# CHARACTERIZATION AND SIMULATION OF BI-QUADRATIC COPLANAR WAVEGUIDE TAPERS FOR TIME-DOMAIN APPLICATIONS

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## ABSTRACT

The design and performance of a novel coplanar waveguide (CPW) taper for picosecond pulse applications is described. We have investigated tapers with largely differing widths varying from 62.5 $\mu$m to 900 $\mu$m. The circuit characteristics were simulated both in time domain and frequency domain using a 3D transmission-line-matrix (TLM) method. We found an optimum bi-quadratic shape which reduces the reflections from more than 5 % to below 2 % in comparison to a linear taper. The circuits were measured in the frequency range up to 40 GHz with a wafer prober. At 40 GHz, the insertion loss values were less than 0.4 dB. For a double taper risetimes of 6.4 ps were achieved which correspond to a bandwidth of 55 GHz.

## INTRODUCTION

In the design of planar microwave circuits low-reflection tapers are required to provide broadband connections between components of different geometric dimensions. CPW technology is inherently suitable for this purpose due to a large range of possible centerline widths by adjusting the gap of the CPW and the offset between centerline and adjacent groundplanes of the structure. In time-domain applications, signals with short risetimes are reflected at the transition [1] [2] and cause repetition-rate dependent dips in the waveform. Thus, non-transforming tapers are essential elements that avoid alteration of the transient waveform if optimized for constant characteristic impedance in direction of propagation.

## BI-QUADRATIC COPLANAR TAPER

The bi-quadratic taper shown in Fig. 1 is part of the entire structure (see Fig. 4) which is composed of a transmission line with width $w_1$ and length $l_1$, a taper section of length $l_{\text{taper}}$, a CPW of different width $w_2$ and length $l_2$, a second taper and another CPW with width $w_3 = w_1$ and length $l_3 = l_1$. The taper section itself consists of three parts, a quadratic expanding section, a linear section and a quadratic decreasing section, each of identical length. The relatively long straight sections separating the tapers are necessary for time-domain measurements to resolve the locations of reflections. The structures have been fabricated on alumina substrates ($\epsilon = 9.8$) of 0.254 mm thickness. The characteristic impedance was optimized for 50 $\Omega$ operation, however is not restricted to this value.

Due to the lack of accurate models for CPW structures in the available computer-aided engineering (CAE) software we use a full-wave analysis for circuit design. In general, three-dimensional field analysis is required in

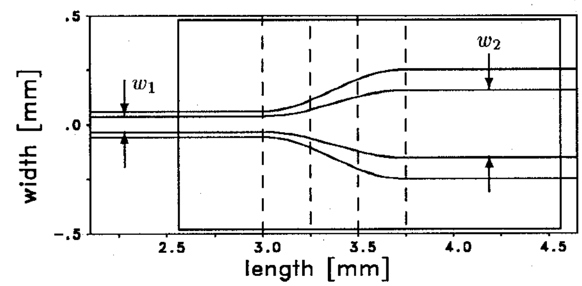


**Figure 1:** Layout of bi-quadratic CPW taper (simulated section), area of inset shown in 3D-plots in Figs. 6 and 7, dashed: quadratic part - linear part - quadratic part of taper.

