Mathematical Analysis of Novel Low Phase Deviation Variable Attenuator

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***Abstract* — A conventional variable attenuator has phase deviation characteristics on an attenuation process. In this paper, a novel phase deviation compensating method in a variable attenuator design is proposed and analyzed mathematically. The proposed method uses a transmission line terminated with the PIN diode. By control characteristic impedance and electrical length of the transmission line, a trace of input reflection coefficient at the transmission line can be crossed the zero point of Smith chart on an attenuation process. The fabricated variable attenuator shows a 2.9° of phase deviation for 33 dB signal attenuation at 2.14 GHz. And the reflection characteristics also have measured less than -27 dB on the overall attenuation range.**

***Index Terms* — Attenuation, low phase deviation, PIN diode, transmission line, zero crossing.**

I. INTRODUCTION

The precise signal control is very important to maximize a number of mobile subscribers in the modern digital mobile-communication systems. The variable attenuator for the signal level control is especially one of the most important signal control blocks as well as the variable phase shifter for the signal phase control.

Generally, the conventional variable attenuator structures can be categorized into two types; T–type and π-type resistive circuit models. The variable resistivity can be implemented by using a dynamic conductance of PIN diode or the variable transconductance of GaAs MESFET according to electrically controllable currents [1]. Even though the GaAs MESFET can be used for a large signal level control, the control circuit of attenuator is complex and the overall variable attenuator is more expensive than the PIN diode attenuator. The PIN diodes have been widely used in a variety of microwave and radio frequency (RF) applications including antenna switches, phase shifters and attenuators. When the PIN diode is used in the variable attenuator, the attenuation is due to variation of junction resistance controlled by the forward bias current [1] [2]. In the previous several studies, various kinds of attenuator have been proposed. A defected ground structure transmission line and PIN diode were used to transform the impedance of the transmission line [3]. A hybrid attenuator was made by combination of a MESFET and PIN diodes [4]. The PIN diode controlled variable attenuator was employed a 0-dB branch line directional coupler [5].

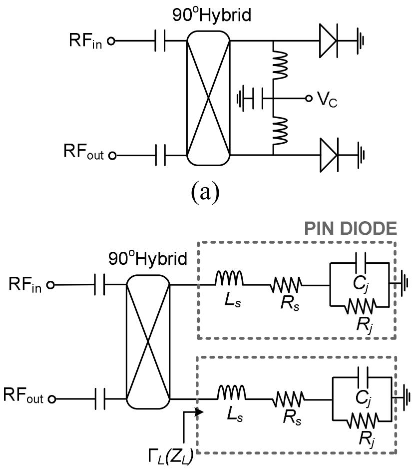
The phase deviation of attenuated signal is usually ignored which is due to nonlinear components of the PIN diodes and transistors. In order to maintain the fixed signal phase characteristics, another signal phase control process is required. Also, a lot of efforts to mitigate phase deviation of attenuator have performed, but the low phase deviation variable attenuator designs are not easy and the low phase deviation range is not broad [6]~[8].

In this paper, a novel low phase deviation variable attenuator is proposed. We can make the low phase deviation variable attenuator by employing the transmission line terminated with the PIN diode, which the transmission line makes the input reflection coefficient trace to cross zero point (“0”) on Smith chart. The transmission line characteristic impedance and its electrical length equations for the low phase deviation variable attenuator are derived mathematically and verified.

II. PROPOSED METHOD & MATHEMATICAL ANALYSIS

Fig. 1 shows the block diagram of the conventional reflective type variable attenuator using the PIN diodes and its equivalent circuit. A 3dB 90° hybrid is used to get good input/output reflection coefficient characteristics. In the reflective type circuits using 3 dB hybrid, the reflection coefficient of PIN diode is equivalent to the transmission coefficient (or signal attenuation) of the variable attenuator. As it can be seen from the equivalent circuit, parasitic components except a junction resistance (R_j) are causative of the phase deviation on signal attenuation. A load impedance (Z_L) and reflection coefficient (Γ_L) of the PIN diode can be expressed with (1) and (2).

