NEW TIME DOMAIN REFLECTOMETRY TECHNIQUES SUITABLE FOR TESTING MICROWAVE AND MILLIMETER WAVE CIRCUITS

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ABSTRACT

A superconducting circuit based time domain reflectometer with deconvolution has achieved a record 2.5 ps rise time at the DUT's interface. The corresponding spatial resolution is approaching 0.1mm for high dielectric media. Examples for applications are given. The "tail effect" caused by large discontinuities is eliminated by deconvolution. An innovative "partial reflection" calibration is suggested to improve the resolution for on-chip tests.

Introduction

Using Time Domain Reflectometry (TDR) or Time Domain Transmission (TDT) techniques to detect discontinuities in transmission lines is well know. However, TDR applications in testing microwave and millimeter wave circuits are largely restricted because of poor spatial resolution, tail effect after large discontinuities, and the difficulties of on-chip calibration.

This paper reports the progress made in solving these problems.

1. Deconvolution code was developed to improve the performance of a superconducting circuit based TDR to a record 2.5 picosecond rise time and a spatial resolution approaching 0.1 mm in high dielectric media.

2. The deconvolution was used to eliminate the tail effect after a large discontinuity, and it is able to recover small discontinuities which were obscured by large aberrations.

3. Partial Reflection Calibration for deconvolution is suggested to improve the spatial resolution for on-chip tests.

Deconvolution Enhanced Superconducting TDR

The spatial resolution of a TDR can be expressed as the following:

$$\Delta x = \frac{CT_r}{2\sqrt{\varepsilon_{eff}}} \qquad (1)$$

Here C is the speed of light in a vacuum, T_r is the rise time of TDR, ε_{eff} is the effective dielectric constant of the medium.

A superconducting circuit based TDR, the HYPRES PSP-750 [1] has an internal rise time (T_r) of 5 ps. However, the external T_r measured at the output is degraded to 8-10 ps due to connector bandwidth limitations. Deconvolution code was developed to improve the resolution.

For a linear system with impulse response h(n), the discrete time domain input x(n), and the output y(n) are related by a convolution:

$$y(n) = \sum_{j=0}^{N-1} h(j)\, x(n-j), \quad n = 0, 1, 2, ..., N-1 \qquad (2)$$

A FFT of (2) gives the frequency domain relation:

$$Y(i) = H(i)\, X(i), \quad i = 0, 1, 2, ..., N-1 \qquad (3)$$

The direct solving of X(i) in (3) is an "ill-conditioned" problem. A filter should be used for deconvolution as follows [2]:

$$X(i)=\frac{Y(i)}{H(i)}\ \frac{|H(i)|^2}{|H(i)|^2+\gamma F(i)G},\ i=0,1,\ldots,N-1 \qquad (4)$$

Here

$$F(i)=\left[2\,Sin\left(\frac{\pi i}{N}\right)\right]^4,\ i=0,1,\ldots,N-1. \qquad (5)$$

And,

$$G=\frac{1}{N}\sum_{i=0}^{N-1}\left(\mathrm{Re}\,[H(i)]^2+\mathrm{Im}\,[H(i)\,]^2\right) \qquad (6)$$

represents a normalization factor. γ is an optimizing parameter chosen for the best compromise between fidelity and resolution. With the help of the G-factor, a default value of γ=3 is set for the PSP-750, which is able to achieve good results for 80% of the tests. The other 20% needs an adjustment of γ.

The TDR deconvolution requires only two calibrations; a 50Ω load to set the reference, and a short-circuit to obtain the frequency response $H(i)$. For TDT, only a 50Ω line through calibrations is required.

Since the connector is a linear component, its effect on the test signal rise time can be easily eliminated by deconvolution. Furthermore, to a certain extent, the built-in step generator and sampler in the TDR can be treated as linear systems. In other words, the rise time after deconvolution can be even faster than its internal value. Indeed, a 2.5 record rise time was achieved (Figure 1). According to equation (1), this result translates into a spatial resolution of better than 0.4mm in an air medium. For high dielectric media, the spatial resolution approaches 0.1mm.

Figure 2 shows the TDT traces for a 2-18 GHz directional coupler. The multi-step coupling sections are clearly resolved after deconvolution. Figure 3 shows the TDR traces for a W-band mixer circuit. The TDR was used to design a hermetically sealed package, including a glass bead and a coaxial to coplanar interface, operating from DC to 70 GHz. The result is shown in Figure 4.

Recovery from "Tail Effect"

One problem in microwave testing is the Device Under Test (DUT), such as an FET, is often not directly reachable. Accessary components, such as a DC-block, bias-T, etc., are inserted between the DUT and the TDR. The large aberration caused by these accessaries gives rise to a "tail effect" due to resonance or multi-reflection. The small discontinuities of interest behind the accessaries get "lost" in the large aberrations. Figure 5 (a) illustrates an example of this.

