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DESIGN OF VECTOR MODULATOR USING LOW PHASE DEVIATION ATTENUATORS WITH LARGE AMPLITUDE VARIATIONS RANGE

G. Chaudhary and Y. Jeong[*]

Division of Electronics and Information Engineering, IT Convergence Research Center, Chonbuk National University, 567 Baekje-Daero, Deokjin-Gu, Jeonju 561-756, Republic of Korea

Abstract—In this paper, a novel vector modulator (VM) that precisely controls the magnitude and phase of input signals simultaneously is proposed. The proposed VM consists of low phase deviation attenuators, a 90° hybrid splitter, and Wilkinson power combiner. In order to overcome the phase deviation characteristics found in the conventional attenuators, the novel phase compensation technique has been adopted and mathematically analyzed. Linear vector arrays along the center point with large signal magnitude variations in a full 360° phase control are achieved on a polar plane by the proposed VM.

1. INTRODUCTION

Multiple input multiple output (MIMO) systems can provide a higher spectral efficiency and higher effective signal to noise ratio (SNR), so consequently a higher data throughput [1]. However, the performance of MIMO systems is severely affected by an imprecise magnitude and phase control of the signals in each antenna path [2–4]. Recently, various methods such as genetic algorithms and adaptive theory are applied to antenna array for beam-forming and sidelobe rejection [5–11].

The VM is an RF or microwave circuit which can control both the magnitude and phase of transmitted signal simultaneously. With the proper magnitude and phase control obtained by using the VM, the precise beam-forming and unwanted antenna sidelobe rejection can be obtained. The VM is one of key circuits in the radar and linearized

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[*] Corresponding author: Yongchae Jeong (ycjeong@jbnu.ac.kr).

power amplifier systems using a feedforward technique in modern wireless communication systems [12]. The VM is also applicable to different applications such as cancellation of unwanted jamming signals, nulling of antenna reflections in monostatic radar systems, linear filter equalizer, quadrature amplitude modulation and so on.

Several approaches have been proposed in the VM design including variable phase shifter, attenuator [13, 14] and gain controlled amplifiers [15, 16]. These VM designs exhibit some drawbacks, such as the difficulties found in designing high performance variable attenuators with a low phase deviation and variable phase shifters with a constant output signal magnitude. The VM presented in [13] has a huge footprint due to the required phase shifters and attenuators. Another approach is based on reflection-type balanced modulators [15, 16], but it requires a large number of passive distributed combining components, leading to large circuit size requirements even for high operating frequencies. Recently, various studies and researches are going on the field of high frequency (THz) metamaterials which can be used to design in VM for THz applications [17–20].

This paper presents a VM using low phase deviation attenuators. A novel phase compensation method is used in the attenuator to reduce the large phase deviation characteristics found in conventional attenuators. The conventional attenuator with the large phase deviation usually requires the additional phase compensation circuit.

2. MATHEMATICAL ANALYSIS

Figure 1(a) shows the structure of the proposed VM. It consists of a 90° hybrid splitter, low phase deviation attenuators, and Wilkinson power combiner. The 90° hybrid splitter divides the input signal into the in-phase (I, 0°) and quadrature (Q, -90°) components. The low phase deviation attenuators control the signal magnitude and polarity in each I and Q path. The attenuated orthogonal I and Q signals are constructively combined by the Wilkinson power combiner. Mathematically, the output of the VM is:

$$\mathrm{RF_{out}} = \alpha I\angle{-90^\circ} + \beta Q\angle{-180^\circ} \tag{1}$$

where α and β are less than 1.

