Nonlinear System and Subsystem Modeling in Time Domain

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***Abstract*—Nonlinear models of microwave subsystems are identified from time domain measurements. Scattering functions in the form of nonlinear time domain functions are used to derive a system identification model instead of an equivalent circuit. The advantage being the simplicity of the measurement and the developed models and the speed and accuracy of the simulation of the entire system.**

I. Introduction

NONLINEAR circuits and subsystems are usually modeled using equivalent circuits. Parameter extraction of the equivalent circuit is achieved by optimizing the network to match a large number of measured data points. The four scattering parameters (S_{11}, S_{12}, S_{21}, and S_{22}) are measured over the frequency range of interest and for different bias conditions and/or different power levels. It is obvious that a large number of measurements have to be performed and the optimization process is subsequently lengthy as all the data points have to be matched.

Until now time domain measurements have not been considered because there is no previously existing method of modeling the nonlinear network from the results of the time-domain measurements. It is worth pointing out that the Fourier and Laplace transforms do not apply to nonlinear networks and thus there is no obvious duality between frequency and time domain measurements. For nonlinear networks, the shape and amplitude of the input time domain functions used is important and depends on the type of network or system to be characterized. A blanket use of impulse functions is not suitable as in the case of linear networks. Another problem facing the nonlinear systems designer is that working with equivalent circuits is unnecessarily complex and is not required. The systems designer works with individual subsystem blocks and requires the modeling to be at the subsystem level of hierarchy rather than at the level of equivalent circuits represented by basic circuit elements.

Given the above problems facing the systems designer, we ask the following questions:

- Is there an alternative to make a large number of measurements in the frequency domain and at several bias conditions?

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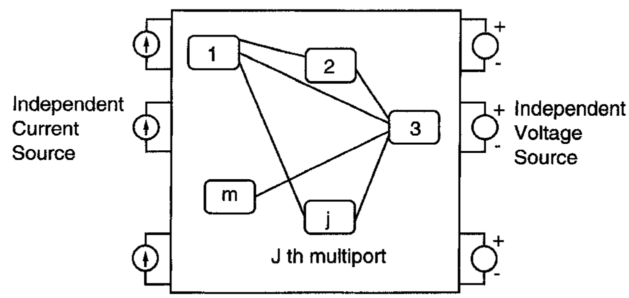

Fig. 1. System modeling using multiports.

- Is there a better and more efficient method of measurements in the time domain?
- Can the time-domain data produce an accurate nonlinear mathematical model?
- Can the developed model be used in a simulator that is capable of simulating an entire system?

The answer to all these questions is "yes" and this paper describes the method by which this is achieved.

II. Multiport Approach to System Design

The time domain system simulation technique developed deals with an interconnection of multiports [1], [2]. Multiports can represent networks with lumped, distributed, and nonlinear elements. Each multiport is represented by nonlinear time domain transfer functions and the overall network is composed of a number of individual multiports connected in an arbitrary way. The overall network of multiports is derived and solved in the time domain. Multiport modeling using nonlinear time domain scattering functions leads to a computational efficient and numerically stable algorithm.

A general system composed of individual multiports is shown in Fig. 1. The individual multiports are composed of lumped, distributed elements and dependent sources. The lumped elements are linear and nonlinear resistors and inductors. The distributed elements are transmission lines coupled or uncoupled embedded in homogenous or inhomogeneous media. The overall network is composed of m individual multiports and independent sources. Each multiport will be represented by the nonlinear time domain transfer function models which are the scattering functions of the multiport. The required output of the modeling process is the time domain scattering functions model of each multiport without the need to develop an equivalent circuit.

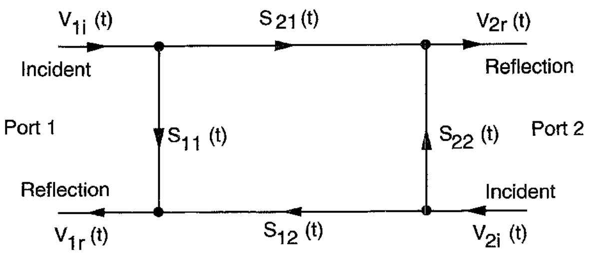

Fig. 2. Time domain scattering functions model of a linear or nonlinear two ports.

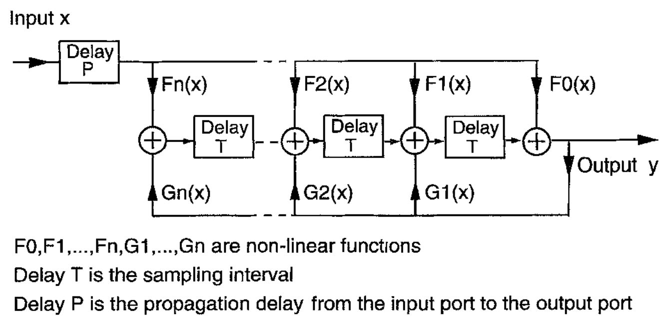

Fig. 3. Nonlinear time domain transfer function.

III. Time Domain Modeling

Linear and nonlinear subsystems can be modeled using time domain measurement data and then the entire system consisting of the individual subsystems can then be very effectively analyzed. The models of the subsystem use linear or nonlinear time domain transfer functions, not conventional equivalent circuits. This approach gives computationally efficient nonlinear models which can be identified from time domain measurements. This results in a much reduced effort and volume of the measured data compared to frequency domain measurements. In the frequency domain a large number of measurements have to be carried out to determine all four scattering parameters, in amplitude and phase, as functions of frequency and at a number of power levels. In the time domain the response is a real function and usually much fewer power levels and time points are required to model nonlinear systems. The method has been applied to model filters, amplifiers and mixers [3]. Scattering functions for these system are modeled by nonlinear transfer functions in the time domain as shown in Fig. 2.