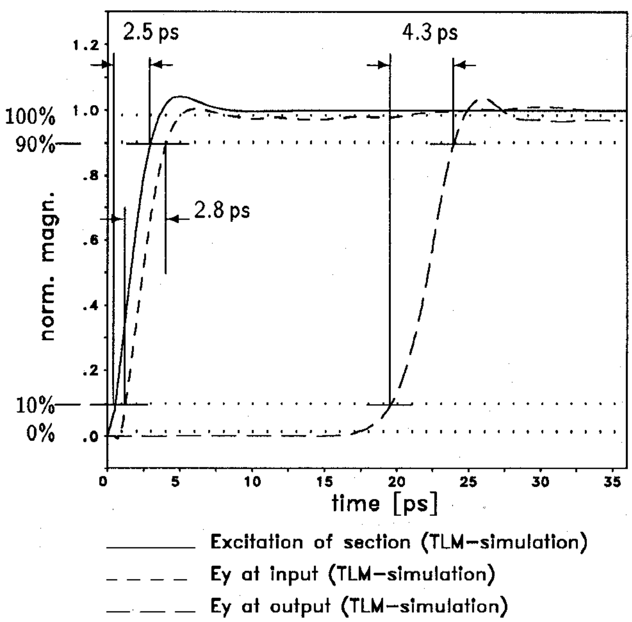


**Figure 2:** Step response of single bi-qauadratic CPW taper, excitation 2.5 ps, damping factor $\delta = 0.707$, $w_1 = 62\,\mu$m, $w_2 = 300\,\mu$m, $w_3 = 62\,\mu$m, $l_{\text{taper}} = 0.75$ mm, $l_{\text{total}} = 2.0$ mm (TLM-simulation).

planar circuits. We employ the three-dimensional transmission-line-matrix method (3D-TLM) for modeling the transient electromagnetic field in the planar structures. The circuit was discretized in both space and time by a transmission line mesh. This mesh embodies all electromagnetic properties of the space under consideration, including boundary conditions, losses, permittivity, and permeability. The TLM method yields the time response of the structure by computing the scattering and the propagation of wave pulses in the transmission line mesh employing Huygen's model of wave propagation. TLM schemes based on the symmetrically condensed node formulation introduced by *Johns* [3] are used due to the absence of dispersion towards the main-axis direction. We applied appropriate nonuniform orthogonal meshes for the discretization of the CPW taper to obtain an optimum adaption of the TLM mesh to the geometry of the structures.

## TIME-DOMAIN CHARACTERIZATION

We simulated the taper area, as shown in Fig. 1. The structure was excited at the input port of the taper with a second order step function (damping factor $\delta = 0.707$ and 0.6). The computed step response with a 2.5 ps excitation step (Fig. 2) yields an effective risetime of $t_{r,10\%\text{-}90\%} = \sqrt{4.3^2 - 2.5^2}\,\text{ps} = 3.5\,\text{ps}$. The computed and measured step response of the taper section for a step with a 10 ps risetime is shown in Fig. 3. A risetime reduction from 10 ps to 10.6 ps is simulated which corresponds to an effective risetime of the taper calculated by the equation $t_{r,10\%\text{-}90\%} = \sqrt{10.6^2 - 10.0^2}$ ps to 3.5 ps which agrees with the value obtained for the 2.5 ps excitation step.
S-parameter measurements (0.1 GHz to 40 GHz) of the entire structure and FFT of the data (corresponding risetime of the equivalent excitation step due to frequency domain windowing is $t_{r,10\%\text{-}90\%} = 11.0\,\text{ps}$ ) results in a risetime of 12.7 ps (Fig 3). After correction we obtain an effective risetime of $t_{r,10\%\text{-}90\%} = \sqrt{12.7^2 - 11.0^2}$ ps = 6.4 ps which corresponds to a bandwidth of 55 GHz.
For comparison of simulation and measurement we calculate the risetime of two cascaded taper sections to $t_{r,10\%\text{-}90\%} = \sqrt{3.5^2 + 3.5^2}\,\text{ps} = 4.9\,\text{ps}$. This value does not include the influence of the remaining straight CPW sections with a length of 8 mm. Thus the risetime will further reduce to approximately $t_{r,10\%\text{-}90\%} = \sqrt{2} \cdot 4.9\,\text{ps} = 6.9\,\text{ps}$.
Time-domain reflectrometry (TDR) (inv. FFT of frequency data) of two different CPW bi-quadratic and linear tapers ($w_1 = 62.5\,\mu\text{m}$, $w_2 = 300\,\mu\text{m}$, ratio 1:4.8 and $w_1 = 62.5\,\mu\text{m}$, $w_2 = 900\,\mu\text{m}$, ratio 1:14.4 ) are shown in Fig. 4 and 5, respectively. These tapers were used in circuit design for low loss delay lines and large coupling capacitors for ultra-broadband circuits. Reflection values at the taper as low as 2 % − 3 % and insertion loss values of 0.8 dB at 40 GHz were obtained. The location of the reflections and the layout of the taper in Fig. 4 and 5 are drawn to scale. Comparison of the quadratic and linear taper of 910 $\mu$m width shows an improvement in reflections from 4.8% to 1.5% ($t = 40\,\text{ps}$), whereas little change is shown for the taper of 310 $\mu$m width.

