The Effect of Impedance Mismatch on Phase Linearity of GCPW Loaded Transmission Lines and Shunt Stubs

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Abstract — **This paper presents a study on the effect of impedance mismatch on phase linearity (group delay variations) in grounded coplanar waveguide (GCPW) structures. Two 400 ps GCPW delay lines were designed using a short circuited stub and a transmission line. The structures were simulated over a wide frequency range (0.1 GHz- 5 GHz) using both ADS circuit model and CST electromagnetic simulation tool. Based on mathematical analysis and simulation results, impedance mismatch appears to have a large effect on group delay variations in stubs when compared to transmission lines. The simulated time delay of the short circuited stub shows a maximum delay deviation of ±0.75% and ±7.4% for 1.6% and 5.8% impedance mismatch values, respectively. On the other hand, the transmission delay line simulation results show only ±0.1% and ±1.5% for the same impedance mismatch. For the electromagnetic simulation, the presented results indicate even larger variation of time delay for GCPW short stub as it reaches ±3.75% and ±7.5% at 2 GHz and 4.5 GHz for 1.6% impedance mismatch, respectively.**

Keywords — **coplanar waveguides, switched delay lines, linear phase, shunt stubs, phase shifters, impedance mismatch.**

I Introduction

For many wideband RF and microwave systems, linear phase response is equally desirable and a challenging design characteristic. Examples include, but are not limited to: adaptive antennas and radar systems (where phase characteristics is controlled for successful beam forming and target tracking [1]), wideband multicarrier power amplifiers (feed-forward amplifiers require precise delay to suppress distortion) and leakage cancellation systems to keep signals out of phase over a wide band of frequencies [2]. Over the next decade, a new generation of wireless communication systems (e.g. 5G systems) is expected to be deployed, inevitably pushing signal bandwidths into a multiple of 100 MHz, increasing carrier frequency and requiring much precise control of signal phase matching and time delay. High performance phase shifters/time delay circuits keep a distortion of wideband signals to minimum thanks to a linear phase (resulting in a constant group delay). Moreover, parameters as low insertion loss, small size, low cost and tunability (large delays with fine resolution) are also desirable [3]. Switched delay line structures usually satisfy bandwidth, cost and linearity requirements, and together with MEMS switches, can achieve low insertion loss below 1 dB and low switch control power consumption [4]. Many modern MEMS devices come in packages with 0.5 mm pitch between RF ports which are usually integrated using CPW structures as an attractive alternative to microstrip lines [5]. The design of short and open GCPW stubs was introduced earlier by Anand et al. [6] with optimised insertion and return loss characteristics over a wide range of frequency. However in practice, finite fab-

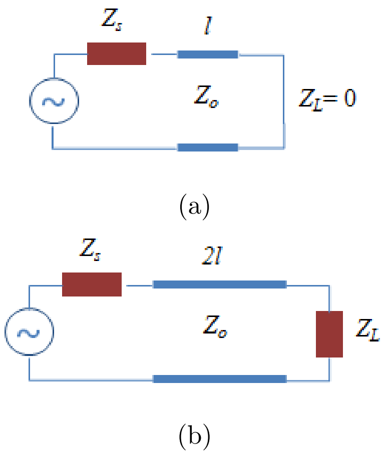

Fig. 1: (a) short circuited stub, (b) loaded transmission line

rication tolerances may severely affect their performance. This paper explores the effect of characteristic impedance mismatches due to fabrication tolerances on group delay variations of wideband GCPW delay line structures. The article is organized as follows. Section II presents a mathematical analysis on the phase response of transmitted and reflected signals in lossless transmission lines and stubs which are expressed as a function of impedance mismatches. In Section III, the design of two 400 ps GCPW delay lines using a short circuited stub and a transmission line is presented together with the simulation results.

II Mathematical Analysis

Consider a lossless transmission line terminated by a short circuit load ($Z_L = 0$) as shown in Fig. 1a. Given that the characteristic impedance Z_o of the line is perfectly matched to the source impedance Z_s, then the input impedance Z_{in} and reflection coefficient Γ seen from the source can be expressed based on transmission line theory [8] using (1) and (2). In this case, the phase of the reflection coefficient ($\angle\Gamma$) has a linear response at any frequency range as seen in (3).

$$Z_{in} = jZ_o tan(\beta l) \tag{1}$$

$$\Gamma = \frac{tan^2(\beta l) - 1 + 2jtan(\beta l)}{1 + tan^2(\beta l)} \tag{2}$$

$$\angle\Gamma = tan^{-1}(\frac{2sin(\beta l)cos(\beta l)}{sin^2(\beta l) - cos^2(\beta l)}) = -2\beta l \tag{3}$$