The model in Fig. 2 is similar to that used in frequency domain analysis but the equations describing the model are now written and solved in the time domain. The reflected voltages $v_{1r}(t)$ and $v_{2r}(t)$ are given by

$$v_{1r}(t) = S_{11}(v_{1i}(t)) + S_{12}(v_{2i}(t)) \qquad (1a)$$

$$v_{2r}(t) = S_{21}(v_{1i}(t)) + S_{22}(v_{2i}(t)) \qquad (1b)$$

where $S_{11}(v_{1i}(t)), S_{12}(v_{2i}(t)), S_{21}(v_{1i}(t))$, and $S_{22}(v_{2i}(t))$ are now functions of the incident voltages $v_{1i}(t)$ and $v_{2i}(t)$.

This is an important difference between frequency domain scattering parameters which are only functions of frequency and time domain scattering functions which are functions of the instantaneous values of the signal. The advantage of solving the equations in the time domain is that the scattering functions can be updated at each time step according to the signal strength. This of course depends on having the associate nonlinear model for each scattering function. Using the scattering functions signal flow chart to represent the interconnection of subsystem, the whole system can be simulated in the time domain explicitly and efficiently without the need to use iteration to solve nonlinear equations. It should be also mentioned here that this technique will require separate identification of the transfer, feedback and reflection characteristics of each subsystem in order to simulate the interaction between the subsystems when connected together. The incident, reflected and transmitted waves which are used to identify the scattering functions of the subsystems are measured in the time domain.

The time domain models of the subsystem do not use conventional equivalent circuits but consist of the following elements:

- adders;
- nonlinear multipliers;
- linear multipliers;
- differentiators;
- integrators;
- linear and nonlinear delays.

This gives simpler and more accurate models than the equivalent circuit approach as it dispenses with the need to obey Kirchhoff's laws. One problem arises from this approach is the stability of the developed models. Stability can be guaranteed if no feed back is used however this restriction may increase the complexity of the model. With this approach each subsystem is identified separately and a time domain model for each scattering function is developed. The effect of the power supply can also be identified. For example a nonlinear amplifier can be regarded as a three-port network with the power supply input as the third port in the network. An example of time domain nonlinear model structure is shown in Fig. 3. This general model structure can simulate linear, nonlinear, lumped and distributed system. It is an autoregressive moving average (ARMA) filter in nonlinear form.

Leontaritis and Billings [4] derived the conditions for existence and validity of this input-output model. The first condition is that the system must be of finite dimension, that is a finite order. The second condition is that the linearized system around the zero input equilibrium points has the maximum possible order. Such a condition will hold provided the system, when operated near the zero input equilibrium points can be successfully represented by a linear model. Most physical systems including microwave systems satisfy the above two conditions. The modeling process extracts the parameters and the nonlinear functions, treating the subsystem as a black box. No internal information of the subsystem is necessary known, only the external measurable characteristics

The advantages of this approach are summarized below.

- A large system can be divided into smaller subsystems and the models for each subnetwork are derived separately.
- A library of subsystems models can be developed and stored for future use without the need of an equivalent

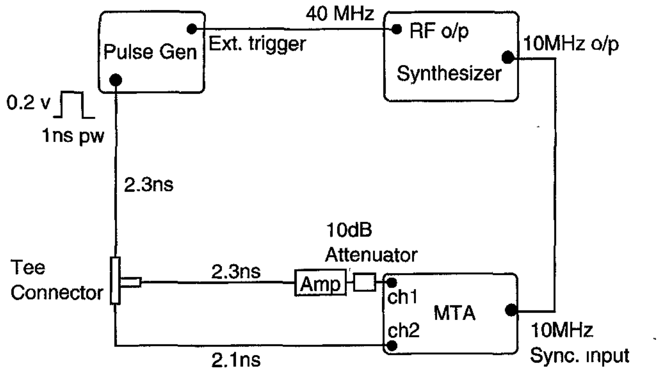

Fig. 4. Time domain scattering function measurement system for amplifier.

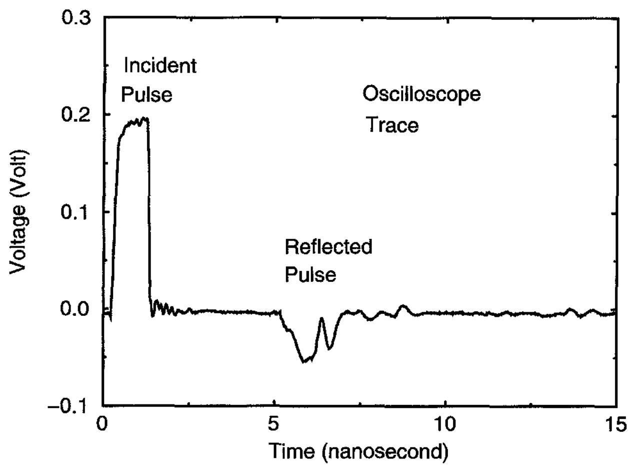

Fig. 5. Measured incident and reflected waveforms of the amplifier.

circuit. This includes amplifiers, mixers, oscillators, filters and couplers.