## THREE-DIMENSIONAL FIELD DISTRIBUTION

3D-plots of the simulated transversal field components $E_y$ and $H_y$ in a plane below the metalization are shown in Fig. 6, at $t_1 = 19.0\,\text{ps}$ and in Fig. 7, at $t_2 = 35.7\,\text{ps}$. At time $t_1$ the front corner of the step is visible, whereas at time $t_2$ the field components are shown after the step traveled past the end of the taper.

## FREQUENCY DOMAIN CHARACTERIZATION

The wideband frequency characteristics can be evaluated by Fourier transformation of the transient time-domain results. The computed S-parameters of a single taper are shown in Fig. 8. $S_{21}$ has to be extrapolated for comparison with the

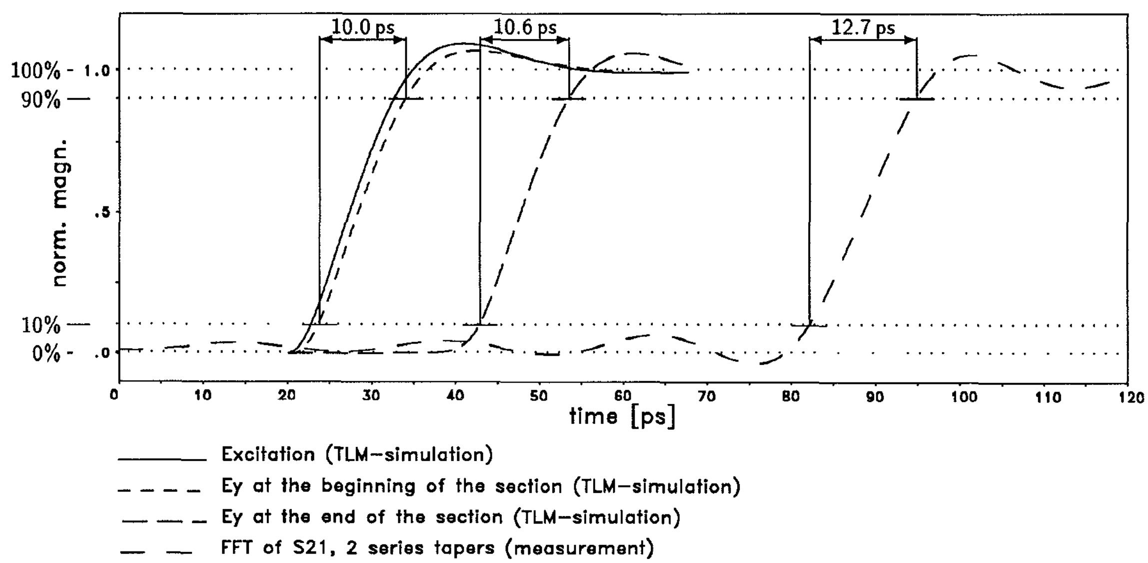


**Figure 3:** Step response of single bi-qauadratic CPW taper (TLM-simulation), excitation 2.5 ps, damping factor $\delta = 0.6$, $w_1 = 62\,\mu\text{m}$, $w_2 = 310\,\mu\text{m}$, $w_3 = 62\,\mu\text{m}$, $l_{\text{taper}} = 0.75\,\text{mm}$, $l_{\text{sim}} = 2.6\,\text{mm}$, $l_{\text{meas}} = 12.0\,\text{mm}$, and inv. FFT of S-parameter of two tapers (measurement).

