An Integrated Circuit for Network Analysis within 50-200 GHz

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***Abstract*--This paper presents an integrated circuit, based on nonlinear transmission lines (NLTL), for a vector network analyzer system (VNA) within 50-200 GHz. It is the first integrated circuit containing all elements of a S-Parameter test set: A multiplier to generate the RF signal, directional couplers to separate the incident and reflected waves, and a pair of high speed sampling circuits to convert the signals down to lower frequencies.**

I. Introduction

Recent progress in III-V devices, especially with InP based HEMTs and HBTs [1], demand characterization over an extended bandwidth. But commercial broad-band on-wafer S-parameter measurement set-ups are presently limited to 120 GHz bandwidth. We have fabricated an IC for a new measurement system for 50–200 GHz network analysis. NLTLs are used, because they generate high frequency signals in a very wide bandwidth and they can also be used to drive high speed sampling circuits. Among improvements over earlier reported work [2], the present IC uses true directional couplers for high directivity, uses low-order harmonic generation in the stimulus signal generation, and processes the detected (IF) signals directly in the frequency domain, without using time-domain / Fourier transform methods. A high pass-filter at the output of the source frequency multiplier equalizes its output power spectrum, further increasing the signal-to-noise ratio at high frequencies. By mounting buffer amplifiers close to the chip, the IF can be increased to 20 MHz which decreases the phase noise and allows to use the HP8510 directly for IF processing. Together, these improvements substantially increase the system signal-to-noise ratio and directivity. The assembly of the network analyzer (NWA) integrated circuits into active probes, will allow accurate on-wafer network analysis up to 200 GHz.

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II. Design and results

As in earlier work [3], diodes with an exponential doping profile are used for the NLTL. This combines a large capacitance variation and a high breakdown voltage (13 V) with a high large-signal cutoff frequency (2.5 THz).

Fig. 1 shows the block diagram and fig. 2 a microphotograph of the fully integrated circuit. A NLTL used as a frequency multiplier generates the RF stimulus signal. The NLTL was designed for a drive frequency from 34 to 50 GHz, so the second, third and fourth harmonics cover the 68 to 200 GHz bandwidth. Due to lower insertion loss at lower frequencies, the NLTL also operates from 25 to 50 GHz, which increases the bandwidth of the measurement system from 50 to 200 GHz. Fig. 3 shows the output waveform of this NLTL with a fall time of 3.2 ps. The NLTL drives the test port through a directional coupler. The coupler functions as a bias tee, isolating the NLTL frequency multiplier from the DC bias applied to the test port. Further, the coupling increases with frequency, thereby reducing the variation of the DUT drive power with frequency. Two additional couplers are integrated to get the incident and reflected wave and two high speed sampling circuits are used to convert the signals down to 20 MHz IF. The sampling circuits are driven by a second NLTL, operating at half of the frequency of the stimulus NLTL (12.5 to 25 GHz). To reduce reflections from the bias connection, a low pass filter is also integrated on the IC.

The coplanar directional couplers were designed for 10 dB coupling using a 3D simulator [4] to calculate the impedances Z_{even} and Z_{odd} and the complex propagation constants γ_{even} and γ_{odd}. Compared with microstrip couplers, coplanar couplers can easily achieve a high directivity over a wide bandwidth, because the effective dielectric constants of the two modes are nearly the same and almost independent of the frequency. To verify the simulation the same coupler was scaled for a center frequency of 90 GHz and measured. Fig 4 shows the directivity and the coupling of the simulation and the measurement. Below 10 GHz signal levels drop below the instrument noise floor, and the isolation cannot be measured accurately. The couplers used in the integrated circuit were scaled for 180 GHz center frequency. To measure the directivity of this coupler, two additional test circuits with a NLTL for the RF source, a second NLTL with a high speed sampler for measuring and the coupler are implemented as test structures on the wafer. In one circuit the coupler can be measured in forward direction, in the other circuit in backward direction. Fig. 5 shows the measured directivity.

The directional couplers at the source frequency multiplier are designed for 6 dB coupling at a center frequency of 200 GHz. This combines relatively high coupling at high frequencies with sufficient attenuation especially at the fundamental frequency.

