately $20\mu m$). In the case of EO sampling, beam alignment is difficult and different characteristics are obtained when the probe beam is moved, making transfer function measurements difficult.

The frequency domain results for S_{21} and S_{11}, obtained from the two optoelectronic measurements and a HP8510 network analyzer (magnitude data) are shown in Figs 4-7. The reference planes for this data are the input and output of the DUT, so corrections have been made for the corresponding line loss (in S_{21}) and phase shift. The line loss and phase constant were determined experimentally, the phase constant for this geometry being approximately linear with frequency through 32 GHz. The magnitude results compare favorably, but some differences exist in the phase. These differences need to be addressed. A difficulty in performing the frequency domain measurement is in accurately moving the reference plane from external to the SMA launchers onto the test mount to the DUT.

Based on the measurements performed with both EO and PC sampling, several conclusions can be drawn. EO sampling provides greater resolution, but is less sensitive. With the current system, the smallest electrical signal which can be detected on the microstrip line is 6 mV for EO sampling and 0.2 mV for PC sampling. If it is assumed that the largest electrical voltage on the line is 300 mV (considering the linear range of operation of the current DUT) the dynamic ranges become 34 dB for EO and 63.5 dB for PC sampling. Unfortunately, this number does not represent a realistic range when accuracy is considered. There are a number of sources of error, including laser noise, assumptions of identical gaps in PC sampling and normalization in EO sampling. Consider as a measure of this error for the PC case the norm-square difference between two data sets. If this measure of the error is expressed as

$$E = \frac{\int |f_1(t) - f_2(t)|^2 dt}{\int |f_1(t)|^2 dt} \qquad (6)$$

for data sets $f_1(t)$ and $f_2(t)$, then for example measured data at the input, E is 10% and at the output, 3%. The translation stage which provides the optical time-delay for the measurement has a location error which results in a frequency error bound of ± 0.02 GHz.

CONCLUSION

The use of optoelectronic techniques for the characterization of microwave and millimeter-wave integrated circuits provides many desirable features, particularly for on-wafer probing. Comparisons of both photoconductive and electro-optic sampling techniques have been made with results obtained from frequency domain measurements. Reasonable agreement was obtained in the amplitude, with some discrepancy being evident in the phase. Improvements in the accuracy are necessary, which necessitates addressing issues such as the measurement reference used.

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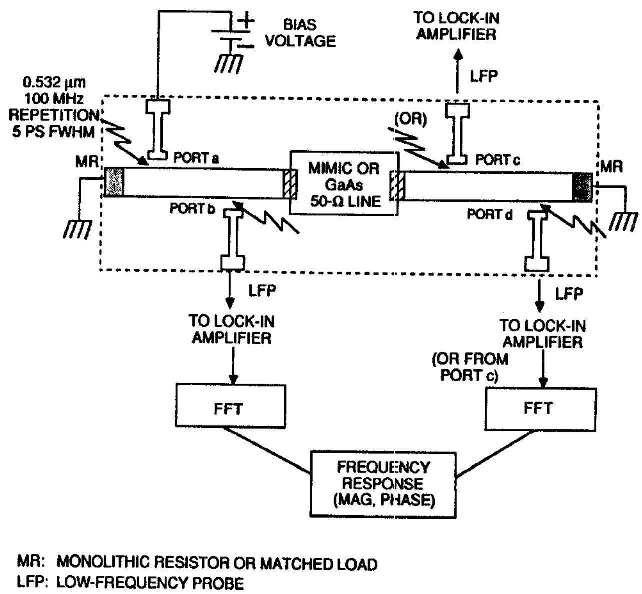

Figure 1. Schematic for optoelectronic measurement system using photoconductive sampling.

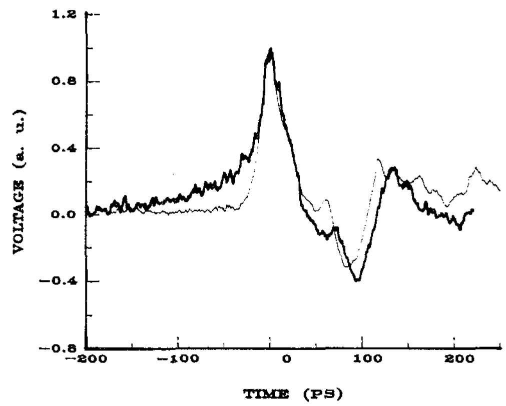

Figure 2. Sampled time-domain signal at the input using PC (bold) and EO (light) sampling.

