A Novel Three Phase-States Phase Shifter

K.Nakahara, S.Chaki, N.Andoh, H.Matsuoka,
N.Tanino, Y.Mitsui, M.Otsubo and S.Mitsui

Optoelectronic and Microwave Devices Laboratory
Mitsubishi Electric Corporation
4-1, Mizuhara, Itami, Hyogo 664 Japan

ABSTRACT

A novel compact phase shifter switching three phase-states has been demonstrated. The novel phase shifter circuit is constructed by adding switching FETs to a conventional single-stage 2-phase-states phase shifter. A conventional 3-stage 2-phase-state phase shifter can be replaced by the novel 2-stage 3-phase-state phase shifter. The total chip size of the newly developed phase shifter is reduced to 2/3 of the conventional one. This paper reports on the design and the experimental results of the novel reflection and loaded-line types phase shifter MMICs.

INTRODUCTION

Various types of multi-bits digital phase shifter have been developed. The most popular type is reflection/loaded-line type. This configuration is superior to other configuration such as low-pass/high-pass because of both high phase-accuracy and low insertion-loss. However,the disadvantage is its larger chip size.

This paper presents a novel phase shifter of reflection/loaded-line type, which adds one more phase state to conventional 2 phase states.

By cascading several 3-phase-states phase shifters, the total chip size is successfully reduced to 2/3 of a conventional one. The experimental results is also presented.

CIRCUIT DESIGN

(1) Reflection - type phase shifter

The S_{21} of a reflection-type phase shifter consisting of a 3 dB coupled line and lossless terminating networks is expressed as[1];

$$S_{21} = -j\Gamma_T = -j\frac{jX_T - 1}{jX_T + 1} \qquad (1)$$

$$\angle S_{21} = \mathrm{Arctan}\left(\frac{1 - X_T^2}{2X_T}\right) = \frac{\pi}{2} - \theta \qquad (2)$$

where Γ_T and $X_T (= \tan\theta)$ are the reflection coefficient and the normalized reactance of a terminating network respectively.

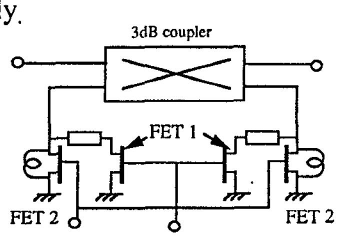


Figure 1 Schematic circuit diagram of a reflection-type phase shifter

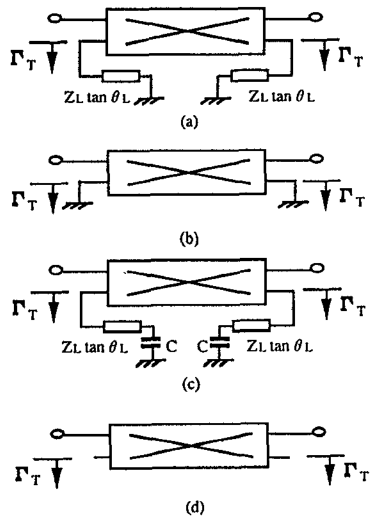


Figure 2 Equivalent circuit diagram of the refrection-type phase shifter corresponding to each phase state

OF1

Figure 1 shows a schematic diagram of a novel reflection-type phase shifter. The phase shifter has 4 phase-states. The terminating network consists of a transmission line terminated by a switching FET1 and a switching FET2 which is connected in parallel with an inductor to make a resonant circuit with the drain-to-source capacitance C_{DS} of the FET2.

Figure 2 shows four equivalent circuits corresponding to each phase-state of the phase shifter shown in Fig.1.

Case a : $\angle S_{21}$ is $\frac{\pi}{2}-\frac{\phi}{2}$.

In this case, FET1 is on state, and FET2 is off state. The impedance Z_L and the electrical length θ of the transmission line should be determined from Eq.3.

$$X_T=Z_L\tan\theta_L=\tan\left(\frac{\phi}{4}\right) \qquad (3)$$

Case b : $\angle S_{21}$ is $\frac{\pi}{2}$.

In this case, FET2 is on and X_T is zero.

Case c : $\angle S_{21}$ is $\frac{\pi}{2}+\frac{\phi}{2}$.

In this case, both FET1 and FET2 are off.The drain-to-source capacitance C_{DS} of the FET1 should be determined from Eq.4.

$$X_T=Z_L\left(\frac{\frac{-1}{\omega C}+Z_L\tan\theta_L}{Z_L+\frac{1}{\omega C}\tan\theta_L}\right)=\tan\left(-\frac{\phi}{4}\right) \qquad (4)$$

Case d : $\angle S_{21}$ is $-\frac{\pi}{2}$. X_T is $-\infty$

The schematic circuit diagram of the reflection-type phase shifter (TYPE 1) is shown in Fig.3. Figure 4 shows the phasor diagram of the phase shifter (TYPE 1). As shown in Fig.4, three phase-states (45,90,135 deg.) can be obtained.

The schematic circuit diagram of the another reflection-type phase shifter(TYPE 2) is shown in Fig.5 and Fig. 6 respectively. The attainable three phase-states are 45,135,270 deg.