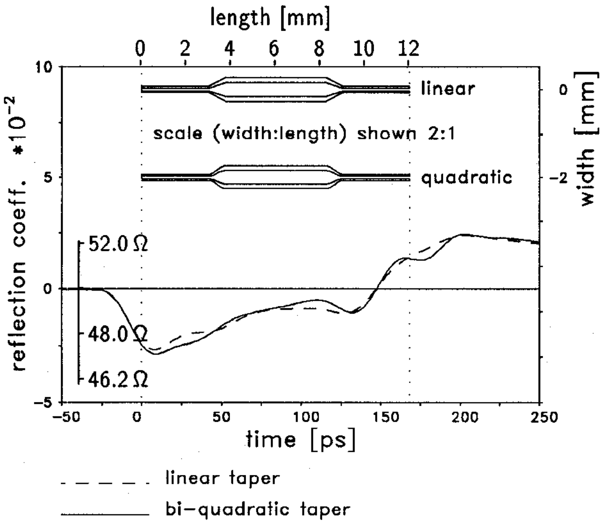


**Figure 4:** Input reflection coefficient (measurement) of linear and bi-quadratic coplanar taper from inv. FFT of S11, $w_1 = 62\,\mu\text{m}$, $w_2 = 310\,\mu\text{m}$, $w_3 = 62\,\mu\text{m}$, $l_{\text{taper}} = 0.75\,\text{mm}$, $l_{\text{total}} = 12.0\,\text{mm}$.

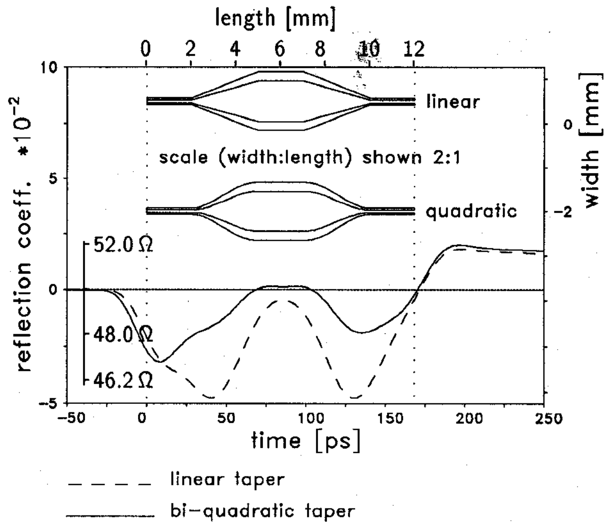


**Figure 5:** Input reflection coefficient (measurement) of linear and bi-quadratic coplanar taper from inv. FFT of S11, $w_1 = 62\,\mu\text{m}$, $w_2 = 910\,\mu\text{m}$, $w_3 = 62\,\mu\text{m}$, $l_{\text{taper}} = 1.5\,\text{mm}$, $l_{\text{total}} = 12.0\,\text{mm}$.