To characterize the sampling circuit linearity, a test sampling circuit was driven with a single 36 GHz RF input and the output was measured with its harmonics. As the result in fig. 6 shows, the harmonic generation is negligible for input powers below 0 dBm. In the NWA circuit, the measured signals are attenuated by the couplers at least by 10 dB, hence S-parameters of amplifiers with an output power up to 10 dBm can be measured.

One NWA circuit is connected to an on-wafer sampler, so the stimulus signal power at the DUT can be measured. Fig. 7 shows the result, when the multiplier NLTL is driven with 12 dBm input power. The output power varies from –14 to –35 dBm over the 50-200 GHz bandwidth, 5-15 dB lower than simulated. The discrepancy lies in the frequency-dependent attenuation of the sampling circuits, which is approximately 1 dB at lower frequencies and increases up to estimated 10 dB at 200 GHz. In addition in this simulation the couplers could not be simulated with skin-effect losses. At 200 GHz, the stimulus signal power is –35 dBm, which is sufficient for a high signal-to-noise ratio at the IF ports. The stimulus power of –14 dBm can be too high for amplifiers to ensure linearity, so a second IC was fabricated with an additional coupler in the stimulus signal path to attenuate the drive power at lower frequencies. The power at the DUT for this circuit is below –25 dBm for all frequencies.

To measure the directivity of the full integrated circuit, the incident and reflected waves of a NWA circuit with the open test port are compared with the measurement of a second NWA circuit with a nominal 50 Ω (44 +/– 1.5 Ω) chip resistor (fig. 8). The directivity is > 10 dB, dropping to ~7 dB in a band between 160-190 GHz. In combination with high signal-to-noise ratios, the directivity should be sufficient to permit calibration to 200 GHz.

III. Conclusion

We have demonstrated the first NLTL-based integrated circuit for network analysis within 50-200 GHz which can be used as a S-parameter test set for the HP8510. Packaging these chips into active probes will permit accurate and convenient on-wafer S-parameter measurements and will be performed in the near future at our institute.

IV. References

[1] R. Pullela, Q. Lee, B. Agarwal, D. Mensa, J. Guthrie, L. Samoska, and M. J. W. Rodwell, "A >400 GHz f_{max} transferred-substrate HBT integrated circuit technology", Device Research Conf. Tech. Dig. 1997, pp. IIIB-2.

[2] R. Y. Yu, M. Reddy, J. Pusl, S. T. Allen, M. Case, M. J. W. Rodwell, "Millimeter-wave on-wafer wave form and network measurements using active probes", IEEE Transactions on Microwave Theory and Techniques, vol. 43, no. 4, pp. 721-729, April 1995.

[3] M. J. W. Rodwell, M. Kamegawa, R. Y. Yu, M. Case, E. Carman, K. S. Giboney, "GaAs nonlinear transmission lines for picosecond pulse generation and millimeter-wave sampling", IEEE Transactions on Microwave Theory and Techniques, vol. 39, no. 7, pp. 1194-1204, April 1991.

[4] HP85180A High-Frequency Structure Simulator, Hewlett Packard.

