An Ultra Broad Band Reflection Type 180^o Phase Shifter with Series and Parallel LC Circuits

Kenichi MIYAGUCHI, Morishige HIEDA, Kazuhiko NAKAHARA, Hitoshi KURUSU*, Masatoshi NII**, Michiaki KASAHARA, and Tadashi TAKAGI

Information Technology R&D Center, Mitsubishi Electric Corp.
5-1-1 Ofuna, Kamakura-city, Kanagawa 247-8501, Japan
e-mail: k-miya@isl.melco.co.jp
*High Frequency & Optical Semiconductor Division, Mitsubishi Electric Corp.
**Communication Systems Center, Mitsubishi Electric Corp.

Abstract — **An ultra broad band reflection type 180^o phase shifter is proposed. It is composed of a 3-dB Lange coupler and a pair of novel reflective terminating circuits. The reflective terminating circuit switches two states of series and parallel LC circuits and it can achieve an 180^o phase difference independently of frequency. Using a simplified circuit model without parasitic circuit elements, we have derived the determining condition of circuit elements to achieve 180^o phase difference for all frequencies. The fabricated reflective terminating circuit MMIC has achieved a phase difference of 183 +/- 3^o over 0.5 to 30 GHz. The 180^o phase shifter MMIC has demonstrated a phase shift of 187 +/- 7^o over 0.5 to 20 GHz band.**

I. INTRODUCTION

Recently, phase shifters have been widely used in Active Phased Array Antenna for beam steering. There are various kinds of phase shifters such as switched line type, loaded line type, high-pass/low-pass filter type and reflection type [1]-[2]. The reflection type phase shifter, which consists of 3-dB hybrid coupler and a pair of reflective terminating circuits through impedance transformers, is able to operate in a relatively wide frequency range. But, it still has a restriction of operating band width because of poor frequency characteristics of the impedance transformers [3].

We have devised an ultra broad band reflection type 180^o phase shifter which is composed of a broad band 3-dB Lange coupler and a pair of novel reflective terminating circuits. The reflective terminating circuit switches two states of series and parallel LC circuits and it can achieve an 180^o phase difference characteristics independently of frequency. Using a simplified circuit model without parasitic circuit elements, we have derived the theoretical condition of the circuit elements to achieve 180^o phase difference independently of frequency. The reflective terminating circuit and the 180^o phase shifter have been designed and fabricated by 0.5um p-HEMT MMIC technology. The reflective terminating circuit MMIC has achieved a phase difference of 183 +/- 3^o over 0.5 to 30 GHz. The 180^o phase shifter MMIC has demonstrated a phase shift of 187 +/- 7^o over 0.5 to 20 GHz frequency band.

II. THEORY

Figure 1 shows a schematic diagram of a reflection type phase shifter. It consists of a broad band 3-dB hybrid coupler and a pair of reflective terminating circuits. Figure 2 shows a schematic diagram of a novel reflective terminating circuit. In figure 2, Ls and Cs correspond to inductor and capacitor of series LC circuit, while Lp and Cp are inductance and capacitance of parallel LC circuit, respectively. The reflective terminating circuit switches series and parallel LC circuits by switching circuit.

Reflection coefficients Γs and Γp of series and parallel LC circuits are given by

$$\Gamma_S = \left|\Gamma_S\right| e^{j\phi_S} = \frac{Z_S - Z_0}{Z_S + Z_0} \tag{1}$$

$$\Gamma_P = \left|\Gamma_P\right| e^{j\phi_P} = \frac{Z_P - Z_0}{Z_P + Z_0} \tag{2}$$

where

$$Z_S = j\omega L_S + \frac{1}{j\omega C_S} \tag{3}$$

$$Z_P = \frac{1}{\frac{1}{j\omega L_P} + j\omega C_P} \tag{4}$$

In equation (1)-(4), Z_S and Z_P are the impedance of series and parallel LC circuits, and Φs and Φp are the reflection phase of series and parallel LC circuits, respectively. Z_0 is the impedance of 3-dB hybrid coupler. Using equation (1) and (2), Φs and Φp can be written as

$$\phi_S = \tan^{-1}\frac{2Z_0\left(\omega L_S - \frac{1}{\omega C_S}\right)}{\left(\omega L_S - \frac{1}{\omega C_S}\right)^2 - Z_0^2} \quad (5)$$

$$\phi_P = \tan^{-1}\frac{2Z_0\left(\frac{1}{\omega L_P} - \omega C_P\right)}{1 - Z_0^2\left(\frac{1}{\omega L_P} - \omega C_P\right)^2} \quad (6)$$

Phase difference Φ is defined by the following equation

$$\begin{aligned}\phi &= \phi_S - \phi_P \\ &= \tan^{-1}\frac{2Z_0\left(\omega L_S - \frac{1}{\omega C_S}\right)}{\left(\omega L_S - \frac{1}{\omega C_S}\right)^2 - Z_0^2} - \tan^{-1}\frac{2Z_0\left(\frac{1}{\omega L_P} - \omega C_P\right)}{1 - Z_0^2\left(\frac{1}{\omega L_P} - \omega C_P\right)^2}\end{aligned} \quad (7)$$