If the accessaries before the DUT are linear, their adverse tail effects can be eliminated using deconvolution. Figure 5 (b) shows the result; the aberration is gone, and the spatial resolution is improved.

Improved Resolution For On-Chip Tests

If the DC-block or bias-T are built in on an IC chip, they are not detachable from the DUT behind them. Then, the method described above is no longer applicable due to on-chip calibration difficulties.

The 50Ω load calibration is impossible in this case. However, the short-circuit calibration for obtaining impulse response can be replaced by the following procedure.

First, a short-circuit is still possible at the interface of the chip to obtain the frequency response $H_0(i)$. Obviously, this only represents the TDR system itself. It does not account for the frequency response degradations caused by the inserted accessories in front of the DUT. With these accessories, the compensation requires additional calibrations. This can be done by two identical partial reflections; one before the accessaries to obtain a frequency response $H_1(i)$, while the other is done after the accessaries to obtain frequency response $H_2(i)$. The frequency response needed to perform the deconvolution is represented in the following equation:

$$H(i) = Ho(i)\left[\frac{H_1(i)}{H_2(i)}\right] \quad i = 0, 1, ..., N-1 \qquad (7)$$

The deconvolution by using $H(i)$ given in (7) is able to recover the frequency response degradation caused by the accessories.

The key here is to achieve two identical partial reflections. If the transmission lines before and after the accessaries are identical, a metal block with smooth, flat surfaces placed on the top of lines will provide identical reflections at two locations.

To prove the idea, tests were done on three different lines: Two microstrip lines on DUROID 5880 and 6006, and a coplanar line on quartz. Figure 6 shows how the block repeatedly reflected more than 50% of the total energy back. If the dynamic range is sufficient, the deconvolution with such a calibration is able to improve the spatial resolution for on-chip tests. However, due to the lack of 50Ω reference, the aberration of "tail effect" is still a problem for on-chip tests.

Conclusions

A superconducting TDR with software enhancement achieved a record rise time of 2.5 picoseconds at the DUT's interface, which corresponds to a spatial resolution approaching 0.1mm in high dielectric media. This high accuracy spatial resolution is essential for testing microwave and millimeter circuits.

The deconvolution is also able to recover the "lost" small discontinuities from the large aberrations generated by substantial discontinuities in front of them.

An innovative partial reflection calibration can be used for deconvolutions to improve the spatial resolution of on-chip tests.

References

[1] Stephen R. Whiteley, G. K.G. Hohenwarter, and S. M. Faris, "A Josephson Junction Time Domain Reflectometer with Room Temperature Access". IEEE Trans. Magn., MAG-23, no. 2 p.899, March 1987.

[2] William L. Gans, "Calibration and Error Analysis of a Picosecond Pulse Waveform Measurement System at NBS", Proc. IEEE, Vol. 74, No. 1, 1986, pp 86-90

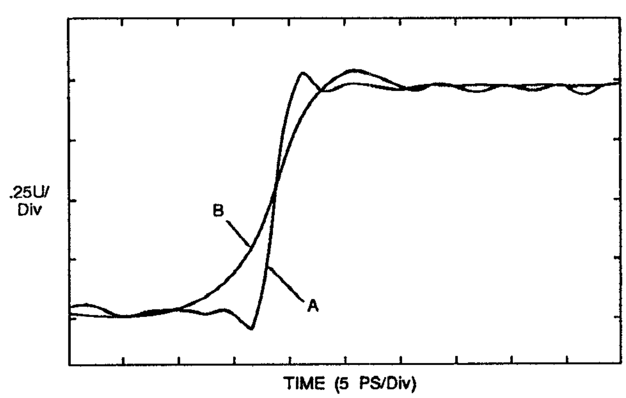

Figure 1. Rise time at DUT interface:
A - After deconvolution, $T_r = 2.49$ ps
B - Before deconvolution, $T_r = 8.29$ ps

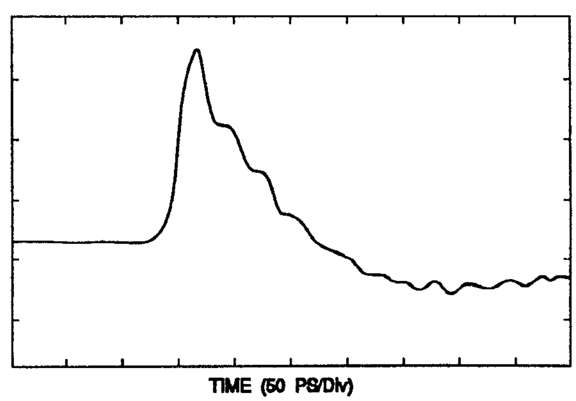

Figure 2. TDT trace of a 2 - 18 GHz directional coupler.