$$Z_L = R_S + j\omega L_S + \frac{R_j}{1 + j\omega R_j C_j} = \left(R_S + \frac{R_j}{1 + (\omega R_j C_j)^2} \right) - j\left(\frac{\omega R_j^{\,2} C_j}{1 + (\omega R_j C_j)^2} - \omega L_S \right) \tag{1}$$

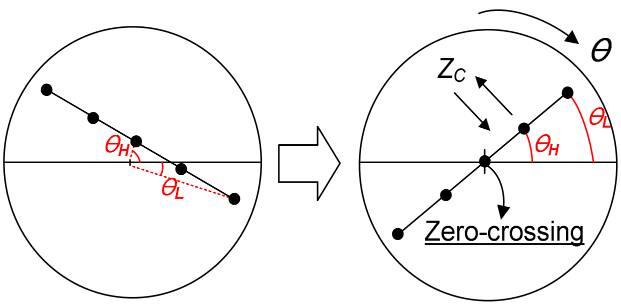


(a)

(b)

Fig. 1. Conventional reflective type variable attenuator using the PIN diode (a) block diagram and (b) equivalent circuit.

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{\left(R_S + \dfrac{R_j}{1+(\omega R_j C_j)^2} - Z_0\right) - j\left(\dfrac{\omega R_j^{\,2} C_j}{1+(\omega R_j C_j)^2} - \omega L_S\right)}{\left(R_S + \dfrac{R_j}{1+(\omega R_j C_j)^2} + Z_0\right) - j\left(\dfrac{\omega R_j^{\,2} C_j}{1+(\omega R_j C_j)^2} - \omega L_S\right)} \tag{2}$$

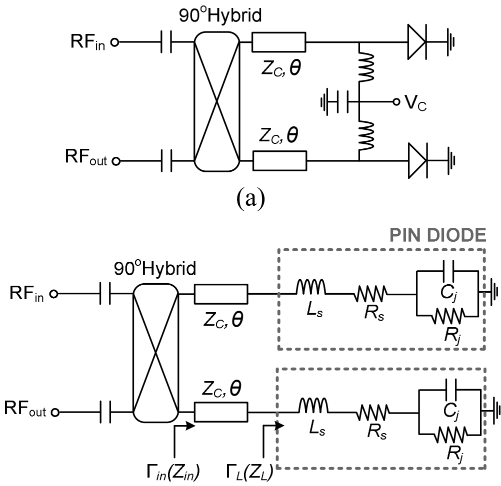


(a) (b)

Fig. 2. (a) Phase deviation characteristic of the reflection coefficient in the conventional reflective type variable attenuator and (b) phase trace of the phase compensating variable attenuator.

Fig. 2 (a) shows a magnified figure of conventional reflective type variable attenuator, where the minimum attenuation point is located the longest point from the zero point in Smith chart and the maximum attenuation point is the closest point. Since the Γ_L trace of the conventional variable attenuator does not pass through the zero point, it is obvious that there is a phase deviation (θ_L-θ_H) between the maximum and the minimum attenuation point. And this can be explained that the Γ_L is not a "zero-crossing". However, the phase deviation could be suppressed if the Γ_L trace is straight with the zero-crossing as Fig. 2 (b). This can be done with the transmission line terminated with PIN diode, which the characteristic impedance (Z_C) and electrical length (θ) of transmission line must be derived properly to zero-cross in Smith chart.

The block diagram of the proposed low phase deviation variable attenuator using the 3dB 90° hybrid and its equivalent circuit are shown in Fig. 3. The input impedance (Z_{in}) of transmission line terminated PIN diode is expressed in (3). Because the input reflection coefficient (Γ_{in}) must be zero-crossed, the Z_{in} must be matched on 50 + j0 Ω in one point among the overall Γ_{in} tracing points. The variables A and B are used to avoid complexity.



(a)

(b)

Fig. 3. (a) Block diagram of proposed a novel low phase deviation variable attenuator and (b) its equivalent circuit.

$$\begin{aligned} Z_{in} &= Z_C \frac{Z_L + jZ_C \tan\theta}{Z_C + jZ_L \tan\theta} \\ &= Z_C \frac{\left[A(Z_C + B\tan\theta) - (B - Z_C\tan\theta)A\tan\theta\right]}{(Z_C + B\tan\theta)^2 + (A\tan\theta)^2} \\ &\quad - \frac{j\left[(B - Z_C\tan\theta)(Z_C + B\tan\theta) + A^2\tan\theta\right]}{(Z_C + B\tan\theta)^2 + (A\tan\theta)^2} \end{aligned} \tag{3}$$

where $A = R_S + \dfrac{R_j}{1+(\omega R_j C_j)^2}$ and $B = \dfrac{\omega R_j^{\,2} C_j}{1+(\omega R_j C_j)^2} - \omega L_S$.