- The model characterizing a nonlinear subsystem can be derived to match experimental data without the need to develop a physically realizable equivalent circuit. This gives a greater flexibility in modeling active devices.

IV. Time Domain Scattering Function Measurement System

The incident, reflected and transmitted waves which are used to identify the scattering functions of the subsystems are measured in time domain. The measurement setup is based on the Hewlett Packard Microwave Transition Analyzer and is shown in Fig. 4 with an amplifier as the device under test. The incident pulse from the generator travels toward the tee connector and splits into two equal parts. One part travels through the amplifier and enters channel 1 of the sampling oscilloscope as the transmitted wave. The other part travels toward the channel 2 as the incident wave. The reflected wave from the amplifier travels back to the tee connector. One part returns to the generator, another part travels to the channel 2 as the reflected wave. In Channel 2, the incident and reflected waves are separated in time by twice the delay of the transmission line between the tee connector and the amplifier. The measured waveforms are

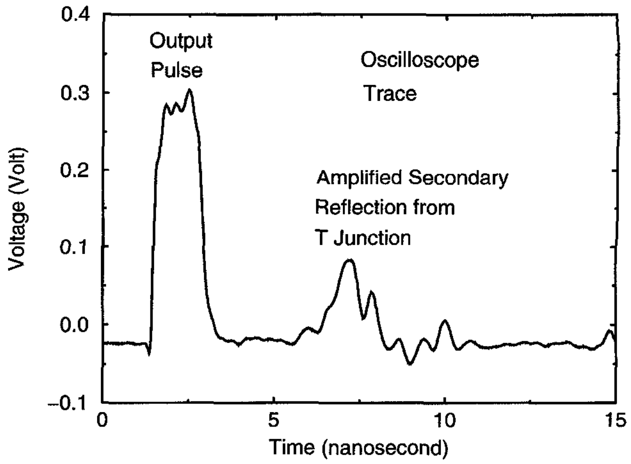

Fig. 6. Measured transmitted waveforms of the amplifier.

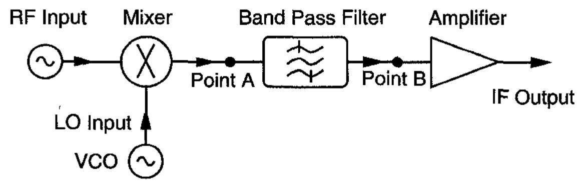

Fig. 7. The microwave receiver system.

shown in Figs. 5 and 6. The system is calibrated using a short circuit and a matched termination to remove the errors introduced by the tee connector and the transmission lines. The random noise in the time domain measurement will affect the accuracy of the model identified. The measurement noise is minimized by averaging sixty-four measurement samples. Signal propagation delay is measured first and then the output response used in time domain modeling is aligned with the input with no delay . The linear small signal model is obtained by fitting the measurement using Steiglitz–Mcbride iteration [5] and then the model is extended to the nonlinear large signal region by fitting the large signal measurements using a least square optimization algorithm. The choice of incident waveform is important to identify an accurate model of the subsystem in time domain. A pulsed wave is found to be optimal for amplifiers and filters in terms of accuracy and efficiency. The pulse parameters should be chosen such that its usable spectrum covers the operating input frequency and the amplitude covers the nonlinear range of the subsystem to be identified. A sinusoidal incident wave is found to be most suitable to identify models for mixers due to the complicated output waveform resulting from the mixing process. Directional couplers are used to separate the incident sine wave and the reflected wave. The incident, reflected and transmitted waves are all measured in the time domain and the measurement forms the basis from which the model is derived.

V. Modeling of Microwave Systems

To illustrate the developed procedure a complete microwave receiver will be modeled. The receiver consists of the following subsystems: a voltage-controlled oscillator (VCO), a

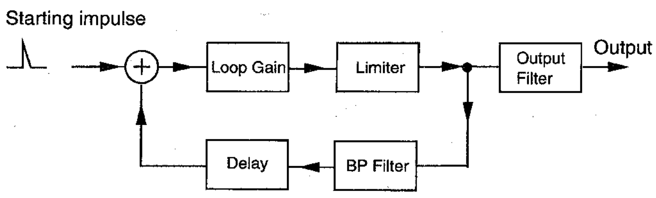

Fig. 8. Structure of the voltage controlled oscillator model.

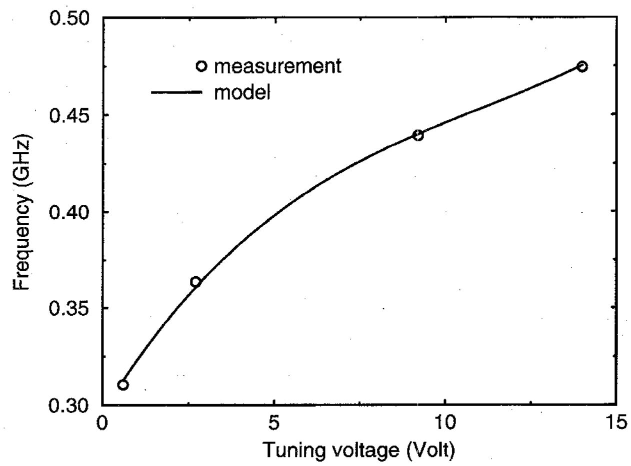

Fig. 9. Tuning characteristic of the voltage controlled oscillator.

balanced mixer, a bandpass filter and a nonlinear amplifier as shown in Fig. 7. The system model must take into account the nonlinear characteristics of each subsystem and the interaction between subsystems when the whole system is assembled. The first step in the system simulation is to measure each of the subsystems separately and to develop a model from time domain measurements. Then all the models are put together to obtain the overall system responses. The following sections describe the modeling of each individual subsystem.

