A NLTL-Based Integrated Circuit for a 70-200 GHz VNA System

O. Wohlgemuth, B. Agarwal*, R. Pullela*, D. Mensa*, Q. Lee*, J. Guthrie*, M. J. W. Rodwell*, R. Reuter, J. Braunstein, M. Schlechtweg, K. Köhler

Fraunhofer Institut IAF, Tullastr. 72, D-79108 Freiburg, Germany, Phone: +49 761/5159-533, Fax: +49 761/5159-565, Email: olwo@iaf.fhg.de

*Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106, Phone: 805-893-3244, Fax: 805-893-3262, Email: rodwell@ece.ucsb.edu

Abstract

We present an integrated circuit, based on nonlinear transmission lines (NLTL), for network analysis within 70-200 GHz. This is the first integrated circuit containing all elements of a S-Parameter test set: A multiplier to generate the RF signal, couplers to divide the incident and reflected waves, and a pair of high speed sampling circuits to convert the signals down to lower frequencies.

Introduction

Within the last few years, the improvement of III-V technology, especially InP based HEMT and HBT integrated millimeter-wave circuits [1] demands characterization over an extended bandwidth. Commercial broad-band on-wafer S-parameter measurement set-ups are presently limited 120 GHz bandwidth. We have fabricated an IC for a new measurement set-up for 70-200 GHz network analysis. 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 use of time-domain / Fourier transform methods. High pass-filtering within the source frequency multiplier equalizes its output power spectrum, further increasing the signal / noise ratio at high frequencies. Together, these enhancements substantially increase the system signal / noise ratio and directivity. With assembly of the NWA integrated circuits into active probes, accurate on-wafer network analysis to 200 GHz should be feasible.

Design and results

As in earlier work [3], NLTLs with exponential doping profiles are used. Fig. 1 shows a block diagram of the fully integrated circuit and fig. 2 a picture. A NLTL used as a frequency multiplier generates the RF stimulus signal. The drive frequency for this NLTL is 34 to 50 GHz, and hence the second, third and fourth harmonics cover a 68-200 GHz bandwidth. Fig. 2 shows the output wave form of this NLTL with a fall time of 4.1 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 DUT drive power with frequency. The incident and reflected waves are monitored by two additional directional couplers, and are downconverted to a 20 MHz IF by a pair of high speed sampling circuits. The sampling circuits are driven by a second NLTL, designed to operate at a frequency from 17 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 to calculate Z_{even} and Z_{odd}. To measure the directivity, 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. 4 shows the measured directivity.

Sampling circuit linearity was characterized using a single-frequency 36 GHz RF input (fig. 5). Harmonic generation is negligible for input powers below 0 dBm. Given the 10 dB insertion loss of the directional couplers, S-parameters of amplifiers with an output power up to 10 dBm can be measured.

To measure stimulus signal power at the DUT, one NWA chip is connected to an on-wafer sampler. The measured power levels (fig. 6) vary from –15 to –35 dBm over the 50-200 GHz bandwidth, 5-15 dB below that expected. The discrepancy lies in the frequency-dependent attenuation of the sampling circuits, in excess coupler losses, and in transmission line skin-effect losses. At –35 dBm @ 200 GHz, the stimulus signal power is sufficient for high signal / noise ratio at the IF ports. 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 (fig. 7) to the measurement of a second NWA circuit with a nominal 50 Ω (44 +/– 1.5 Ω) chip resistor. The directivity is c.a. 10 dB, dropping to ~5 dB in a band between 160-190 GHz. In combination with high signal / noise ratios, the directivity should be sufficient to permit calibration to 200 GHz.

Conclusion

We have demonstrated the first NLTL-based integrated circuit for network analysis within 70-200 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.

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.