Figure 2 shows the equivalent circuit of the conventional and proposed low phase deviation attenuators. The input impedance Z_L of conventional attenuator looking into PIN diode as shown in Fig. 2(a) is given as:

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

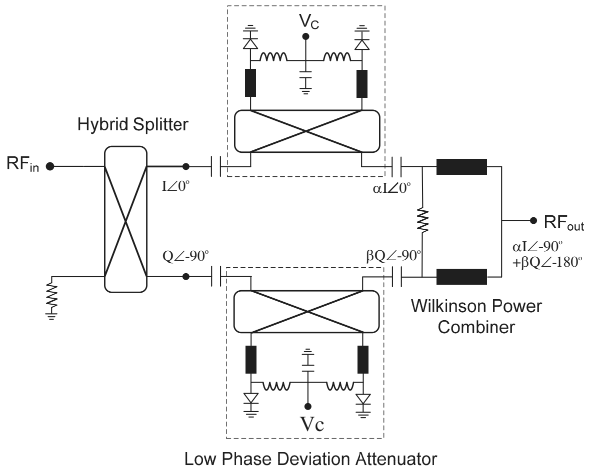
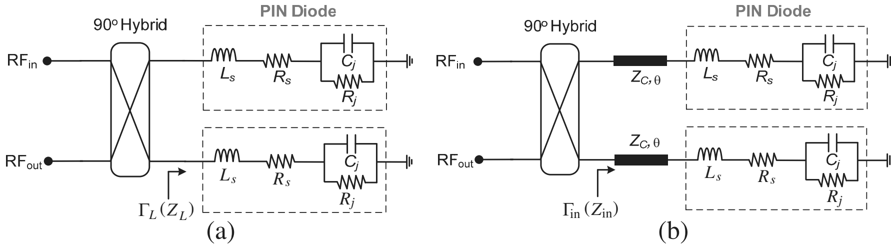


Figure 1. The proposed structure of vector modulator.



(a) (b)

Figure 2. Equivalent circuit of (a) conventional attenuator and (b) proposed the low phase deviation variable attenuator.

Similarly, as described in [21], the input impedance Z_{in} when looking into the transmission line terminated with a PIN diode as shown in Fig. 2(b) is given as:

$$\begin{aligned} Z_{\text{in}} &= Z_c A \frac{(Z_c + B\tan\theta) - (B - Z_c\tan\theta)\tan\theta}{(Z_c + B\tan\theta)^2 + (A\tan\theta)^2} \\ &\quad - j\frac{(Z_c + B\tan\theta)(B - Z_c\tan\theta) + A^2\tan\theta}{(Z_c + B\tan\theta)^2 + (A\tan\theta)^2} \end{aligned} \tag{3}$$

where the values of A and B are:

$$A = R_s + \frac{R_j}{1 + (\omega R_j C_j)^2}, \quad B = \frac{\omega C_j R_j^2}{1 + (\omega R_j C_j)^2} - \omega L_s \tag{4}$$

In order to obtain the zero input reflection coefficients on Smith chart, Z_{in} must be matched with $Z_0 + j0\,\Omega$ by:

$$-\left(AZ_c^2-Z_0A^2-Z_0B^2\right)\tan^2\theta-2Z_0Z_cB\tan\theta+AZ_c^2+Z_0Z_c^2=0 \tag{5}$$

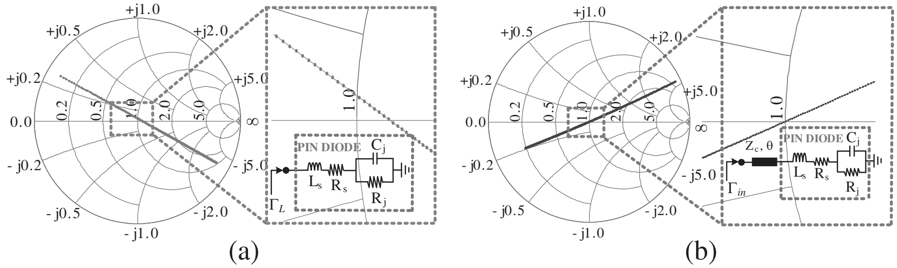
$$-BZ_c\tan^2\theta+\left(B^2-Z_c^2+A^2\right)\tan\theta+BZ_c=0 \tag{6}$$

With these conditions, the characteristic impedance and electrical length of transmission line at the zero crossing point on Smith chart can be found by simultaneously solving (5) and (6).