In order to obtain a broad band phase shift characteristic, Φ has to satisfy the following condition for all frequencies

$$\frac{d\phi}{d\omega} \equiv 0 \qquad \text{(for all } \omega) \quad (8)$$

Substituting equation (7) into equation (8), we can obtain a following polynomial equation

$$\begin{aligned}&L_P\left(1+\omega^2 L_S C_S\right)\left[1+Z_0^2\left(\frac{1}{\omega L_P}-\omega C_P\right)^2\right] \\ &\quad -C_S\left(1+\omega^2 L_P C_P\right)\left[\left(\omega L_S-\frac{1}{\omega C_S}\right)^2+Z_0^2\right]=0\end{aligned} \quad (9)$$

The coefficients of all terms have to be zero to satisfy equation (9) for all ω. Then we derive the determining condition as follows

$$Z_0 = \sqrt{\frac{L_S}{C_P}} = \sqrt{\frac{L_P}{C_S}} \quad (10)$$

Substituting equation (10) into equation (7) leads to

$$\phi = 180^\circ \quad (11)$$

As a result, it has been shown that an exact 180^o phase difference of the reflective terminating circuit is obtained without frequency dependence by satisfying the determining condition of equation (10).

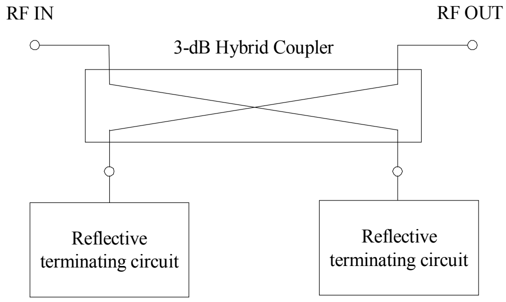


Fig. 1. Schematic diagram of a reflection type phase shifter.

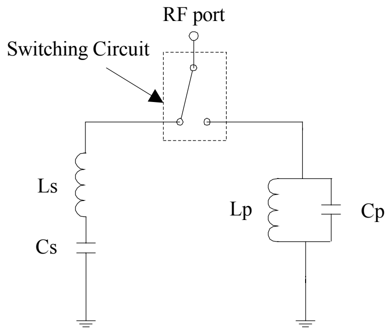


Fig. 2. Schematic diagram of a novel reflective terminating circuit.

III. DESIGN OF REFLECTIVE TERMINATING CIRCUIT

Figure 3 shows a schematic diagram of proposed 180^o reflective terminating circuit. It consists of only a few circuit elements of built-in inductor Lb, built-in capacitor Cb, and a pair of FET1 and FET2. These FETs are used as switching elements.

Figure 4 shows equivalent circuits of ON and OFF states of the 180^o reflective terminating circuit, respectively.

In figure 4 (a), by neglecting the ON state resistances Ron1 of FET1 and Ron2 of FET2, the circuit can be simplified to a parallel LC circuit, which corresponds to the parallel resonant circuit of Lp/Cp in figure 2. In figure 4 (b), when the admittance of series capacitance circuit consisting of Cb and Coff2 is small enough to be neglected, the circuit can be simplified to a series LC circuit which corresponds to the series resonant circuit of Ls/Cs in figure 2. Therefore, figure 3 can be identical to figure provided that Lb plays a role of Lp and Ls simultaneously. From equation (10), Cp, Cs, and Coff1 must be equal to Cb. We have the determining condition for circuit shown in figure 3. When the resonant frequency of the parallel and the series LC circuits is set to be ω_0, circuit elements of Lb, Cb, and Coff1 are given as follows

$$L_b = \frac{Z_0}{\omega_0} \qquad (13)$$

$$C_b = C_{off1} = \frac{1}{\omega_0 Z_0} \qquad (14)$$

At ω_0, loss of the parallel LC circuit cannot be neglected because of the parasitic resistances Ron1 and Ron2. Therefore, ω_0 has to be optimally determined considering the parasitic elements of FETs.

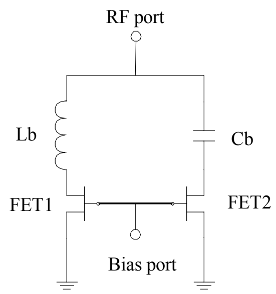


Fig. 3. Schematic diagram of proposed 180° reflective terminating circuit.

