Millimeter-Wave Network Analyzers Based on Photonic Techniques

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Abstract—**We report the active photonic probes which enable on-wafer measurements of electrical scattering parameters with a bandwidth exceeding 300 GHz. The probes employ a high-speed uni-traveling-carrier photodiode to optically generate the electrical stimulus and the electro-optic sampling technique to measure the electrical response signals. The probe modules are packaged using micro-optic technology and exhibit excellent optical characteristics. They are easy to use and enable reliable and reproducible measurements and should help to overcome the bandwidth-limitation of present all-electronic systems.**

I. INTRODUCTION

Driven by the rapid increase in the demand for frequency bandwidth, solid-state electronics has made a tremendous progress well into the millimeter and sub-millimeter wave regions. For example, the operating frequencies of transistors have reached the terahertz range [1], and some integrated circuits (ICs) are now able to operate at over 100 GHz [2]. In order to diagnose these components, broadband measurement systems capable at least of the same bandwidth are required. However, conventional techniques for measuring *electrical signals* suffer from insufficient bandwidth. The highest bandwidth for commercially available broad-band vector network analyzers (NAs) is 110 GHz for *full-band* operation, which are capable of measurement with instantaneous wide-band frequency sweeps from a few tens of megahertz to millimeter-wave frequencies, and they only can operate in the linear or small signal regime. This frequency limit can be extended to upper millimeter-wave [3] and submillimeter-wave frequencies [4], although several sets of transmitter/receiver modules with relatively narrow bandwidths have to be prepared to fully cover the continuous frequency range of interest.

Against this background, novel measurement techniques based on all-electronic approaches have been proposed [5]-[8]. Nonlinear-transmission-line (NLTL) circuits are employed as signal generators, and Schottky-diodes are used as sampling gates [5]. An electrical signal sampling circuit with a bandwidth of 725 GHz [6] and NAs that operate across the 7-200 GHz [7] and 70-230 GHz [8] bands have been reported. Millimeter-wave monolithically integrated circuit (MMIC) technology is the key to achieving the broadband operation of these instruments. With an all-electronic approach, generating >300-GHz broadband signals is a greater challenge than detecting such signals.

To overcome the several technological limitations on all-electronic approaches, there has been increasing interest in photonic techniques [9]. Network analysis based on photonic techniques was first demonstrated with promising results exhibiting a bandwidth exceeding 700 GHz [10]. This system, however, suffered from difficulties in instrumentation and a lack of detection sensitivity, which made it unsuitable for practical applications. In this paper, we describe a new scheme to overcome these limitations and build an over-300 GHz photonic NA [11]. We also present the fully integrated and packaged version of this system [12], which can be used for on-wafer multi-port measurements of scattering parameters (S-parameters).

II. PHOTONIC NA SYSTEM

Our objective is to fabricate a broadband system with enough flexibility and versatility to allow users to concentrate their work only on the measurements. For such purpose, the system has to be completely integrated and packaged in a user-friendly manner. It is designed in a probe configuration to allow an easy access to devices under test (DUTs) on wafer and a full-band measurement merely with a single setup.

Figure 1 (a) illustrates the concept of ultrabroad-band network analyzer, based on time-domain photonic techniques. A photograph of the photonic NA's integrated probe heads is shown in Fig. 1(b). All the functions of stimulus, sampling and bias for the device under test (DUT) are integrated into a probe-head structure dedicated

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to multi-port S-parameter measurement of devices and circuits with coplanar waveguide (CPW) type access electrodes. One of the major advantages of this configuration over all-electronic systems is that the excitation source and the measurement planes are very close to the DUT with no other elements such as, for example, connectors, directional couplers and frequency converters inserted in the electrical signal paths.

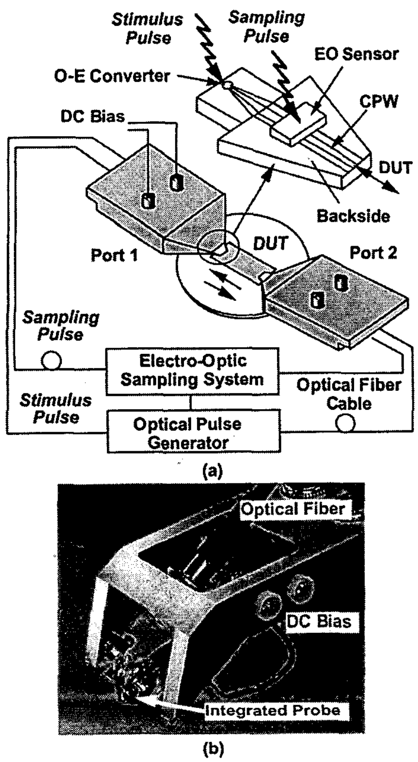

Fig. 1. Photonic millimeter-wave network analyzer. (a) System configuration. (b) Photograph of the packaged probe.