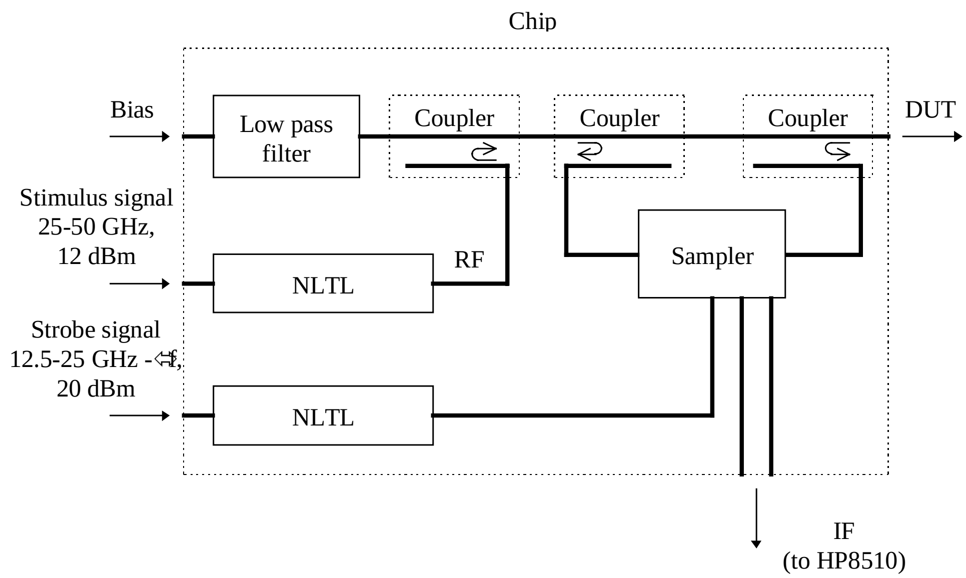

Fig. 1: Block diagram of the chip.

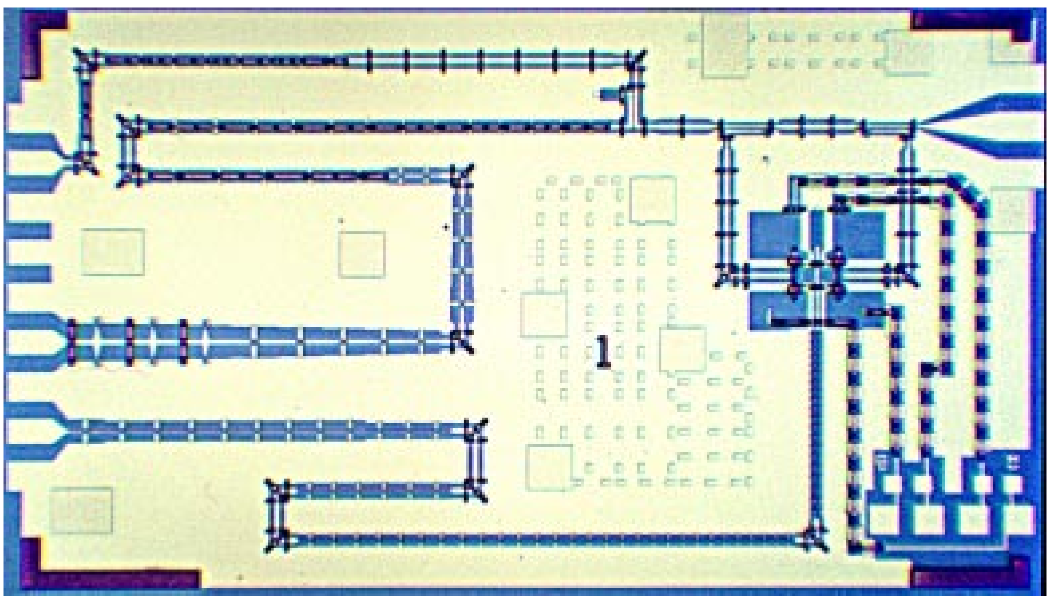

Fig. 2: Microphotograph of the chip. Chip size 3.4 x 2 mm^2.

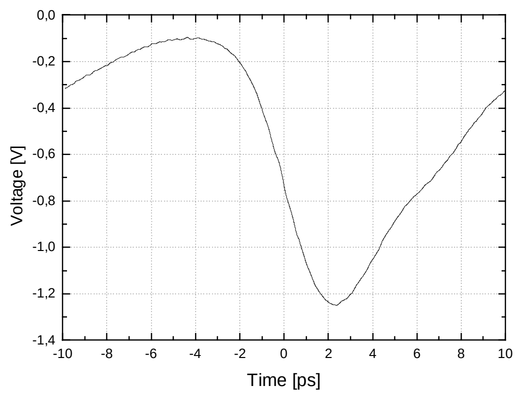

Fig. 3: Measured voltage waveform of the stimulus NLTL with 12 dBm input power at 50 GHz, fall time ~3.2 ps.