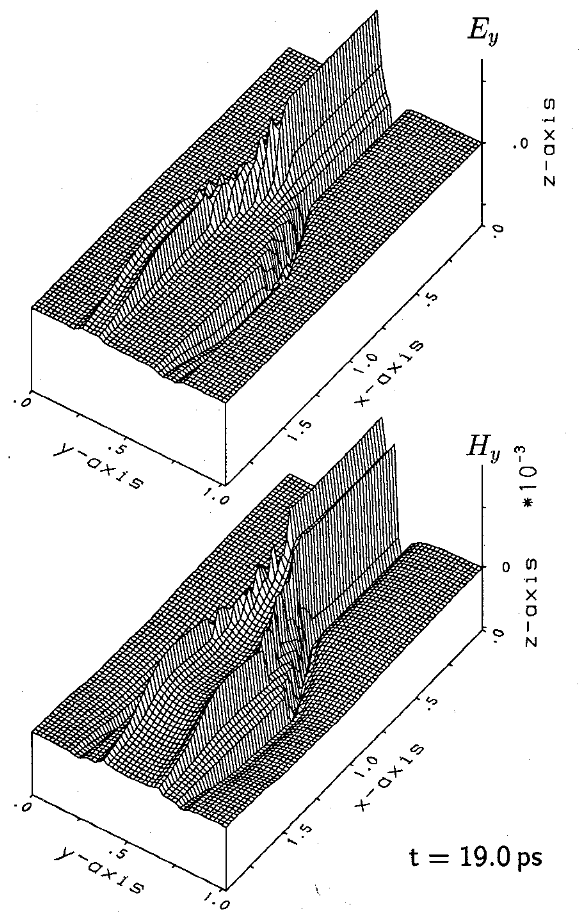


**Figure 6:** Field component $E_y$ and $H_y$ at $t = 35.7\,\text{ps}$, excitation with $t_r = 2.5\,\text{ps}$ step, damping factor $\delta = 0.707$ (taper section as shown in Fig. 1).

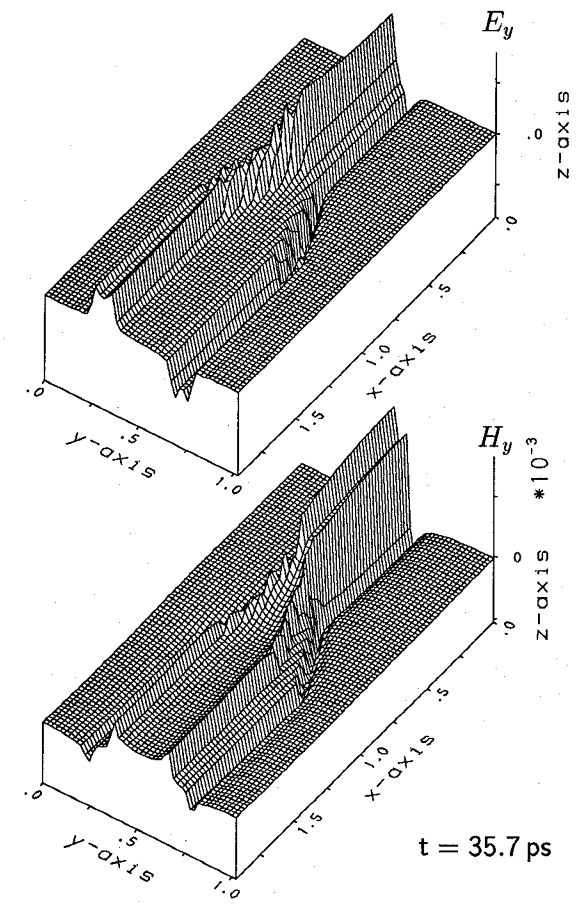


**Figure 7:** Field components $E_y$ and $H_y$ at $t = 35.7\,\text{ps}$, excitation with $t_r = 2.5\,\text{ps}$ step, damping factor $\delta = 0.707$ (taper section as shown in Fig. 1).

measurement of the entire structure, thus obtaining a value of approximately 1.2 dB at 40 GHz. The calculated $S_{11}$ (only one taper considered) corresponds also resonably well with the measurement. The measured S-parameters for 310 $\mu$m and 910 $\mu$m width are shown in Fig. 9 and 10, respectively. In both cases we obtain an improvement for $S_{11}$ of up to 8 dB, depending on the frequency, whereas $S_{21}$ is only slightly dependent on the shape of the taper.

## CONCLUSION

Novel bi-quadratic low-reflection coplanar waveguide (CPW) tapers of constant impedance and of different geometric dimensions for use in picosecond pulse applications have been characterized and optimized with the 3D-TLM method. A comparison with measurements in the time-domain and frequency-domain with rise-times of 10 ps and a frequency range of 0.1 GHz to 40 GHz, respectively, is given and proves the superior performance of the bi-quadratic taper and the applicability of the TLM-method for these structures.