A. Voltage Controlled Oscillator

A *Z-comm L-351* VCO has been modeled in time domain. The structure is shown in Fig. 8. The oscillation is started by an impulse and maintained by positive feedback. The loop gain, delay and final gain are functions of the tuning voltage and these functions are identified from the measurements. The sampling time is 0.02 ns, equivalent to a 25-GHz Nyquist frequency which is much higher than the 0.5-GHz maximum output frequency of the VCO. The output frequency of the VCO model and measurements are shown in Fig. 9 and the time domain waveform output of the VCO is shown in Fig. 10. The reflection coefficient of the VCO is identified in the form of a nonlinear time domain transfer function as given in (3). The incident and reflected pulses from the VCO are measured using the same set up as shown in Fig. 4. In this case, the pulse waves and sine waves generated by the VCO appear simultaneously on the sampling oscilloscope trace. The pulse generator and the VCO are separate, independent and uncorrelated sources. The VCO sine wave output appears as noise when the sampling oscilloscope is triggered on the incident pulse wave. Applying the noise filter and averaging

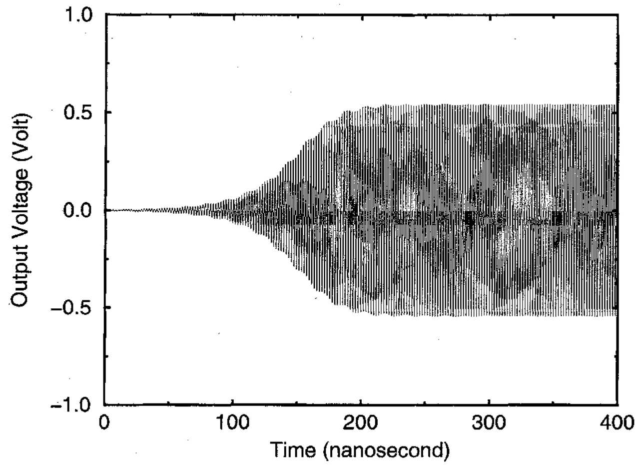

Fig. 10. Transient to steady-state output waveform of the VCO model.

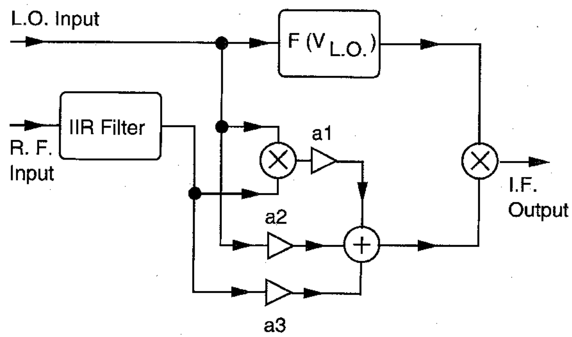

Fig. 11. Structure of the mixer model.

sixty-four samples of the measured waveform will remove the VCO output sine wave from the oscilloscope trace. The extracted incident and reflected pulses are then measured for reflection coefficient modeling.

B. Balanced Mixer

A *Mini-Circuit ZEM-4300* double balance mixer has been modeled next in the time domain. The main time domain nonlinear transfer function consists of a multiplier to simulate the mixing effect as shown in Fig. 11. An amplitude compensation nonlinear function and a frequency compensation infinite impulse response (IIR) filter are used to provide the large signal and wide band modeling capability. The sampling time is 0.02 ns, equivalent to a 25-GHz Nyquist frequency, which is much higher than the 4-GHz maximum input frequency of the mixer. The modeling results are shown in Figs. 12–14. Modeling results are in good agreement with measurements.

C. Bandpass Filter

A *Mini-Circuits SIF-70* bandpass filter has also been modeled in time domain. The four scattering functions are linear time domain transfer functions

$$y(t) = \sum_{i=0}^{n} b_i(x(t-iT)) - \sum_{i=1}^{n} a_i(y(t-iT)) \qquad (2)$$

where T is the sampling time interval and the a_i and b_i parameters are constant in linear system. A fifth-order model is

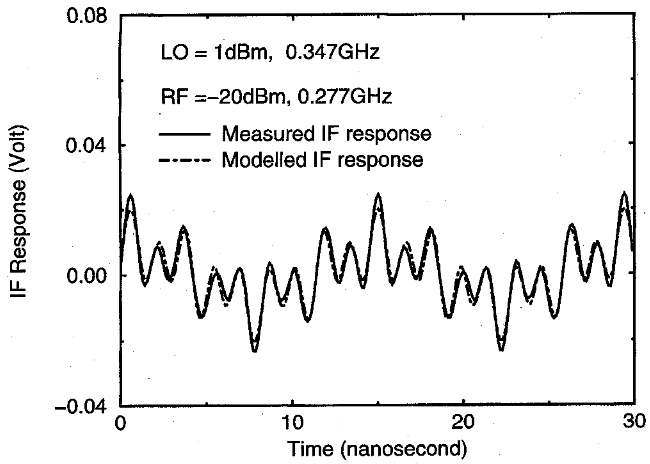

Fig. 12. Time domain responses of the mixer.