In order to show the validity of the mathematical analysis of the proposed low phase deviation attenuator, the input reflection coefficient (Γ_{in}) looking into the transmission line terminated with PIN diode are plotted through MATLAB and compared with the load reflection coefficient (Γ_L) looking into just PIN diode only as like Fig. 2. The equivalent circuit parameters of Avago HSMP-4810 PIN diode were used, whose values are given as $L_s = 1\,\text{nH}$, $R_s = 3\,\Omega$ and $C_j = 0.35\,\text{pF}$. With $Z_0 = 50\,\Omega$, the calculated characteristic impedance and electrical length of the transmission line at the center frequency of 2.14 GHz are 87.8 Ω and 62.6°, respectively.

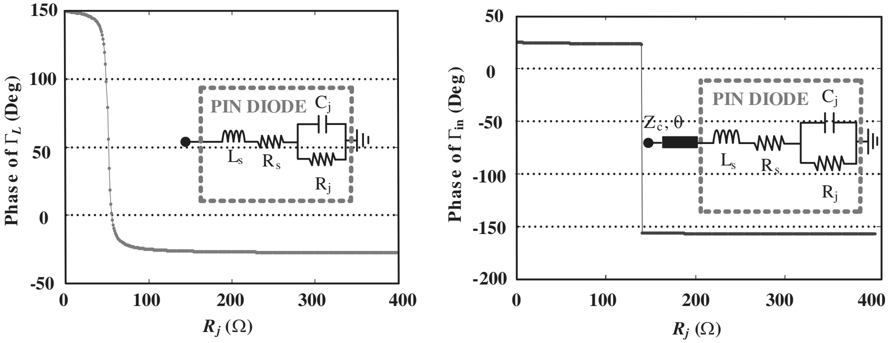
Figure 3(a) shows Γ_L trace of the PIN diode according to the R_j variation. Although the Γ_L trace looks like a straight line passing through the origin, it does not pass through the center point of Smith chart shown in the magnified portion of the figure. As a result, the phase response of the Γ_L according to R_j is not constant as shown in Fig. 4(a). It is due to the parasitic components found in the PIN diode.

Figure 3(b) shows the Γ_{in} trace of the proposed attenuator. The Γ_{in} trace follows a straight line and passes through the center point of Smith chart, shown in the magnified portion of the figure. The phase response of the Γ_{in} according to R_j is shown in Fig. 4(b), which is practically constant over all of the variations of R_j. This result is due to the fact that the transmission line terminated with the PIN



(a) (b)

Figure 3. The simulated reflection coefficient according to the junction resistance: (a) looking into the PIN diode and (b) looking into the transmission line terminated with PIN diode.



(a) (b)

Figure 4. The simulated phase response of the reflection coefficient: (a) the conventional attenuator and (b) the proposed low phase deviation attenuator.

diode compensates for the effect of the parasitic components of the PIN diode. An advantage of the proposed attenuator over the conventional attenuators in [12, 13] is that it can provide dual reverse polarities as well as the constant phase characteristics.

3. THE EXPERIMENTAL RESULTS

In order to show the validity of the proposed VM, the reflection type low phase deviation attenuator was designed and fabricated for frequency band operating at $1.99 \sim 2.29$ GHz with a center frequency of 2.14 GHz and compared with the conventional attenuator. A Rogers Corporation RT/Duroid 5880 substrate with a dielectric constant (ε_r) of 2.2 and a thickness (h) of 31 mils was used.

The measured phase deviation characteristics of the conventional and proposed attenuators are shown in Fig. 5. The conventional attenuator has a phase deviation of 86° for 22 dB signal attenuation, whereas the proposed attenuator has only a 2.9° phase deviation for 37 dB signal attenuation. The input and output return losses of the proposed attenuator are better than 27 dB in the overall attenuation range, respectively.

Based on the novel low phase deviation attenuator presented in the above section, the VM was designed for frequency band operating at $1.99 \sim 2.29$ GHz. The measured magnitude and phase variation of the proposed vector modulator in the linear plane are shown in Fig. 6. The amplitude and the phase variation are constant over the frequency range of $1.99 \sim 2.29$ GHz.

