Time-Domain Network Analysis of MM-Wave Circuits Based on a Photoconductive Probe Sampling Technique

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Abstract

We have developed a photoconductive probe sampling technique with 2-ps temporal resolution and μV sentivity. Using the technique, we have measured S-paramerters of millimeter-wave passive devices with a 120-GHz measurement bandwidth.

Introduction

Conventional purely electronic measurement instruments such as vector network analyzers, spectrum analyzers and sampling oscilloscopes are not effective at above 100 GHz. One major limitation is imposed by the connectors and waveguides needed for signal coupling between the test instrument and the device under test. To overcome those limitations of present measurement techniques, we have developed a photoconductive probe sampling technique which can be applied to the measurement of S-parameters of mm-wave circuit components with a 120-GHz measurement bandwidth [1]. The photoconductive probe sampling technique combines the ultrafast optical technology of 120-fs Ti-Sapphire short pulse laser [2] and microfabrication technology of Silicon-On-Sapphire (SOS) photoconductive sampling probe, which consists of a high-impedance interdigitated photoconductive switch. The technique is based on high-impedance external sampling with 2.1-ps temporal resolution, 8-μm spatial resolution and high signal-to-noise ratio. Also, the measurement point can be very close to the device under test. Therefore, the technique minimizes interconnection discontinuities and consequently errors and uncertainties from device de-embedding procedures.

Experiments and results

Figure.1 is an SEM picture of the photoconductive(PC) sampling probe. It consists of a high impedance metal-semiconductor-metal (MSM) photoconductive switch on a damaged Silicon-On-Sapphire substrate and a Ti contact tip of 3-μm height. Figure.2 shows the experimental set-up used to measure the characteristics of band-block filters of microstripline

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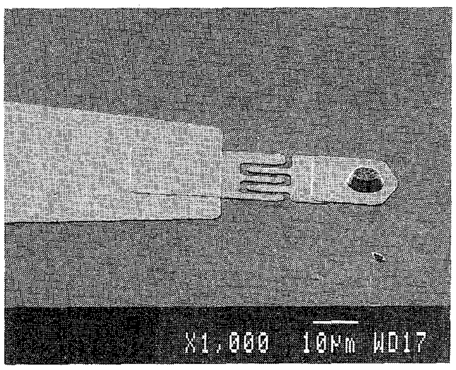

Fig.1 SEM picture of photoconductive sampling probe

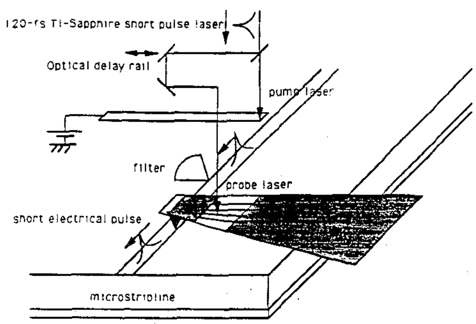

Fig.2 Experimental set-up to measure the transmitted pulse waveform from the band-block filter

structure. The 70-µm wide microstripline and the band-block filter were fabricated on Low-Temperature-Grown GaAs (LT-GaAs) substrate of 100-µm thickness. The structure is part of a 90 GHz to 180 GHz InP-based HEMT doubler which has been demonstrated by the authors (Fig.3) [3]. The subpicosecond carrier lifetime of LT-GaAs enables the generation of 1-ps electrical pulses using a 120-fs short-pulse pump laser [4]. Also, the response of the silicon-on-sapphire photoconductive switch on the probe is < 2 ps, so that the short electrical pulse can be sampled with 2-ps temporal resolution using the short pulse probe beam. The probe touches the microstrip and measures the amplitude of an electrical signal at a specific point in time when the probe laser pulse is hitting the PC switch on the probe. By changing the optical delay between the pump and probe laser beams, one can measure an entire electrical pulse form.

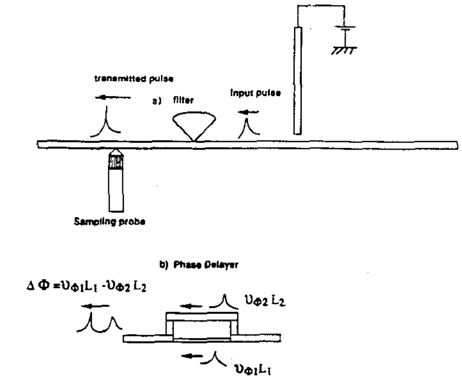

Fig 3. Test structure a) for the characterization of band-block filter, b) for measurement of phase delay of microstrip phase delay line.

Transmitted waveforms were measured from 80-GHz and 100-GHz band-block filters using the probe. The 80-GHz band-block filter has a 212-µm radius with 60 ^{0} angle, and the 100-GHz band-block filter has a 167-µm radius with 60 ^{0} angle. Figure.3 (a) shows the probe position and the test structure containing microstrip, band-block filter and photoconductive switch, which generates the short electrical pulse. The frequency spectrum of the transmitted pulses was calculated by taking their Fourier transform. Figure.4 shows the Fourier spectra of the transmitted pulses. The result shows that the 80-GHz band-block filter, which was designed using a commercially available software package, is in fact filtering the signal at a slightly lower frequency 70 GHz. Filtering is also observed at 150 GHz. The spectral component at 70 GHz is about 1 % of the dc component. Also, the 100-GHz band-block filter is filtering at 100 GHz and 170 GHz. By comparing the Fourier spectra of input, transmitted and reflected pulses, S-parameters of these filters could be calculated. This permits direct evaluation of measured characteristics at mm-wave frequencies as necessary for optimizing circuit performance.