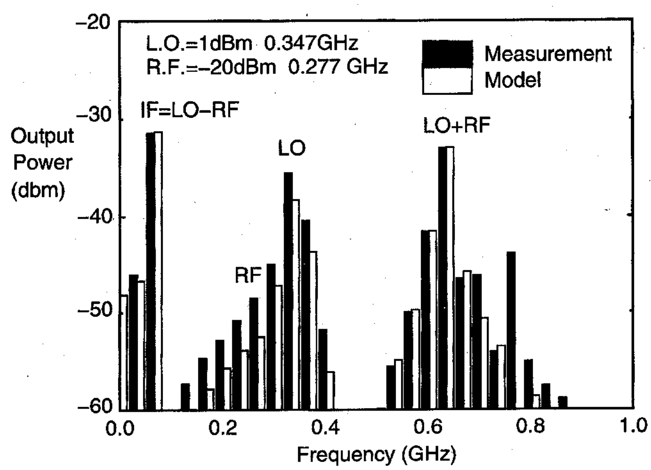

Fig. 13. Output spectrum of the mixer.

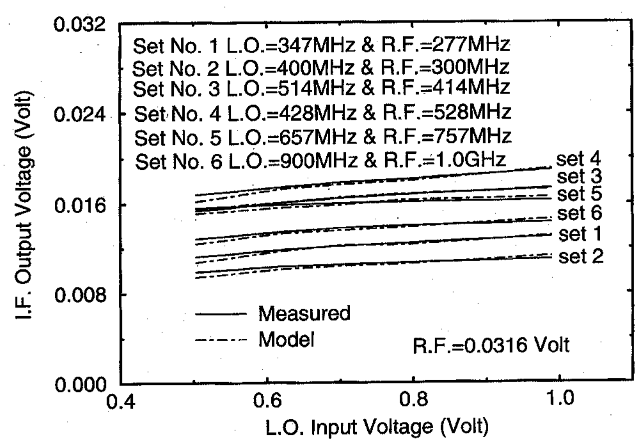

Fig. 14. *IF* output versus *LO* input of the mixer.

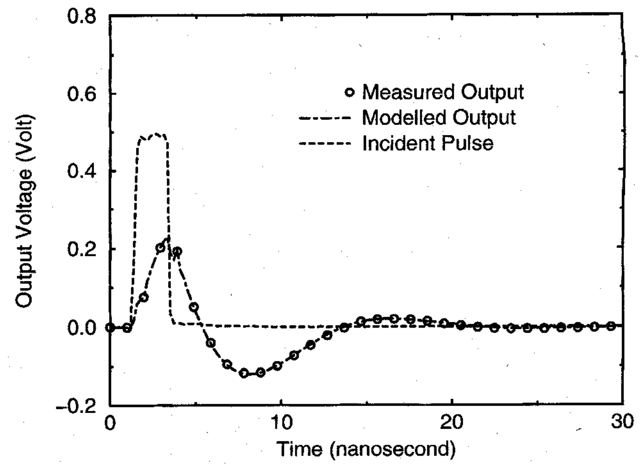

Fig. 15. Time domain responses of the bandpass filter.

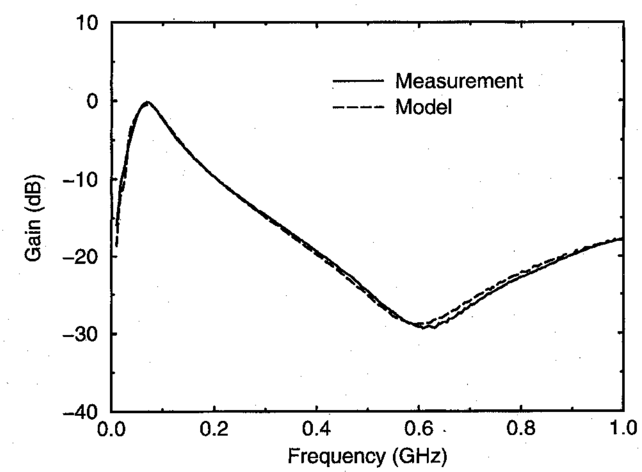

Fig. 16. Frequency responses of the bandpass filter.

used to identify the linear S_{21} scattering function as shown in (2). Sampling time is 0.02 ns, equivalent to a 25-GHz Nyquist frequency, which is much higher than the 0.07-GHz bandpass frequency of the filter. The Steiglitz–Mcbride method [5] is used to extract the a_i and b_i parameters from the input and output time domain measurements. The modeling results are shown in Figs. 15 and 16 and again very good agreement between measurements and simulated results is obtained. The remaining three scattering functions S_{11}, S_{12}, and S_{22} are modeled by a similar method.

D. Nonlinear Amplifier

As an example of a nonlinear two-port, a *Mini-Circuits ZFL-1000LN* amplifier has been modeled in the time domain. The four scattering functions are nonlinear time domain transfer functions as shown in Fig. 3. For this amplifier, hyperbolic tangent $\tanh(x)$ function which resembles the nonlinear saturation characteristic of the amplifier is chosen as the nonlinear function. The measured responses to large signal positive and negative inputs are different, therefore different nonlinear functions are used for positive and negative inputs. The nonlinear transfer function which models the S_{21} scattering function in time domain is

$$y(t) = \sum_{i=0}^{n} F_i(x(t-iT)) - \sum_{i=1}^{n} G_i(y(t-iT)) \quad (3)$$

where T is the sampling time interval and the nonlinear functions are given by

$$F_i = \begin{cases} b_{ip}\tanh(k_{p1}x(t)), & \text{if } x(t) \geq 0 \\ b_{in}\tanh(k_{n1}x(t)), & \text{if } x(t) < 0 \end{cases} \quad (4)$$