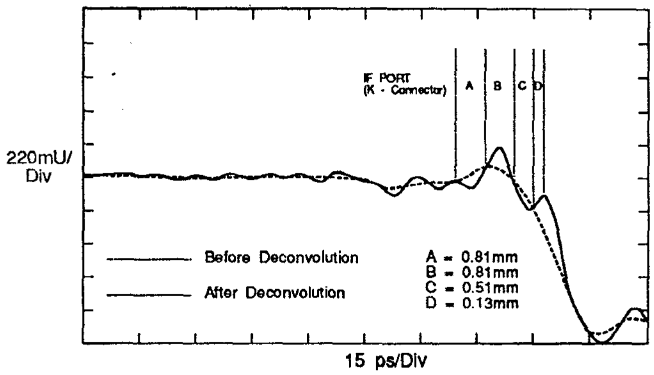

Figure 3. TDR traces for a W-band mixer

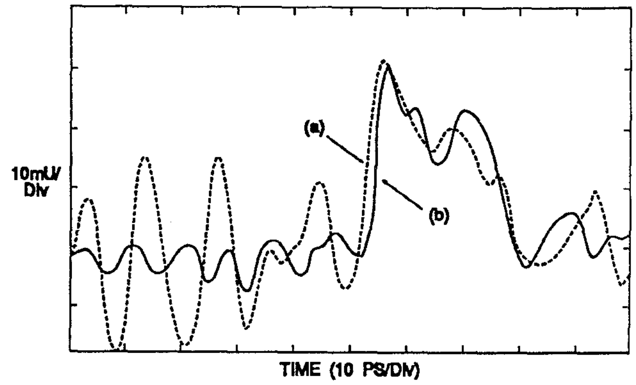

Figure 5. (a) Small discontinuities were obscured by large aberrations due to tail effect (ringing) (b) Recovered after deconvolution

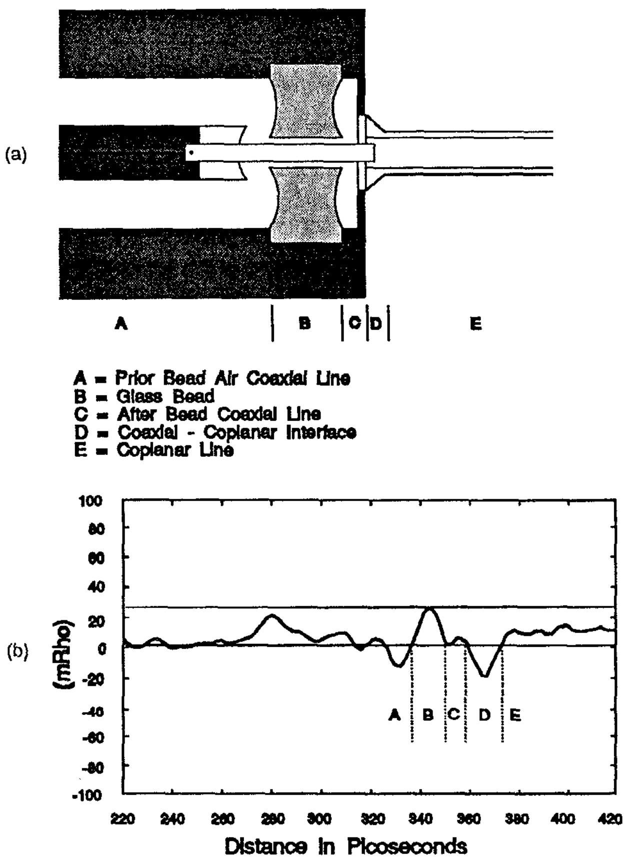

Figure 4. (a) Hermetically sealed coaxial - coplanar interface and (b) its TDR trace.

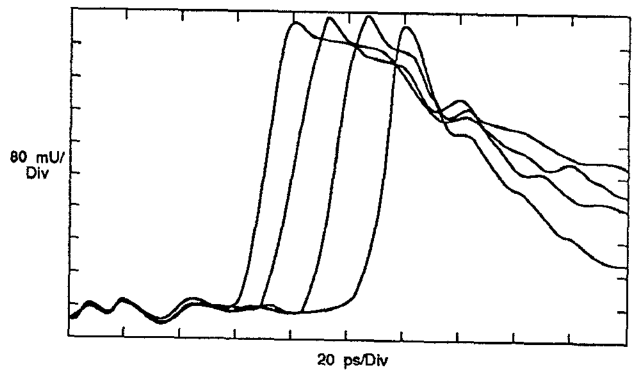

Figure 6. Partial reflection waveforms on 50Ω quartz coplanar line.