## ACKNOWLEDGEMENT

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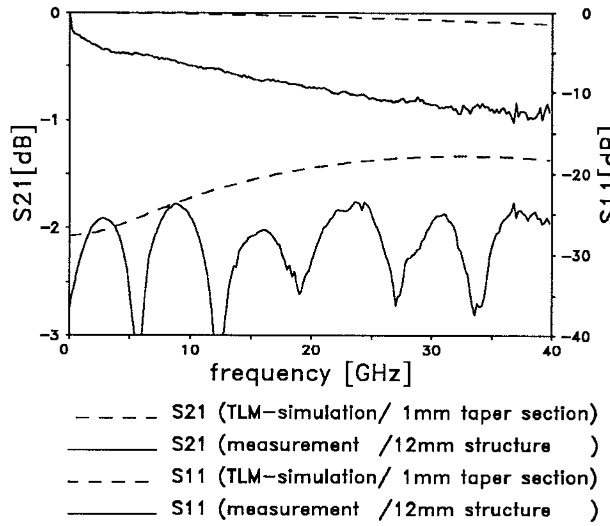


**Figure 8:** Simulated and measured S-Parameters of quadratic taper, $w_2 = 310\,\mu$m.

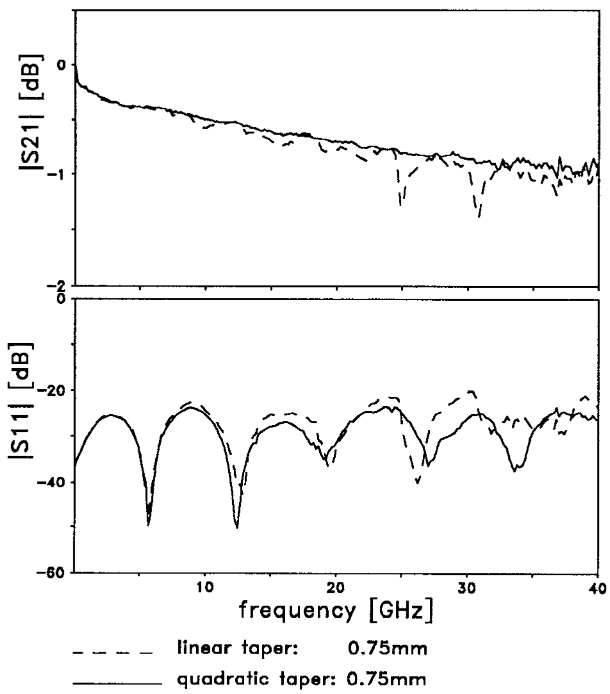


**Figure 9:** $|S21|$ and $|S11|$ of linear and quadratic taper, $w_1 = 62\,\mu$m, $w_2 = 310\,\mu$m, $w_3 = 62\,\mu$m (measurement).

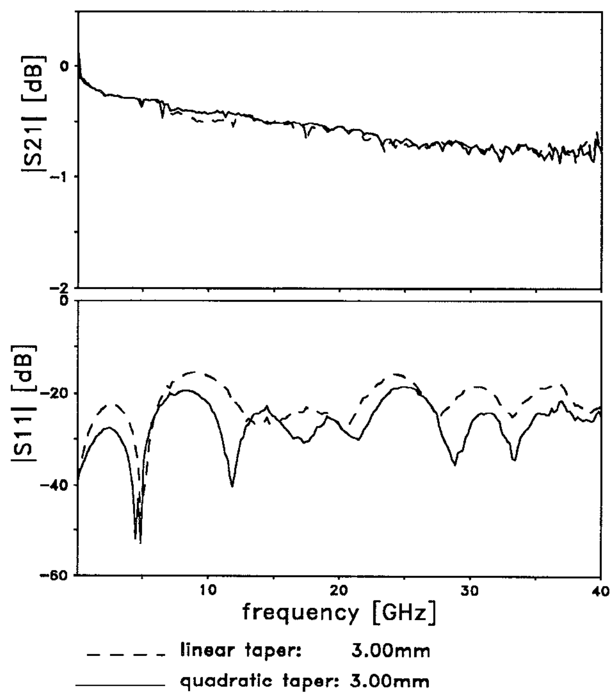


**Figure 10:** $|S21|$ and $|S11|$ of linear and quadratic taper, $w_1 = 62\,\mu$m, $w_2 = 910\,\mu$m, $w_3 = 62\,\mu$m (measurement).