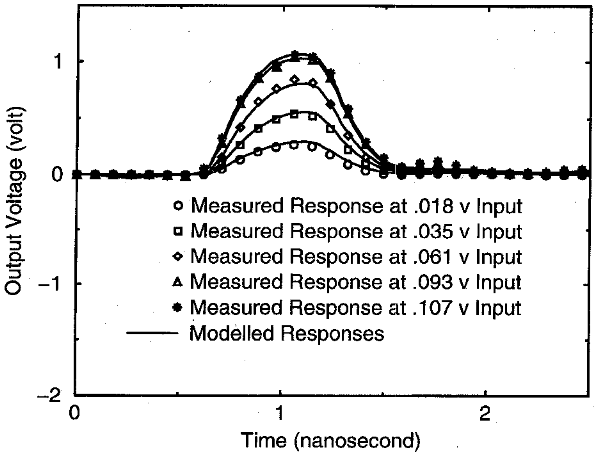

Fig. 17. Positive pulse responses of the amplifier.

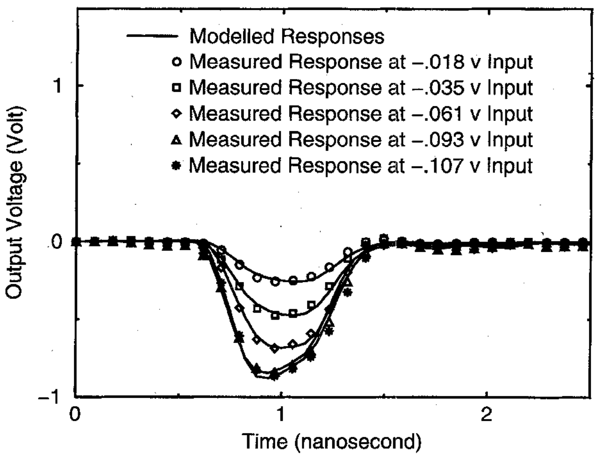

Fig. 18. Negative pulse responses of the amplifier.

$$G_i = \begin{cases} a_{ip}\tanh(k_{p2}x(t)), & \text{if } x(t) \geq 0 \\ a_{in}\tanh(k_{n2}x(t)), & \text{if } x(t) < 0 \end{cases} \tag{5}$$

and $b_{ip}, b_{in}, a_{ip}, a_{in}, k_{p1}, k_{n1}, k_{p2},$ and k_{n2} are constants.

Modeling the amplifier identifies the parameters b, a and k from the measured time domain responses. The ninth-order model given in (3) is used for modeling the nonlinear S_{21} scattering function. Sampling time is 0.02 ns, equivalent to a 25-GHz Nyquist frequency, which is much higher than the 1-GHz cutoff frequency of the amplifier. The time domain modeling results are given in Figs. 17 and 18. The results are post-processed to get the frequency domain characteristics. The gain compression characteristics of the amplifier and the harmonic content of the model are compared to measured results in Fig. 19. Very good agreement is obtained. The other three nonlinear scattering functions are identified in a similar manner.

VI. Complete System Simulation

From the results of the time domain measurement, each subsystem is represented by their scattering functions in the time domain. The entire system can then be built up of the individual subsystems in any desired connection. Two examples of complete systems are given. The first is of

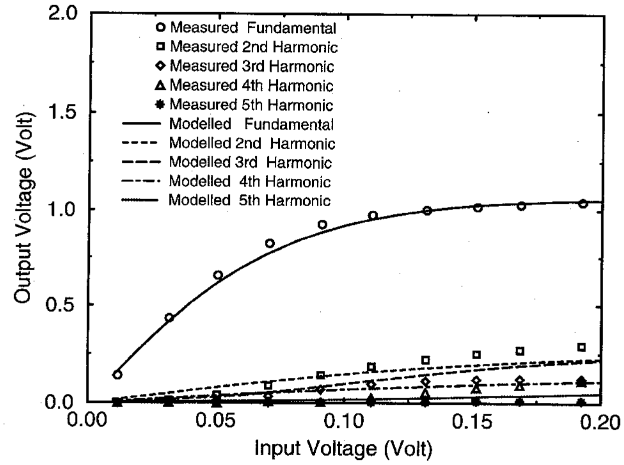

Fig. 19. Input-output characteristics of the amplifier.

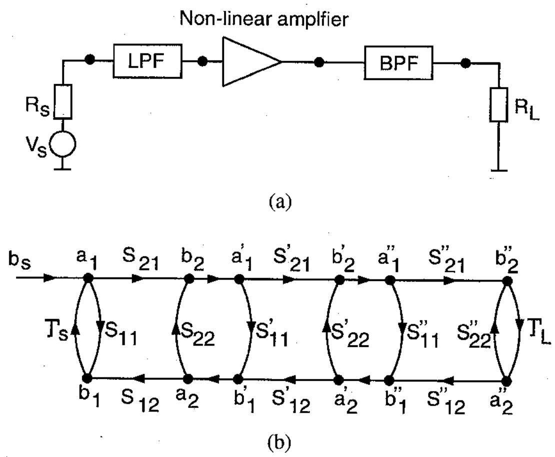

Fig. 20. Scattering functions and signal flow graph of the cascaded nonlinear system.

an amplifier and two filters and the second of a complete microwave receiver.