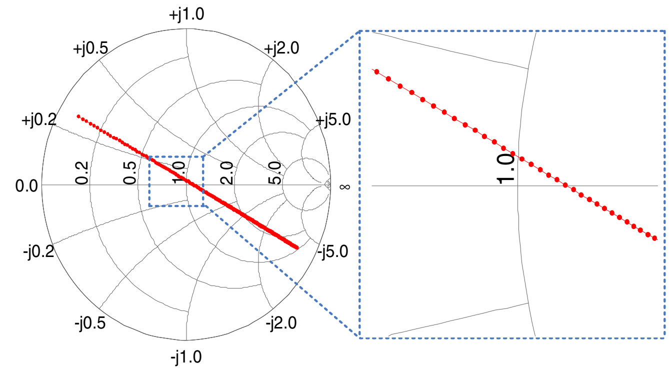
The equation (4) and (5) are the modified real and imaginary part of (3) to satisfy 50 + j0 Ω, where unknown variables are the characteristic impedance (Z_c) and electrical length (θ) of transmission line. Two equations can be solved simultaneously using a MATLAB mathematical analysis program. The characteristic impedance of 87.8 Ω and the electric length of 62.6° are obtained for the zero-crossing of Γ_{in}. The used diode for a simulation is HSMP-4810 of Avago and the parasitic components L_s=1 nH, are R_s=3 Ω, and C_j=0.35 pF, respectively.

$$-\boldsymbol{B}\boldsymbol{Z_C}\tan^2\boldsymbol{\theta} + (\boldsymbol{B}^2 - \boldsymbol{Z_C}^2 + \boldsymbol{A}^2)\tan\boldsymbol{\theta} + \boldsymbol{B}\boldsymbol{Z_C} = 0 \tag{4}$$

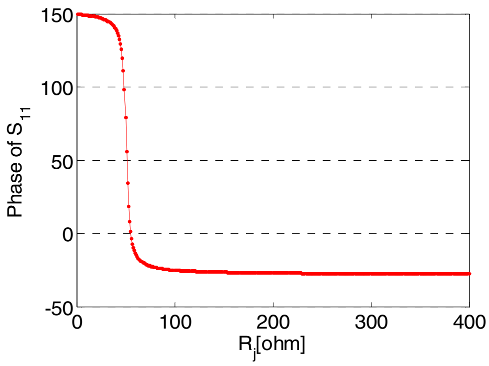
$$(AZ_C^2 - 50A^2 - 50B^2)\tan^2\theta - 100Z_C B\tan\theta + AZ_C^2 + 50Z_C^2 = 0 \quad (5)$$

III. Simulation

Using the MATLAB, the Γ_L trace of the PIN diode can be simulated and shown in Fig. 4 according to R_j variation. Fig. 4 (a) shows the Γ_L drawn on Smith chart and the phase deviation of the Γ_L is expressed in Fig. 4 (b). Even though a broad attenuation can be obtained, the phase deviation of the attenuated signal is also serious. Although a trace on Fig. 4 (a) is a straight line, but does not pass through the centre of Smith chart. This phenomenon is due to the parasitic components of PIN diode.