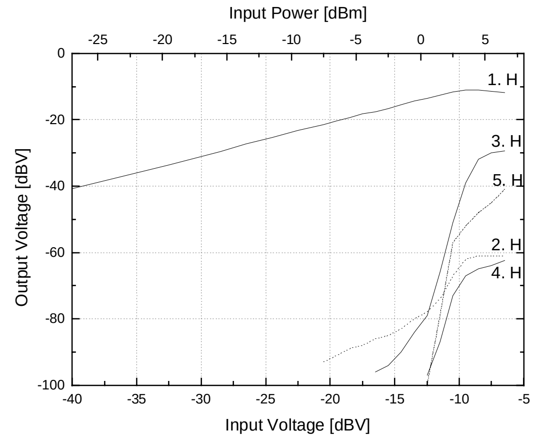

Fig. 6: Nonlinearity of the sampler with a 36 GHz input frequency.

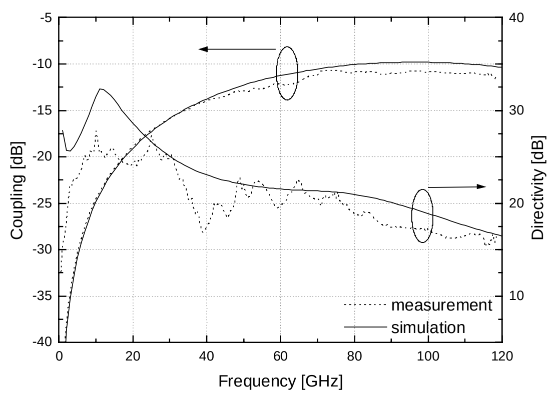

Fig. 4: Simulated and measured coupling and directivity of the coupler, designed for 90 GHz center frequency.

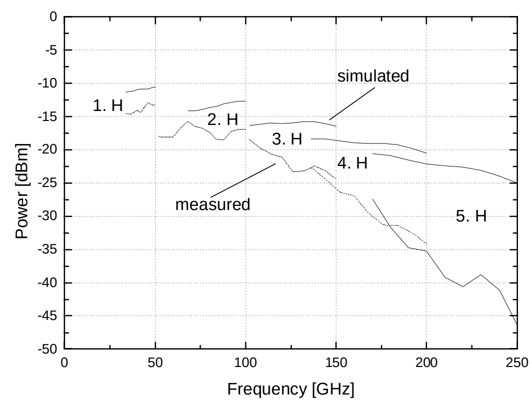

Fig. 7: Simulated and measured power at the DUT. The measurement is not corrected for the sampling circuit attenuation.

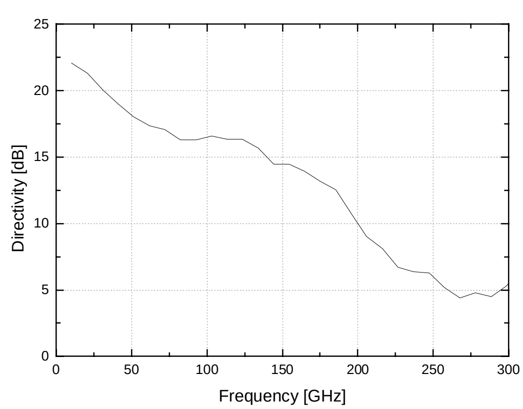

Fig. 5: Measured directivity of the couplers designed for 180 GHz center frequency.

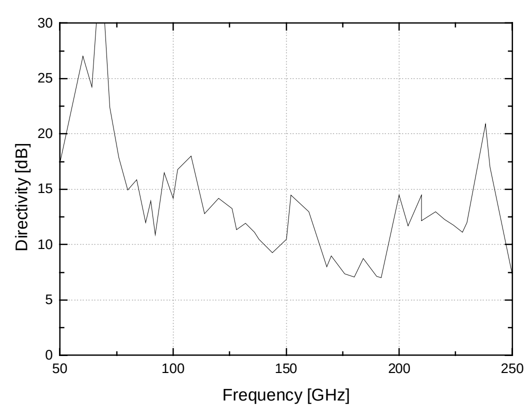

Fig. 8: Measured directivity of the full chip.