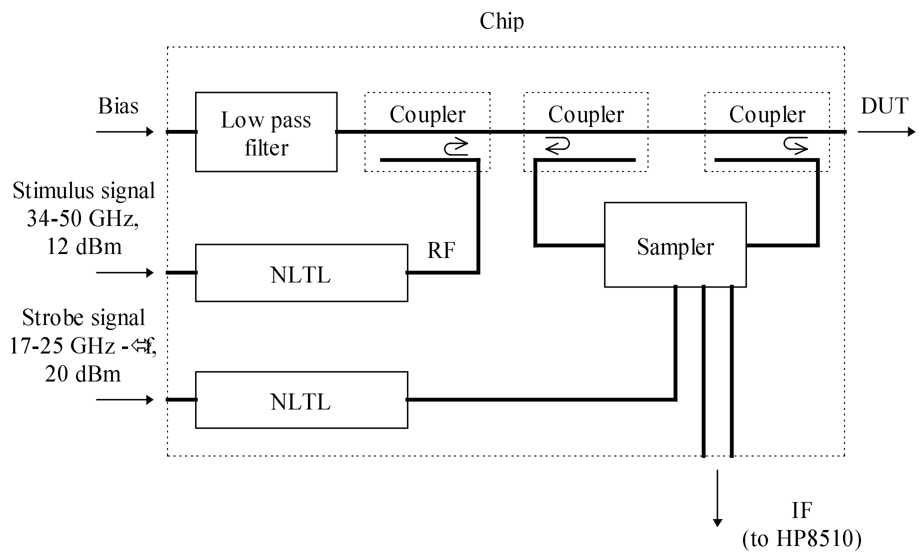

Fig. 1: Block diagram of the chip.

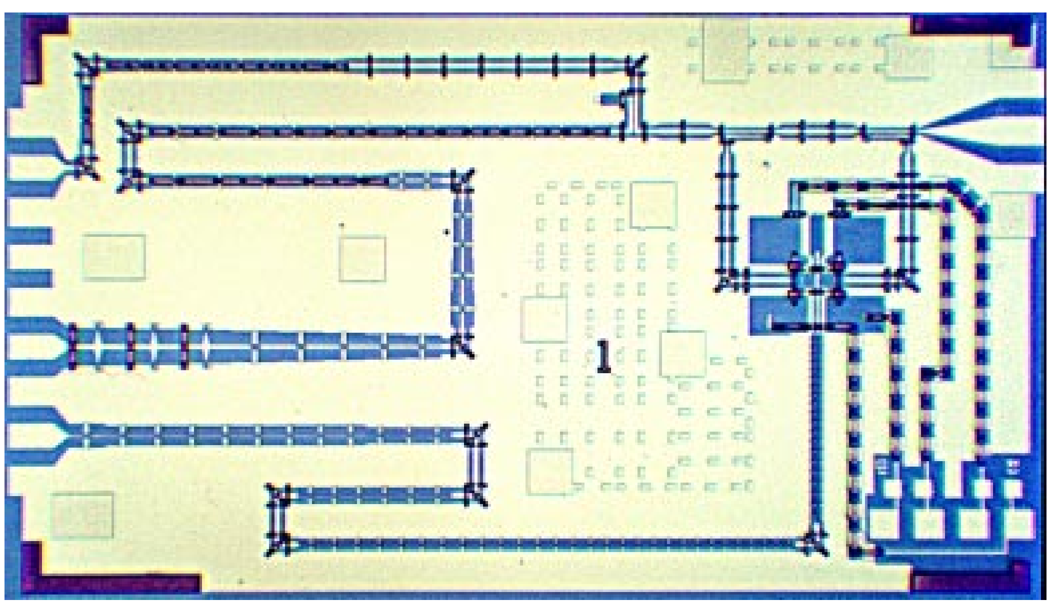

Fig. 2: Picture of the chip.