A. Amplifier System

Fig. 20 illustrates how three cascaded subsystems, a low pass filter, an amplifier and a bandpass filter for example can be simulated in the time domain. Sampling time is 0.02 ns, equivalent to 25-GHz Nyquist frequency, which is much higher than the maximum operating frequency of the individual subsystems.

The various signals in the flow chart are related by

$$\begin{aligned}
a_1(t) &= b_s(t) + \Gamma_s(b_1(t - td_1)) \\
b_1(t) &= S_{11}(a_1(t - td_2)) + S_{12}(a_2(t - td_3)) \\
b_2(t) &= S_{21}(a_1(t - td_4)) + S_{22}(a_2(t - td_5)) \\
a_1'(t) &= b_2(t) \\
a_2(t) &= b_1'(t) \\
b_1'(t) &= S_{11}'(a_1'(t - td_6)) + S_{12}'(a_2'(t - td_7)) \\
b_2'(t) &= S_{21}'(a_1'(t - td_8)) + S_{22}'(a_2'(t - td_9)) \\
a_1''(t) &= b_2'(t) \\
a_2'(t) &= b_1''(t)
\end{aligned}$$

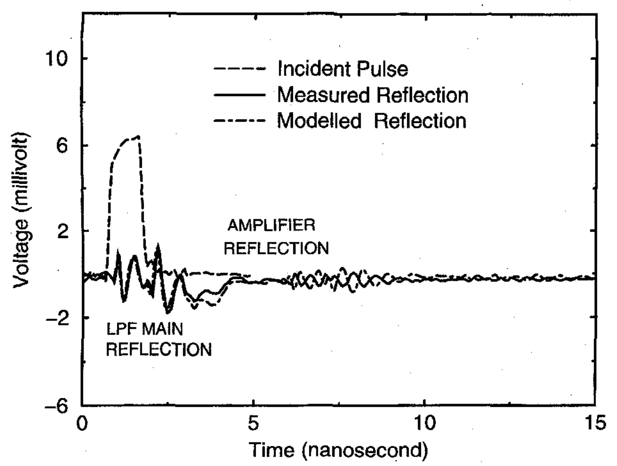

Fig. 21. Reflected waveforms of the cascaded nonlinear system.

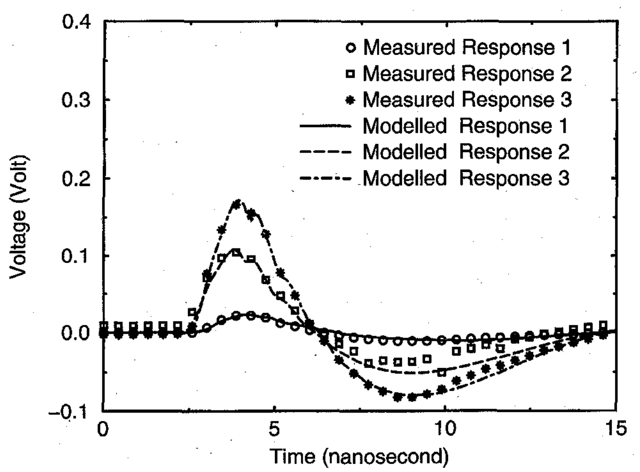

Fig. 22. Transmitted waveforms of the cascaded nonlinear system.

$$
\begin{aligned}
b_1''(t) &= S_{11}''(a_1''(t - td_{10})) + S_{12}''(a_2''(t - td_{11})) \\
b_2''(t) &= S_{21}''(a_1''(t - td_{12})) + S_{22}''(a_2''(t - td_{13})) \\
a_2''(t) &= \Gamma_L(b_2''(t - td_{14}))
\end{aligned} \tag{6}
$$

where, $td_1, td_2, \cdots, td_{14}$ are the time delays in the scattering functions or reflection coefficients.

At each time step, the above equations are solved to obtain the incident and reflected waves. In all microwave networks, the scattering functions will have a certain delay and hence every branch in the signal flow chart contains a delay. The approach is similar to wave digital filter representations without any delay-free loops [6]. In this case the solutions of the above equations at time t only depend on the previous values of the signals and no iterations are required as in the case of the equivalent circuit approach. This is true even if the circuit is nonlinear. To simulate the above cascaded system, every individual subsystem was measured in the time domain and a model for each of the four scattering functions was developed. Then the entire system was modeled and the results compared to measurements. Fig. 21 shows the time domain reflection results and Fig. 22 shows the effect of increasing the input signal amplitude to the transmission result. The simulation results match the measurements accurately.

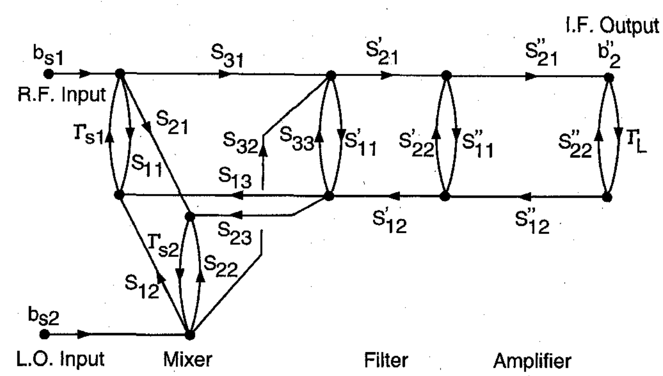

Fig. 23. Scattering functions and signal flow graph of the receiver system.