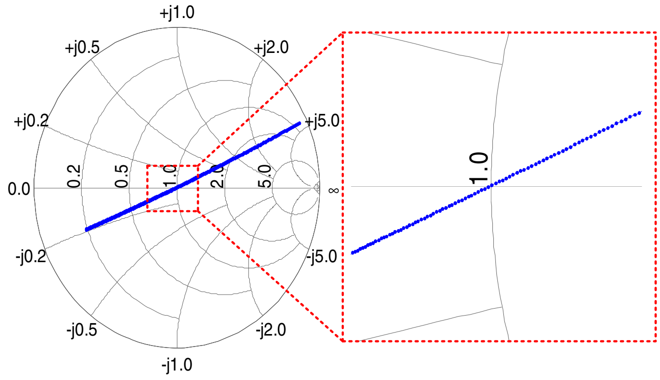
(a)



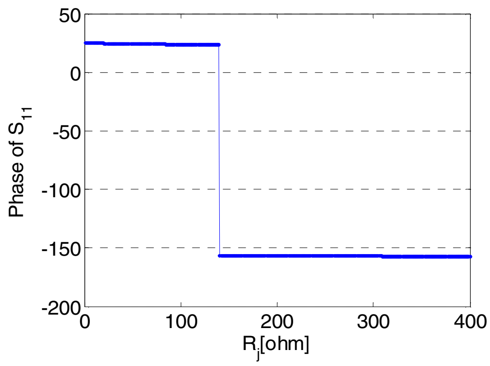
(b)

Fig. 4. Simulation result according to junction resistance variation: (a) Reflection coefficient trace of PIN diode (HSMP-4810) and (b) phase deviation.

Fig. 5 shows the simulated Γ_{in} trace of the transmission line terminated with the PIN diode according to the R_j variation in Smith chart and its phase deviation characteristics with the selected transmission line information (Z_c=87.8 Ω and θ=62.6°). Fig. 5 (a) shows that the Γ_{in} trace is zero-crossing and straight. Fig. 5 (b) shows almost constant phase on the overall R_j variation.



(a)



(b)

Fig. 5. Simulation results of the proposed low phase deviation variable attenuator according to junction resistance variation: (a) Reflection coefficient trace on Smith chart and (b) phase deviation.

IV. Measurement

To show validity of the phase deviation compensating method, the conventional and the proposed reflective type variable attenuator are fabricated and compared. The operating frequency is a wideband code division multiple access down-link frequency band around 2.14 GHz. The used substrate is a teflon of Rogers, where the thickness (h) and the permittivity (ε_r) are 31 mils and 2.2, respectively.

Fig. 6 shows the measurement results of the conventional and the proposed variable attenuator. The conventional attenuator shows the phase deviation of 85° for the signal attenuation of 22 dB, whereas the proposed attenuator shows the phase deviation of 2.9° on the signal attenuation of 35 dB. The return loss (S_{11}) of the proposed low phase deviation variable attenuator is less than -27 dB on the overall attenuation range. And its control voltage range is 0 ~ 0.7 V. These measurement results indicate that the proposed transmission line attached on the PIN diode can compensate the phase deviation of the conventional variable attenuator using the PIN diode properly. Fig. 7 shows a photograph of the fabricated low phase deviation variable attenuator, which size is 24 × 58 mm^2.

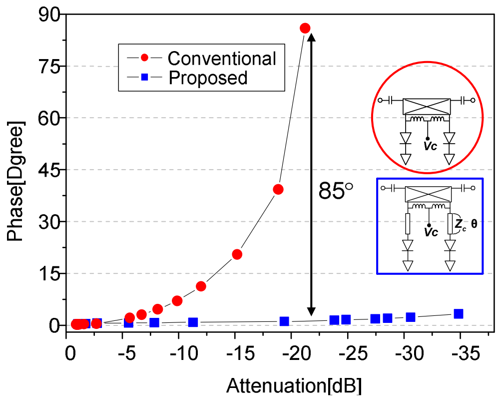


Fig. 6. Comparison of phase deviation measurement results between the conventional and the proposed variable attenuator.


Fig. 7. The photograph of the fabricated a novel low phase deviation variable attenuator.

V. Conclusion

In this paper, we have proposed the novel low phase deviation variable PIN diode attenuator. By just only adoption the transmission line to obtain the zero-crossing reflection coefficient, the phase deviation of the conventional variable attenuator using the PIN diode can be suppressed. We have derived the general equations of transmission line to obtain the characteristic impedance and its electrical length. The measurement result shows very low phase deviation on the overall attenuation range. The novel low phase deviation variable attenuator can be applicable to the required the large dynamic signal attenuation range. Also if the proposed attenuator is used in vector modulators in the microwave circuit applications, the signal control time can be reduced effectively.

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