Connecting two phase shifters in series, the

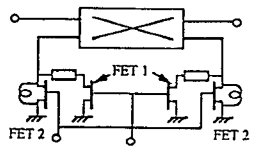
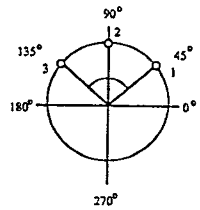


Figure 3 Schematic circuit diagram of the refrection- type phase shifter (3 states :TYPE 1)



Case	FET 1	FET 2	∠S21	Schematic for phase shifter
a	on	off	45°	$Z_L\tan\theta_L$ $Z_L\tan\theta_L$
b	on	on	90°	
c	off	off	135°	$Z_L\tan\theta_L$ C C $Z_L\tan\theta_L$

Figure 4 Phasor diagram for the refrection- type phase shifter (TYPE 1)

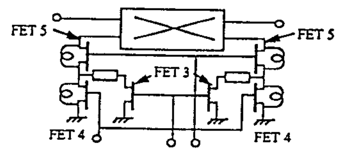
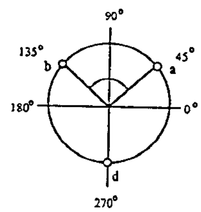


Figure 5 Schematic circuit diagram of the refrection- type phase shifter (3 states :TYPE 2)



Case	FET 3	FET 4	FET 5	∠S21	Schematic for phase shifter
a	on	off	on	45°	$Z_L\tan\theta_L$ $Z_L\tan\theta_L$
b	off	off	on	135°	$Z_L\tan\theta_L$ C C $Z_L\tan\theta_L$
d	on	off	off	270°	

Figure 6 Phasor diagram for the refrection-type phase shifter (TYPE 2)

phasor diagram shown in Fig.7(b) can be obtained. For comparison, a conventional 3-bit 2-phase-states reflection type phase shifter is shown in Fig.7(a). The phase-state sets corresponding to {0, 90, 225deg} and {45, 135, 180, 270deg}are obtained by TYPE 2 and TYPE1 respectively.

The chip size of a conventional reflection-type phase shifter is determined by the 3dB coupler which has quarter-wave long. Since the switching FET circuits are very small compared to the 3dB coupler, the chip size of the novel phase shifter is almost the same as conventional one. Therefore, the chip size can be reduced to 2/3 of the conventional one.

(2) Loaded-line-type phase shifter

Figure 8 (a) shows a schematic diagram of a conventional loaded-line-type phase shifter.

The S_{21} of a loaded-line-type phase shiter is expressed as [2]

$$S_{21} = \frac{1}{-B_i Z_C + jZ_C Y_o} \qquad (5)$$

where B_i is susceptance of switching FET and Z_C is characteristic impedance of a transmission line.

The phase angle of S_{21} is

$$\angle S_{21} = \mathrm{Arctan}\left(\frac{Y_o}{B_i}\right) \qquad (6)$$

If it is assumed $B1 = -B2$, the phase is switched symmetrically about $90°$. The capacitance of off-state FET1 becomes

$$\omega C = \frac{1 - \tan^2 \theta_L}{2 Z_L \tan^2 \theta_L} \qquad (7)$$

The novel loaded-line-type phase shifter has one more phase state by adding a switching FET. The schematic diagram of the novel loaded-line-type phase shifter is shown in Fig. 8 (b).

Figure 9 shows the phasor diagram of the loaded-line-type phase shifter. As shown in Fig.9 three phase-states ($\frac{\pi}{2}-\frac{\phi}{2}$, $\frac{\pi}{2}$, $\frac{\pi}{2}+\frac{\phi}{2}$) can be obtained.

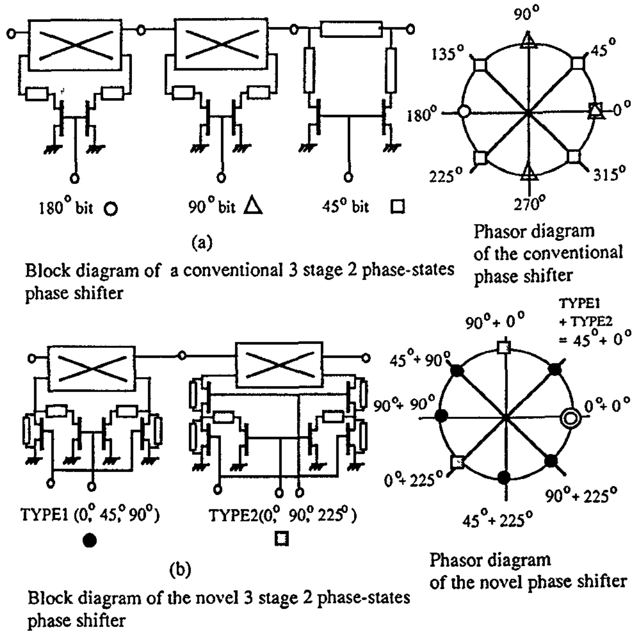


Figure 7 Block diagram of 3bit phase shifter

(a) Block diagram of a conventional 3 bit 2 phase-states phase shifter

(b) Block diagram of the novel 3 bit 2 phase-states phase shifter

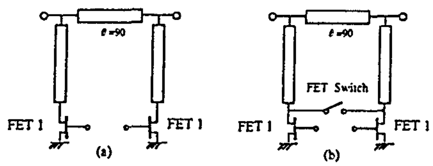
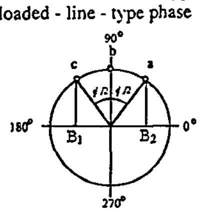