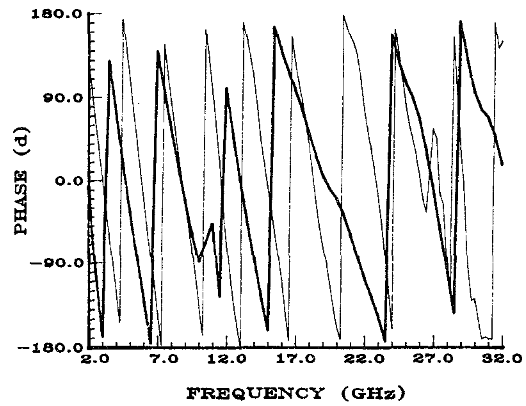

Figure 5. Phase of S_{21} using PC (bold) and EO (light) sampling.

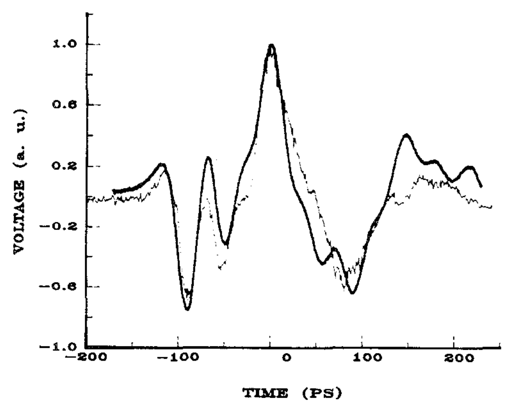

Figure 3. Sampled time-domain signal at the output using PC (bold) and EO (light) sampling.

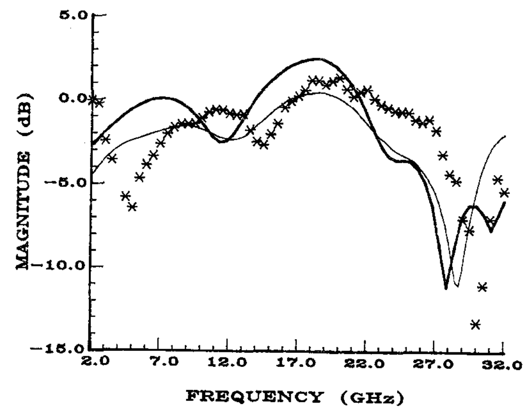

Figure 6. $|S_{11}|$ using PC sampling (bold), EO sampling (light) and from network analyzer (stars).

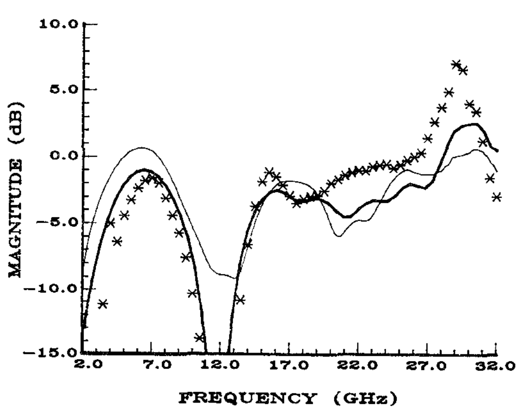

Figure 4. $|S_{21}|$ using PC sampling (bold), EO sampling (light) and from network analyzer (stars).

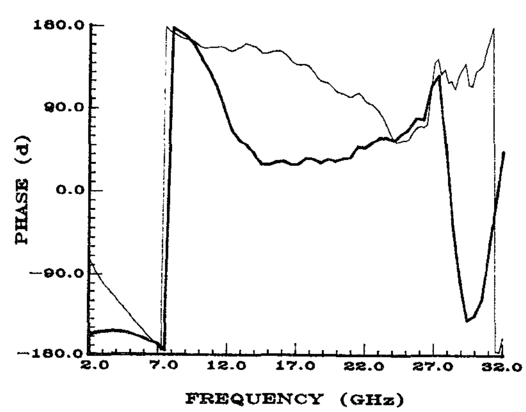

Figure 7. Phase of S_{11} using PC (bold) and EO (light) sampling.