If the impedance of the line is slightly shifted from the nominal source impedance, the ratio of the impedance given by (4) is $\delta \neq 1$. Therefore, the magnitude and the phase of the reflection coefficient changes as indicated by (5) and (6). By comparing (3) and (6) a linear phase response in a short stub is only achieved under the condition given by (7). Similarly for an open circuited stub, the same condition applies.

$$\delta = \frac{Z_o}{Z_s} \tag{4}$$

$$\Gamma = \frac{Z_o^2 tan^2(\beta l) - Z_s^2 + 2jZ_sZ_o tan(\beta l)}{Z_s^2 + Z_o^2 tan^2(\beta l)} \tag{5}$$

$$\angle\Gamma = tan^{-1}(\frac{2\delta sin(\beta l)cos(\beta l)}{\delta^2 sin^2(\beta l) - cos^2(\beta l)}) \tag{6}$$

$$\delta^2 = 1 \tag{7}$$

where β is the propagation constant and l is the length of the transmission line.

Now, consider a lossless transmission line is terminated with a load impedance Z_L as shown in Fig. 1b, where Z_L is perfectly matched to the source impedance ($Z_L = Z_s$). If the characteristic impedance of the line Z_o is again shifted from Z_s (4). Then the magnitude and phase of the transmission coefficient ($T, \angle T$) from the source to the load can be expressed using (8) and (9). In this case, the signal transmitted from the source to the load can be characterized by a perfect linear response at any frequency range under the condition derived directly from (10) and given by (11).

$$T = \frac{(Z_o^2 + Z_s^2)tan^2(2\beta l) + 2jZ_sZ_o tan(2\beta l)}{\frac{1}{(Z_o^2 - Z_s^2)}(4Z_o^2 Z_s^2 - (Z_o^2 + Z_s^2)^2 tan^2(2\beta l))} \tag{8}$$

$$\angle T = tan^{-1}(\frac{2Z_sZ_o}{(Z_o^2 + Z_s^2)tan(2\beta l)}) \tag{9}$$

$$\angle T = tan^{-1}(\frac{2cot(2\beta l)}{\delta + \frac{1}{\delta}}) \tag{10}$$

$$\rho = (\frac{\delta}{2} + \frac{1}{2\delta})^{-1} = 1 \tag{11}$$

Comparing the phase linearity conditions for the two different lines (7) and (11) given that both have the same value of impedance mismatch δ, it can be seen that phase linearity is more sensitive to impedance mismatch in short/open stubs. Because ρ diverges faster to 1 when compared to δ^2.

For example, a 5% impedance mismatch (δ= 0.95) results in ρ= 0.9986 which is greater than δ^2 = 0.9025. Thus the phase linearity is always higher in transmission lines compared to short/open stubs.

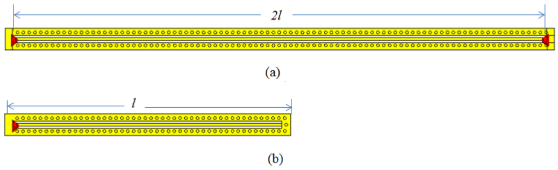

Fig. 2: (a) GCPW transmission line, (b) GCPW short circuited stub

III Simulation Setup and Results

In order to validate the concept presented in this paper, shunt stub and transmission line were designed using GCPW finite ground structures as shown in Fig. 2. The dimensions of the GCPW lines were selected to match a 50Ω system impedance. The lines were shaped using annealed copper (conductivity= $5.813 \cdot 10^7$S/m, surface roughness= 3.4 um and thickness= 33.02 um). The substrate used is Rogers 4003 with dielectric constant $\varepsilon_r = 3.55$, loss tangent= 0.0027 and thickness is 0.203 mm. The width of the signal line is 0.42 mm whereas the gap between the upper ground and the signal line is only 0.3 mm. Both structures were designed to deliver a 400 ps time delay over a wide frequency range from 0.1 GHz up to 5 GHz. Thus the length of the transmission line is twice the length of the short circuited stub. The length of the transmission line (l) required to deliver a 400 ps delay can be calculated using the phase velocity of the corresponding medium as seen in (12) [6].

$$l = v_{phase} \cdot 400 \cdot 10^{-12} = c\frac{400 \cdot 10^{-12}}{\sqrt{\varepsilon_{eff}}} \qquad (12)$$

where $\varepsilon_{eff} = 2.726$ is the effective dielectric constant of the substrate used in this paper.