The measured data arrays from the proposed VM are shown in Fig. 7 on the polar plane. The constellation states of the VM are straight lines passing through the center point of Smith chart. These results were obtained by sweeping the attenuator voltages in the I and Q paths of the VM. The measured input return loss (S_{11}) and the output return loss (S_{22}) were better than 27 dB and 20 dB, respectively, in over all of the control ranges. The photograph of fabricated VM is shown in Fig. 8. The overall circuit size of the fabricated VM is $6 \times 10\,\mathrm{cm}^2$.

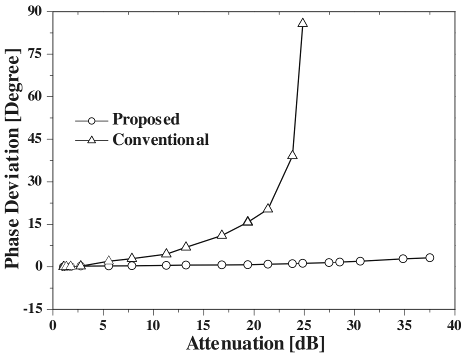
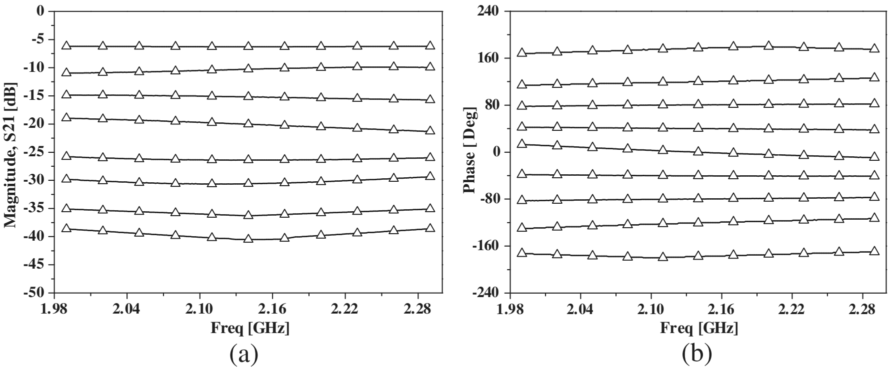


Figure 5. Comparison of phase deviation characteristics of conventional and proposed attenuators.



(a) (b)

Figure 6. The measured (a) magnitude and (b) phase variation of the proposed vector modulator in the linear plane over the frequency range of 1.99 $\sim$ 2.29 GHz.

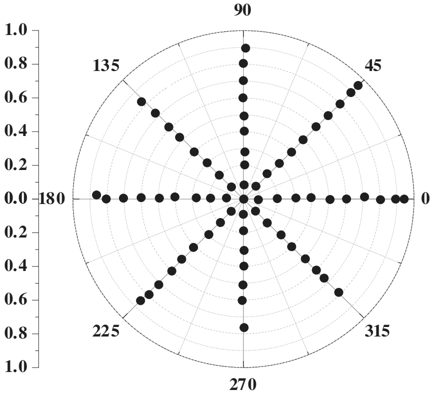


Figure 7. The measured array for the proposed vector modulator in the polar plane.

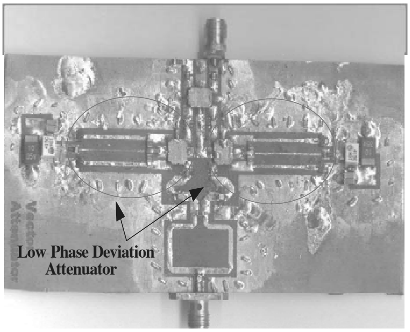


Figure 8. The fabricated vector modulator.

4. CONCLUSION

In this paper, a vector modulator design employing the novel low phase deviation attenuators is presented. The proposed low phase deviation attenuator overcomes the large phase deviation characteristics found in the conventional attenuators, which is one of the critical design issues in vector modulator design. The proposed vector modulator contributes considerably to the precise control of the magnitude and phase of input signals with large magnitude variations in the 360° phase control range. The proposed vector modulator is expected to be applicable to multiple input multiple output systems, the linearization circuits of power amplifiers, jamming cancellation system, monostatic radar systems, linear filter equalizer, and quadrature amplitude modulation.

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