Figure 8 Schematic circuit diagram of loaded-line-type phase shifters

(a) the conventional loaded - line - type phase shifter

(b) the novel loaded - line - type phase shifter



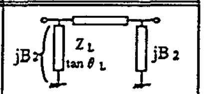
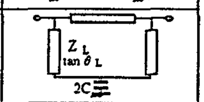
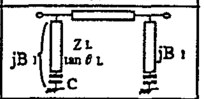
Case	FET 1	FET SW	∠S21	Schematic for phase shifter
a	on	off	$\frac{\pi}{2}-\frac{\phi}{2}$	
b	off	on	$\frac{\pi}{2}$	
c	off	off	$\frac{\pi}{2}+\frac{\phi}{2}$	

Figure 9 Phasor diagram for the loaded-line- type phase shifter

EXPERIMENTAL RESULTS

In Fig.10, newly developed two types of three phase-states reflection-type phase shifters and a conventional 22.5,11.25 bit loaded-line-type phase shifter are integrated into one chip, which operates at X-band. The chip size is 4.0 mm x 5.0 mm.

The measured phase performance and insertion loss of the 5 bit phase shifter is shown in Fig. 11, 12 respectively. The maximum RMS phase error is 10.2 and the maximum insertion loss is 8.3dB over a 10% bandwidth.

The measured phase performance of the 3-phase-states loaded-line-type phase shifter is shown in Fig. 13.

CONCLUSION

The novel 3-phase-state reflection/loaded-line-type phase shifter has been developed. The new configuration can achieve 3-phase-state just adding switching FETs to a conventional single-stage 2-phase-state phase shifter. The chip size was successfully reduced to 2/3 of a conventional one.

<Reference>

[1] Joseph F.White,Microwave Semiconductor Engineering, New York :Van Nostrand Reinhold Company Inc, 1982

[2] Harry A.Atwater,"Circuit Design of the Loaded-Line Phase Shifter,"IEEE Trans.Microwave Theory Tech.,vol.MTT-33, pp626-634,Jury 1985

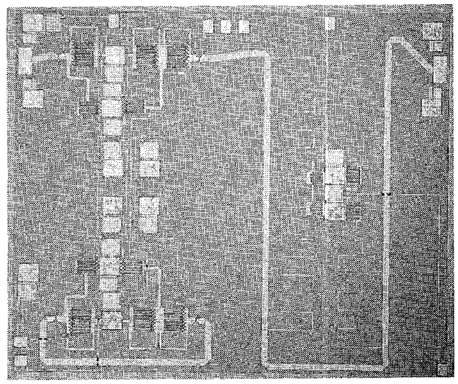


Figure 10 Microphotograph of the novel 5bit phase shifter

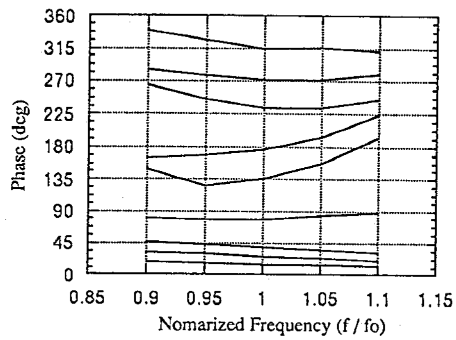


Figure 11 Measured phase performance of the 5bit phase shifter

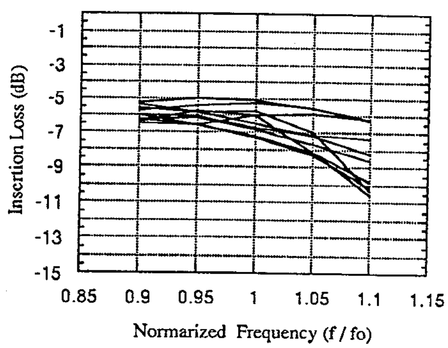


Figure 12 Measured insertion loss of the 5bit phase shifter

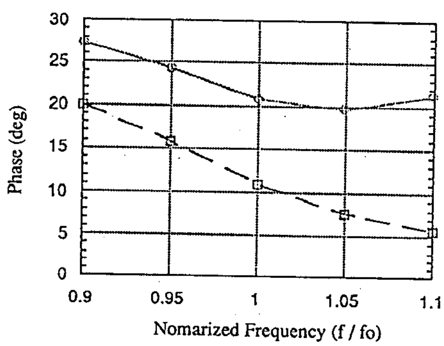


Figure 13 Measured phase performance of the novel loaded-line-type phase shifter (22.5/11.25deg.)