The NA performs time-domain measurements in a pump-and-probe scheme. The frequency-domain S-parameters are calculated by dividing the spectra of the reflected and transmitted waveforms by that of the incident one. A back-illuminated ultrafast unitraveling-carrier photodiode (UTC-PD) [13] is used to generate short electrical pulses when excited with sub-picosecond optical pulses delivered by a compact and extremely stable 1.55-μm fiber laser system. The electrical pulses are then propagated to the DUT on a 50-Ω CPW on quartz designed to carry over 300-GHz bandwidth signals with small dispersion and attenuation. The CPW is terminated on one side with a probe-tip configuration having a 100-μm-pitch contact pad. Full details about the design of these millimeter-wave components can be found in [11]. The over-all system can produce electrical pulses of less than 2 ps pulse-width and up to 1-V peak amplitude. Therefore it is suitable for small and large signal measurements. It is equipped with separate bias networks for the PD and for the DUT, carefully designed in order to minimize the interference with the millimeter-wave measurements. The propagating electrical signals are measured in the time domain using the electro-optic sampling (EOS) technique [9]. This technique has been already applied to the non-contact probing of the internal node in integrated circuits [14]. We use a CdTe EO sensor attached to the surface of the quartz-CPW. The geometrical characteristics of the system are optimized to ensure a perfect time windowing in order to separate in time incident, reflected and transmitted signals. A dynamic range of over 30 dB was obtained with our system in the small-signal operation.

Figure 2 shows the configuration of the optical assembly to realize a compact probe head using micro-optics technology. Two separate optical fibers are used to carry the light as close as possible to their respective target device. Their beams are then collimated and focused. The beam spot diameters on the PD active area and on the EO sensor are 5 and 10 μm, respectively.

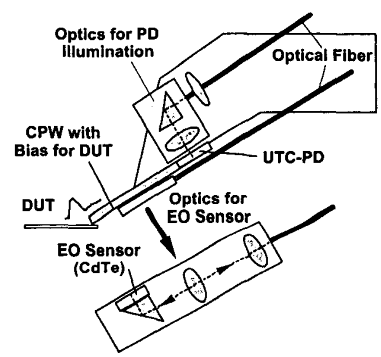

Fig. 2. Schematic of the optical assembly for NA probes.

III. MEASUREMMENTS AND DISCUSSION

A. Characterization of Probes

To evaluate the transfer function of the photonic NA, we characterized a 4.35-mm long CPW on quartz chosen for its excellent propagation characteristics (Fig. 3(a)). The attenuation factor of 1.5 dB/mm and a group delay dispersion of < +/- 1ps at 300 GHz were measured in a separate experiment [11]. The transmission from probe to probe was measured through the CPW, which acts as a simple delay element. We could estimate then the degradation in the bandwidth due to parasitic elements on the probes (EO sensors and DUT bias-networks) and the effect of the probes' contacts. Figure 3(b) shows the superimposed time-domain waveforms measured by the excitation probe and by the receiving one. The spectra of both pulses are shown in Fig. 3(c). The pulse FWHM broadens by 0.8 ps resulting in a 3-dB bandwidth decrease of only 26 GHz. This result includes the effects of the propagation along the portions of CPWs on the probes and the CPW being measured (total length: 7.75 mm) and the distortions due to the probes' contacts and the DUT-bias element, which is responsible of most of the degradation. The maximum measurable frequency of the transmitted signal is 350 GHz, which is determined by the sensitivity of the system. From Fig. 3(c), the dynamic range is about 30 dB up to 100 GHz, and > 20 dB up to 200 GHz. The measured return loss due to the probes' contact was below –20 dB. In the future, a proper calibration will de-embed all the effects relative to the probes. Hence the actual measurement 3-dB bandwidth is expected to exceed the 100 GHz resulting in a total useful bandwidth, allowed by the dynamic range of our system, of over 500 GHz.