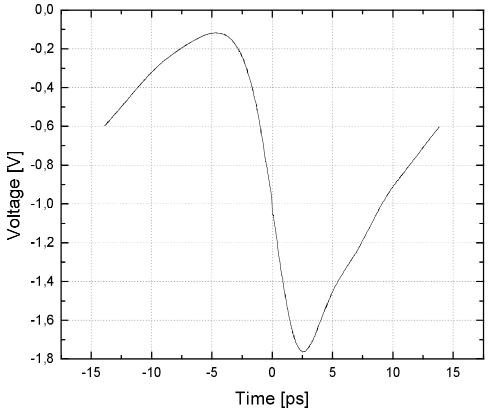

Fig. 3: Measured voltage wave form of the stimulus NLTL with 12 dBm input at 36 GHz, fall time ”4.1ps.

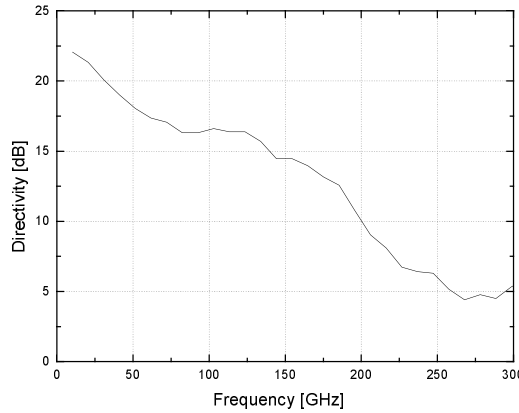

Fig. 4: Measured directivity of the coupler.

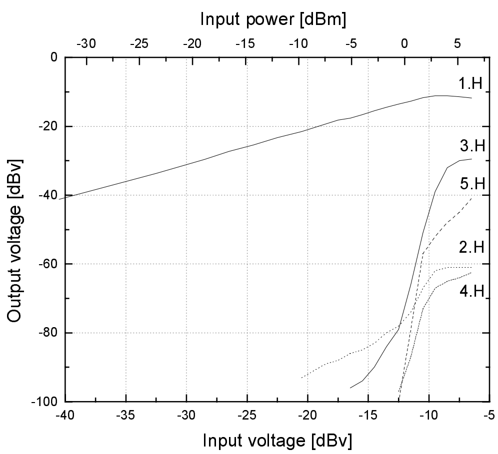

Fig. 5: Nonlinearity of the sampler with a 36 GHz input frequency.

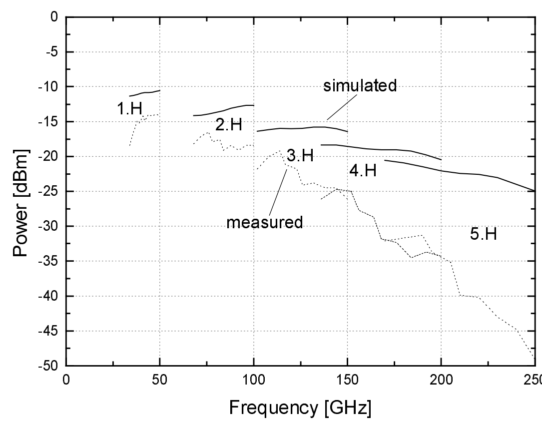

Fig. 6: Simulated and measured power at the DUT. The measurement does not correct for sampling circuit attenuation.

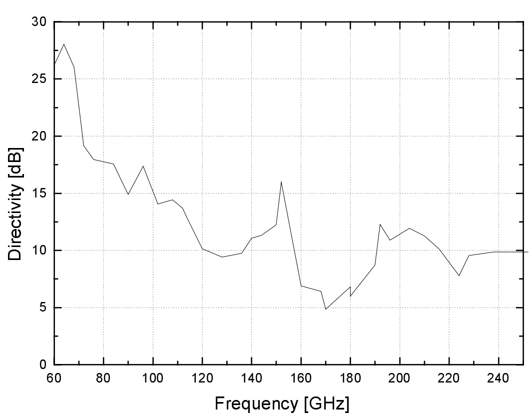

Fig. 7: Measured directivity of the full Chip.