Resonance and Group Delay Variation in True-time Delay Line

Minyoung Yoon, Sangwook Nam
Dept. electrical and computer engineering
Institute of New Media and Communications (INMC), Seoul National University (SNU)
Seoul, Korea
Email:ymy@ael.snu.ac.kr

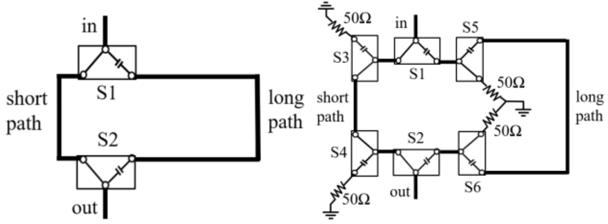
***Abstract*— In this paper, we present issues that must be considered in design of true-time delay (TTD). The application of TTD is a phased array antenna system which can be wideband system due to using of TTD. First off-state capacitor resonance must be avoided when designing a switched line TTD. TTD was designed and fabricated with PCB to confirm that the resonance occurs when the electrical length of the transmission line on the off-state side is an integral multiple of the half-wave length. Cascaded switches can be used to solve the resonance problems. Second factor is group delay variation (GDV) caused by reflected waves due to discontinuity. The proposed transmission line model with discontinuity is used to analyze GDV by reflected waves.**

Keywords—true-time delay; off-state capacitor resonance; isolation; group delay variation

I. Introduction

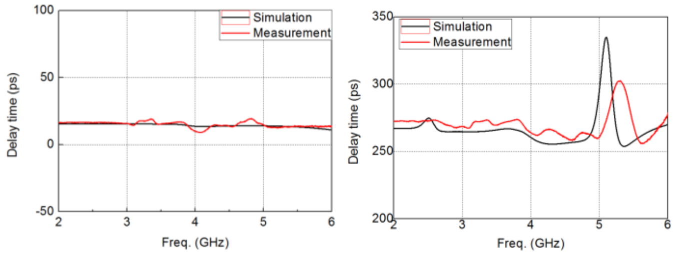
Phased array antennas increasingly find their application in wireless communication and radar systems [1]. One trend in wireless communication systems is the increasing bandwidth requirements [2]. Phased array antenna system with phase shifter is operated in narrowband because of beam squint phenomenon [2]. The wideband application necessitates the use of wideband TTDs for the phased array system. Switched-line configuration is most widely utilized when designing the TTD. In this paper, we present two primary factors that can affect the performance of a TTD of a switched line structure. First factor is off-state capacitor resonance which is occurred due to a switch with fair isolation characteristic for low insertion loss [3]. Second factor is GDV caused by reflected wave due to discontinuity [4].

This paper is organized as follows. Off-state capacitor resonance is shown in Section II. Section III presents group delay variation caused by reflected wave. Section IV concludes the paper with a brief summary.



(a) (b)

Fig. 1. (a) Conventional switched line, (b) switched line using cascaded switches.



(a) (b)

Fig. 2. CST simulation results and VNA measurement results of conventional switched line TTD with each state time delay difference of 15ps and 270ps.

II. Off-state Capacitor Resonance

Conventional switched line with single pole double throw (SPDT) switches is shown in Fig. 1, which can generate resonance if isolation of switches is around 15dB which is fair value of isolation. Long line past the off-state capacitor can be seen as parallel resonator by capacitive coupling. The signals of very small magnitude pass through off-switch capacitor but it becomes the reason of resonance and influences phase characteristic between input and output, so that group delay can be distorted. The resonance occurs when the electrical length of transmission line is an integral multiple of half wave length as

$$L_{resonance} = \frac{N\lambda}{2} \tag{1}$$

where N is a positive integer.

Conventional switched lines are designed and fabricated with two different delay time difference, 15ps and 270ps in Fig. 2 respectively to look into the off-switch capacitor resonance. Simulation has been done in CST Design Studio (DS) which is EM circuit Co-simulation tool. After EM simulation, total circuit simulation with S parameter measurement data of SPDT switches (S3P) is performed with fast time for precise results. SPDT switches, NJG1802K51 of New Japan Radio Company are used for design and measurement. This switches have fare isolation of 16dB at 6 GHz. Long line which has group delay difference of 15ps in (a) of Fig. 2 is shorter than half wave length at 6 GHz. Because the range of the S parameter measurement (S3P) of SPDT switches is up to 6 GHz, resonance is not observed in (a) of Fig. 2. On the other hand, resonance can be observed at around 5 GHz in case of a model with group delay difference of 270ps in (b) of Fig. 2.

Avoidance of off-switch resonance is key point of design of TTD lines. To solve this problem TTD using cascaded switches in Fig. 1 is proposed in [3]. To minimize degradation of TTD performance due to the resonances, switches with an off-state isolation of more than 30 dB are required.

III. Group Delay Variation

Phase distortion is observed by obtaining group delay (GD) parameter [5]. The definition of group delay, which was first introduced in 1930 and is widely used in various books, is the negative derivative of phase for angular frequency (ω) as follows [6]. The phase characteristics must have a linear slope in distortionless systems so that GD is constant for all frequencies. However, any nonlinear phase characteristic over the frequency range will result in group delay variations. For analysis the effects on the GD caused by reflected waves due to discontinuity and impedance mismatch, transmission line model with discontinuity is proposed as in Fig. 3. For simple analysis source impedance and load impedance are matched to Z_0, which means that $\Gamma_S = \Gamma_L = 0$. All of the reflected waves with different phases caused by discontinuity can be added or subtracted to affect phase of frequency response at port 2, resulting in GDV. Summation of all forward waves at the load, V_2^- can be expressed as