The structure was first analysed using ADS 2011 in order to apply the circuit model available in the standard CPW library. Fig. 3 shows the simulated time delay of a 72.6 mm GCPW transmission line at different dimensions for the line (w= 0.42±Δ mm) which can be used as a reference to possible fabrication tolerences. It indicates a maximum time delay deviation of ±0.1% and ±0.75% (±0.4 ps and ±3 ps) for 1.6% and 8.5% impedance mismatch corresponding to a change in the line width of $\Delta = \pm 0.01$ mm and $\Delta = \pm 0.05$ mm, respectively.

On the other hand, Fig. 4 shows the simulated time delay of a 36.3 mm length GCPW short stub which indicate a maximum time delay deviation of ±1.5% and ±7.4% (±6 ps and ±29.5 ps) for the same impedance mismatch values.

Electromagnetic simulation was also carried out for the same 400 ps GCPW structures using CST

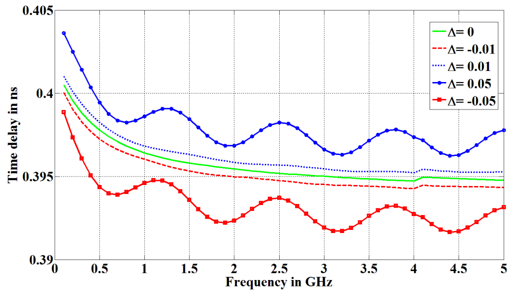

Fig. 3: Simulated time delay of GCPW transmission line at different signal line width (w= 0.42±△ mm) which corresponds to ±1.6% and ±8.5% impedance mismatch, respectively.

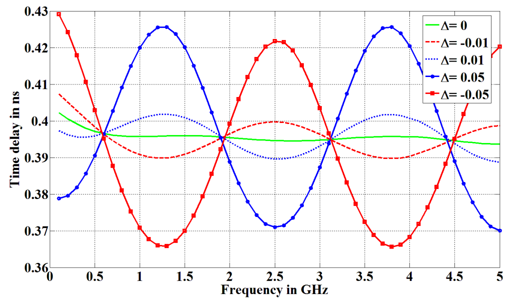

Fig. 4: Simulated time delay of GCPW short stub at different signal line width (w= 0.42±△ mm) which corresponds to ±1.6% and ±8.5% impedance mismatch, respectively.

Microwave Studio simulation. Fig. 5 shows a comparison between the simulated time delay for the wave reflected from the GCPW short stub together with the delay of the wave transmitted through the line given that both lines encounter a 1.6% impedance mismatch (Δ= 0.01 mm). This result agrees with the circuit model on having a larger mismatch effect on stubs compared to transmission line. However, it even indicates larger time delay variation which reaches ±3.75% (±15 ps) at 2 GHz and is further increased to ±7.5% (±30 ps) at 4.5 GHz. This is due to non ideal effects of GCPW having a finite width for the upper ground, in addition to higher modes effect which aren't considered in ADS circuit model.

IV Conclusion

In this paper, a study was presented on the effect of impedance mismatch due to fabrication tolerances on time delay variations of GCPW stubs and transmission lines. A mathematical analysis was applied based on transmission line theory. Two 400 ps delay lines were designed using GCPW short circuited stub and a transmission line. Both structures were simulated using ADS circuit model and CST electromagnetic simulation tool over a frequency range from 0.1 GHz up to 5 GHz. The simulation results of the short circuited stub de-

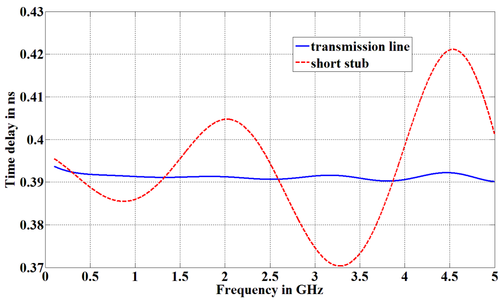

Fig. 5: Simulated time delay of GCPW short stub and transmission line with line width w= 0.42±0.01 mm (1.6% impedance mismatch) using CST electromagnetic simulation tool.

lay indicate a maximum time delay deviation of ±1.5% and ±7.4% for 1.6% and 8.5% impedance mismatch, respectively. While the simulated delay of the GCPW transmission line shows only ±0.1% and ±0.75% for the same impedance mismatch values. The electromagnetic simulation also results in a larger time deviation for GCPW short stub as it reaches a maximum deviation of ±15 ps at 2 GHz and ±30 at 4.5 GHz for 1.6% impedance mismatch.

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