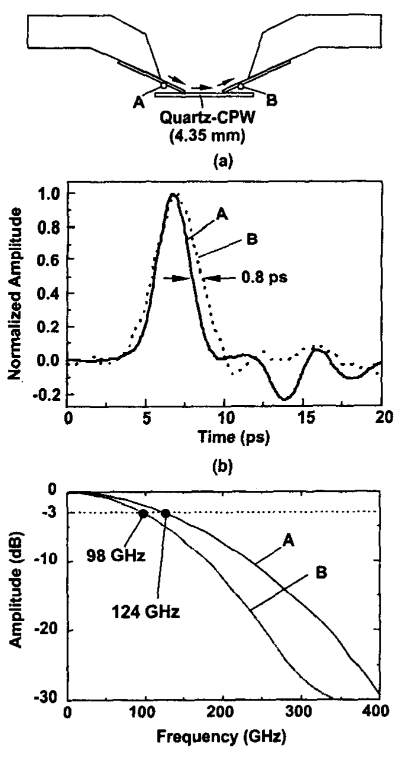

Fig. 3. Time-domain waveforms and corresponding spectra of the excitation pulse (sold line) and the transmitted one (dotted line) from one probe to the other.

B. Measurement of Transistors

To verify the performance of our NA, we measured on wafer the S-parameters of a 0.1-μm gate-length HEMT (DUT) under bias. The expected cut-off frequency of this device exceeds 250 GHz. Appropriate 450-μm long CPW-type electrodes were patterned on the device to access the gate and drain nodes (Fig. 4(a)). Such long electrodes are necessary to keep the reflections from the probes' contact points of the DUT response. Nevertheless, the design of these CPWs ensured minimal dispersion and loss up to over 150 GHz. The magnitudes of the device's four S-parameters including the effect of its electrodes measured by the NA, are compared to the ones obtained with a 40-GHz conventional NA as shown in Fig. 4(b). The conventional NA used was the only one available at the time of the measurements but the authors hope to use in the future a state-of-the-art 110-GHz system to confirm their results. The magnitudes of the conventional NA's S-parameters were used as a reference in order to calibrate the photonic NA's ones. Indeed in the photonic NA measurements, the reference planes are set at the EO-sensor position, 1.7 mm away from the probes' tips, and we didn't de-embed the effects of the section between the EO sensor and the tip. This information is essential in order to extract accurately the phase parameters. We observe an excellent agreement, within 2 dB, between the two measurements. The discrepancy observed for S12 below 10 GHz is due to the limited dynamic range of our system.

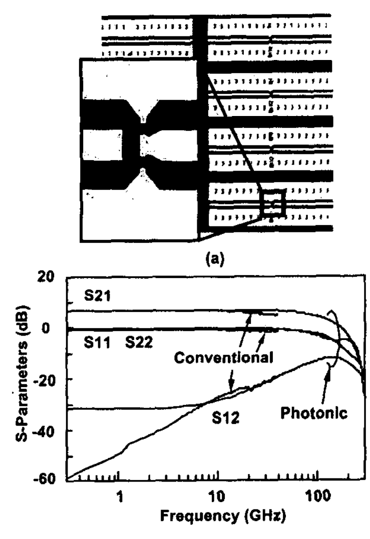

Fig. 4. Comparison between the magnitude of the S–parameters calculated from the photonic NA measurement and conventional ones.

C. Modified Probes

To enhance the probe performance, we have monolithically integrated the CPW and a bias line with the UTC-PD on the rugged sapphire substrate using the wafer-bonging process [15]. The photographs of the fabricated probe chip are shown in Fig. 5.

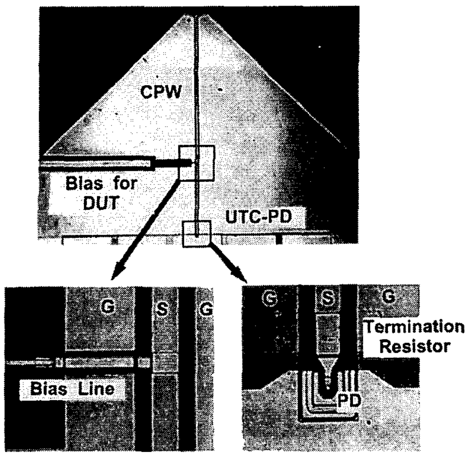

Fig. 5. Photographs of the monolithically integrated NA probe on sapphire substrates.

IV. Conclusion

We fabricated a new type of integrated photonic probe heads for an on-wafer broadband NA designated to S-parameter measurements to over 300-GHz. They include bias circuits to apply DC voltage to the DUTs and a new sophisticated packaging has been developed in order to optically connect the probes to the laser source and the signal processing units. The system can be used for small and large signal characterizations. It has been satisfactorily used to measure passive and active devices with an excellent performance, although the time-gated reflection measurement is generally limited in measuring some low-frequency resonant responses due to the insufficient time window. Additional work is underway to enhance the accuracy of the system by increasing its sensitivity and by using proper calibration. This will especially enable the phase information.

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