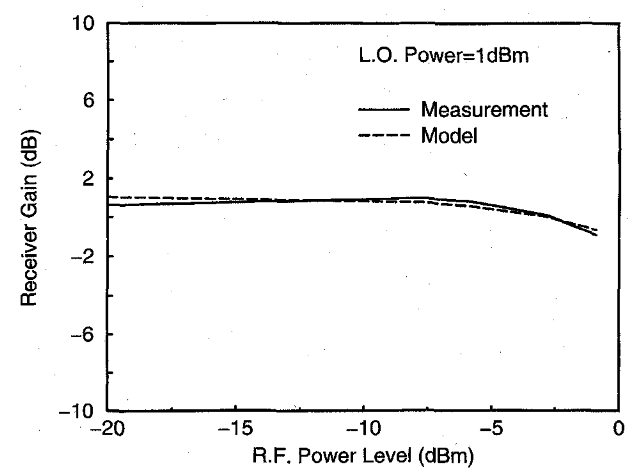

Fig. 24. Receiver gain versus r.f. input level.

B. Microwave Receiver System

As another example of system modeling and simulation example a microwave receiver is to be constructed using the modeled amplifier, double balanced mixer, voltage controlled oscillator and bandpass filter as shown in Fig. 7. The system is to mix two signals at 0.277 GHz and 0.347 GHz and produce an *IF* signal at 0.07 GHz. First each of the subsystems is identified separately, then the whole system is constructed and the measured and simulated response of the overall system are compared. Sampling time is 0.02 ns, equivalent to 25-GHz Nyquist frequency, which is much higher than the maximum operating frequency of the subsystems. The complete signal flow diagram is shown in Fig. 23. The simulation results and measurement are shown in Figs. 24–26. The simulated gain and output waveform of the receiver are in good agreement with measurement.

VII. Summary of Procedures

The procedure for system design then proceeds as follows.

- The engineer designs, buys or otherwise acquires a number of subsystems (amplifier, mixers, oscillators, modulators etc.) which meet individual specifications. The object is to design a complete system using these subsystems and to predict its performance before building the entire system.

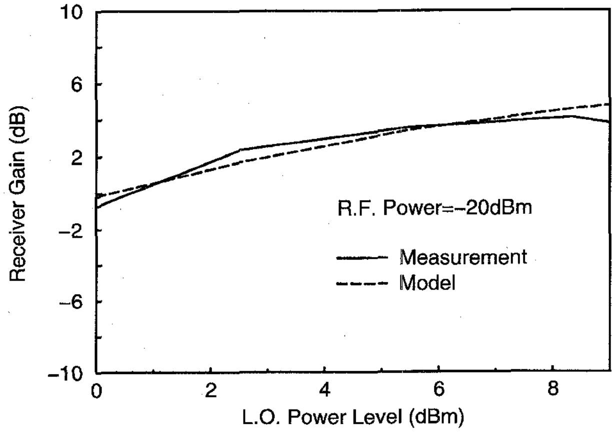

Fig. 25. Receiver gain versus *LO* input level.

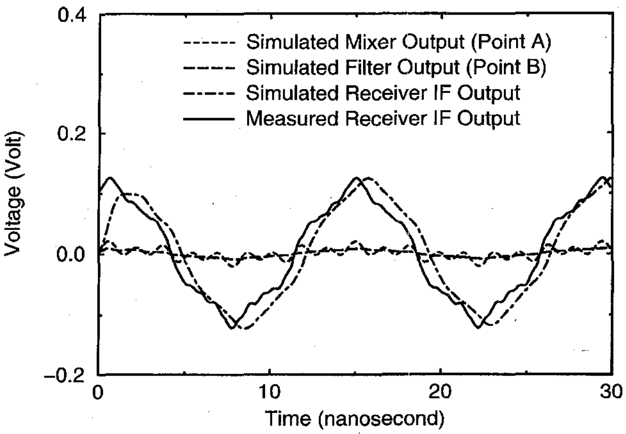

Fig. 26. Output waveforms of the receiver system.

- The next step for the engineer to make a time domain measurement on each subsystem.
- From the time domain measurements a nonlinear or linear model of each subsystem is derived.
- An optional step is to check the frequency domain behavior of the derived nonlinear models. This step is performed using software developed in the project. The facilities is offered since frequency domain characteristics are more recognized by engineer and system designers.
- The next step is to simulate the entire system using the derived subsystem models.
- If the results of the system simulation do not meet specifications, design modifications are made and the above steps repeated.

VIII. Conclusion

A new method of subsystem modeling and system simulation has been developed. Nonlinear modeling and simulation are performed in the time domain. Black box models are used instead of equivalent circuit models. The system simulation can deal with any number of subsystems and any arbitrary connection and interactions between subsystems are simulated simultaneously. A cascade nonlinear amplifier system and a microwave receiver system are modeled and the simulation results agree very well with measurements.

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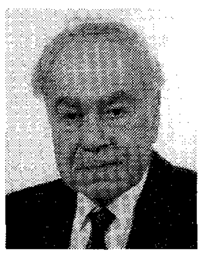

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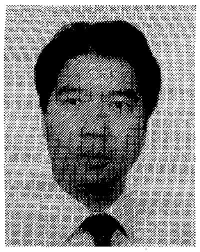

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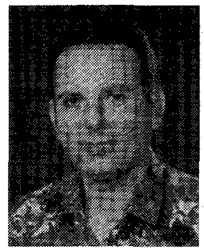

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