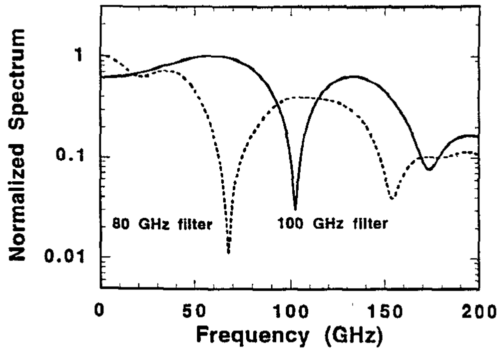

Fig.4 Frequency spectrum of transmitted pulses from the filters.

In addition to the characterizations of mm-wave band-block filters, the phase delay of a microstrip delay line has also been evaluated. Figure.3 (b) shows the test structure used for these measurements. It consists of a short line of length L_1 and delay line of length L_2. Figure.5 shows a phase delay of two measured pulses propagating along two different paths. At 100 GHz, the measured phase difference is $\Delta\Phi = -294^o$ ($\Delta\Phi = \upsilon_{\Phi 1}L_1 - \upsilon_{\Phi 2}L_2$). The difference between the nominal (designed) value ($\Delta\Phi = -350.8^o$ at 100 GHz) and measured value may arise from inaccurate knowledge of the exact phase velocity, especially in the calculation at very high frequencies . Thus although at 10 GHz the difference between the measured and nominal values is $\Delta\Phi_{nom} - \Delta\Phi_{meas} = 6.7^o$, at 100 GHz the discrepancy is much larger (56.8^o).

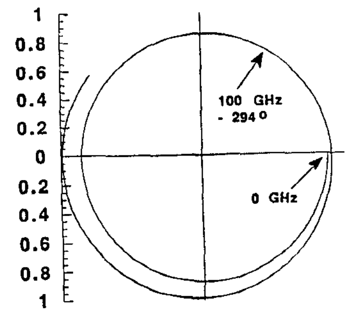

Fig.5 Phase delay between two different paths

Also, we applied the external SOS photoconductive sampling probe for S-parameter measurement of mm-wave microstrip low-pass filter. Fig.6 shows experimental set-up. The probe measures the input signal to the filter and the transmitted signal from the filter. By taking Fourier transform, we can calculate the S-parameter of the filter. The measured S-parameter and the simulation result from a Touchstone program are shown in Fig.7. This demonstrate feasibility of photoconductive probe sampling for S-parameter measurement with > 120 GHz bandwidth.

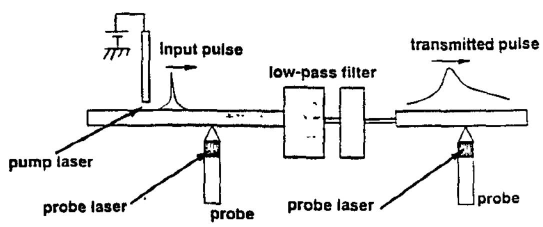

Fig.6 Experimental set-up to measure S-parameter of mm-wave low-pass filter.

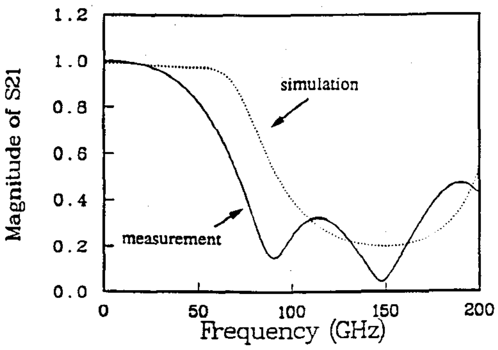

Fig.7 Measured and simulated results of S21

Conclusions

A new photoconductive probe sampling technique which can be applied to mm-wave circuit testing has been developed and demonstrated. The probe technology has shown measurements exceeding 120 GHz and permits reduction of interconnection discontinuities and errors by de-embedding procedures. The probe technology was applied to the characterization of mm-wave band-block filters used in InP-based heterostructure MMIC's for 90 GHz to 180 GHz frequency doubling. MM-wave delay lines have also been characterized and the properties of transmission lines on thin semiconductor substrates have been studied. The results demonstrate the capability of mm-wave circuit testing using the photoconductive probe sampling technique.

References

[1] J.Kim, Y-J.Chan, S. Williamson, J.Nees, S.Wakana,J.Whitaker, D.Pavlidis, 1992 IEEE GaAs IC Symposium.

[2] D.Spence, P.Kean and W.Sibbett, Opt. Lett., 16, 42(1991)

[3] Y.Kwon, D.Pavlidis, P.Marsh, M. Tutt, G.I. Ng and T. Brock, Second International Symposium on Space Terahertz Technology, 1991

[4] S. Gupta, M. Frankel, Y. Valdmanis, J. Whitaker and G. Mourou, Appl. Phys. Lett. (25), 3276 (1991)

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