$$V_2^- = (V_1^+ e^{-\gamma_0 l_{01}} e^{-\gamma_1 l_1} e^{-\gamma_0 l_{02}} \mathrm{T}_1 \mathrm{T}_2) + (V_1^+ e^{-\gamma_0 l_{01}} e^{-\gamma_1 l_1} e^{-\gamma_0 l_{02}} \mathrm{T}_1 \mathrm{T}_2)(\Gamma_1 \Gamma_2 e^{-2\gamma_1 l_1}) + (V_1^+ e^{-\gamma_0 l_{01}} e^{-\gamma_1 l_1} e^{-\gamma_0 l_{02}} \mathrm{T}_1 \mathrm{T}_2)(\Gamma_1 \Gamma_2 e^{-2\gamma_1 l_1})^2 + \ldots \quad (3)$$

where V_1^+ is incident wave generated from a source, Γ_1 and Γ_2 are reflection coefficients at each ends of discontinuity and T_1 and T_2 are transmission coefficients at each ends of discontinuity. To obtain $\angle S_{21}$, S_{21} is calculated as

$$S_{21} = \frac{V_2^-}{V_1^+} = (e^{-\gamma_0 l_{01}} e^{-\gamma_1 l_1} e^{-\gamma_0 l_{02}} \mathrm{T}_1 \mathrm{T}_2)\left\{1 + (\Gamma_1 \Gamma_2 e^{-2\gamma_1 l_1}) + (\Gamma_1 \Gamma_2 e^{-2\gamma_1 l_1})^2 + \ldots\right\} = \frac{\mathrm{T}_1 \mathrm{T}_2 e^{-\gamma_0 l_{01}} e^{-\gamma_1 l_1} e^{-\gamma_0 l_{02}}}{1 - \Gamma_1 \Gamma_2 e^{-2\gamma_1 l_1}} = \frac{X}{1-Y} \quad . (4)$$

The GD can be expressed by obtaining negative derivative of $\angle S_{21}$ for angular frequency (ω) as

$$T_{GD} = -\frac{\partial \angle S_{21}}{\partial \omega} = -\frac{\partial \phi_X}{\partial \omega} - \frac{\partial \left(\tan^{-1}\left(\frac{|Y|\sin(\phi_Y)}{1-|Y|\cos(\phi_Y)} \right) \right)}{\partial \omega} \quad (5)$$

where ϕ_X and ϕ_Y are phase of X and Y respectively. $|Y|$ variation and phase variations of Γ_1, Γ_2, T_1 and T_2 with frequency can be neglected in practical cases and low-loss transmission lines and assuming that β_0, β_1 change linearly with frequency, we can obtain approximation equation of GD as

$$T_{GD} = T_0 + T_1 + T_1 \frac{2|Y|\cos\phi_Y}{1-2|Y|\cos\phi_Y} \quad (6)$$

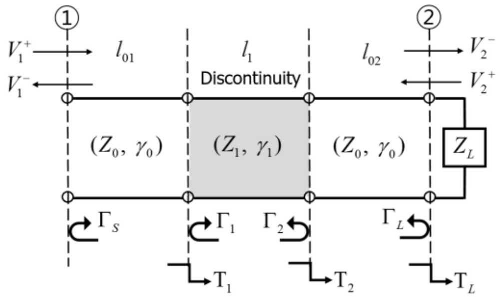


Fig. 3. The proposed transmission line model with discontinuity.

where $T_0 = \frac{d\beta_0}{d\omega} l_{01} + \frac{d\beta_0}{d\omega} l_{02}$ and $T_1 = \frac{d\beta_1}{d\omega} l_1$. Third term of (6) is GDV of reflected wave due to discontinuity in Fig. 3 as follow

$$T_{GDV} = T_1 \frac{2|Y|\cos\phi_Y}{1-2|Y|\cos\phi_Y} \quad . \quad (7)$$

IV. Conclusion

In design of TTDs, two primary factors which can affect the performance of a TTD of a switched line structure must be considered. First factor is off-state capacitor resonance and second factor is GDV caused by reflected waves due to discontinuity and impedance mismatch. The resonance can be generated by the small signals passed through off-switch capacitor, the isolation of switches is a key factor of TTD design. To avoid the resonance, cascaded switches can be used in TTD. GDV can be caused by reflected waves due to discontinuity and impedance mismatch, so matching of network is important in TTD design. Therefore, off-state capacitor resonance and GDV must be considered in TTD design.

Acknowledgment

The authors gratefully acknowledge the support from Electronic Warfare Research Center at Gwangju Institute of Science and Technology (GIST), originally funded by Defense Acquisition Program Administration (DAPA) and Agency for Defense Development (ADD).

References

[1] D. Parker and D. C. Zimmermann, “Phased arrays - part 1: theory and architectures,” Microwave Theory and Techniques, IEEE Transactions on, vol. 50, no. 3, pp. 678-687, 2002.

[2] Skolnik, Introduction to Radar Systems. Tata McGraw-Hill Education, 2003.

[3] M. Yoon and S. Nam, “Avoidance of off-switch resonance in true time delay line using cascaded switches,” 2016 URSI Asia-Pacific Radio Science Conference, pp. 719 - 720, 21-25 August 2016.

[4] A.R. Eskandari and L. Mohammadi, “Group delay variations in wideband transmission lines: analysis and improvement,” International Journal of Soft Computing Engineering (IJSCE), vol. 1, issue. 4, pp. 122-128, 2011.

[5] D. M. Pozar, Microwave Engineering, Third Edition, John Wiley & Sons, 2005.

[6] H. Nyqust and S. Brand, ″Measurement of phase distortion,″ Bell. Syst. Tech. J., vol. 9, no. 3, pp. 522–549, 1930.