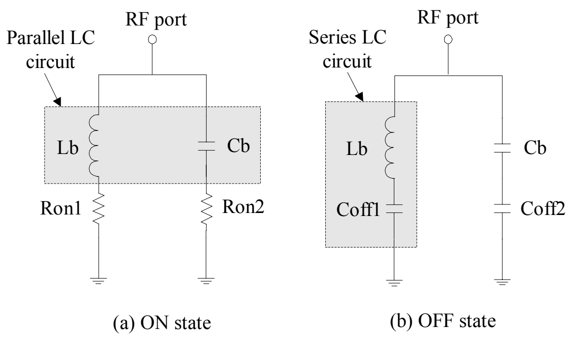


Fig. 4. Equivalent circuits of ON and OFF states of 180° reflective terminating circuit.

IV. FABRICATION

Figure 5 depicts a photograph of a fabricated 180° reflective terminating circuit MMIC. The IC has been fabricated by using 0.5um p-HEMT technology. To minimize amplitude error between ON and OFF states, a resistor is incorporated between source and drain terminals of FET1. Figure 6 shows the simulated and the measured phase difference characteristics of the 180° reflective terminating circuit. Figure 7 shows the return loss characteristics. Both of the measured and the simulated results are in good agreement. The measured phase difference is 183 +/- 3 ° over 0.5 to 30 GHz, and the measured return loss is 2.3 +/- 0.4 dB over 0.5 to 20 GHz band.

Figure 8 presents an ultra broad band reflection type 180° phase shifter MMIC fabricated by the same process. Figure 9 shows the measured and the simulated phase shift characteristics of the phase shifter MMIC. Figure 10 shows the measured and the simulated insertion and return loss characteristics. The measured phase shift is 187 +/- 7° over 0.5 to 20 GHz. The measured insertion loss is 3.7 +/- 0.6 dB over 6 to 20 GHz and the measured amplitude error is less than 1 dB at the same frequency range. The difference between the measured and simulated phase shift are caused by the 3-dB Lange coupler used in it.

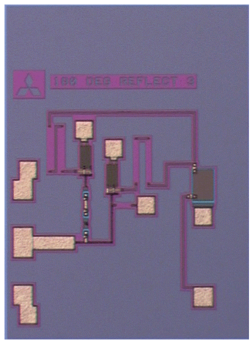


Fig. 5. Photograph of a fabricated 180° reflective terminating circuit MMIC.

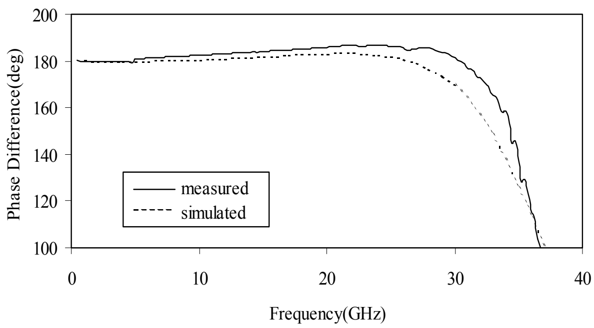


Fig. 6. Phase difference performance of the 180° reflective terminating circuit.

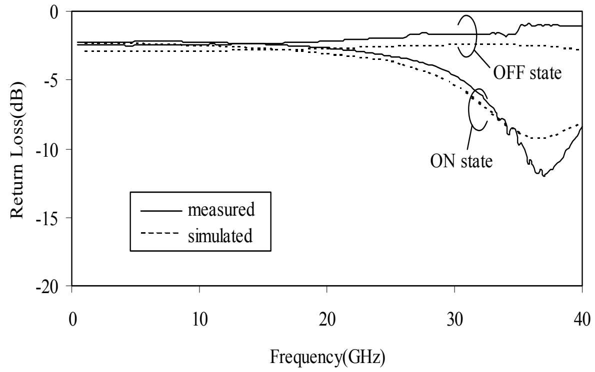


Fig. 7. Return loss performance of the 180^{o} reflective terminating circuit.

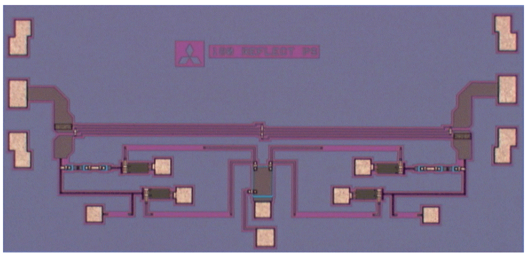


Fig. 8. Photograph of an 180^{o} phase shifter MMIC.

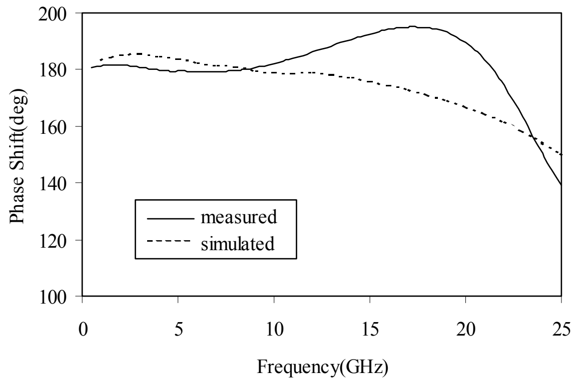
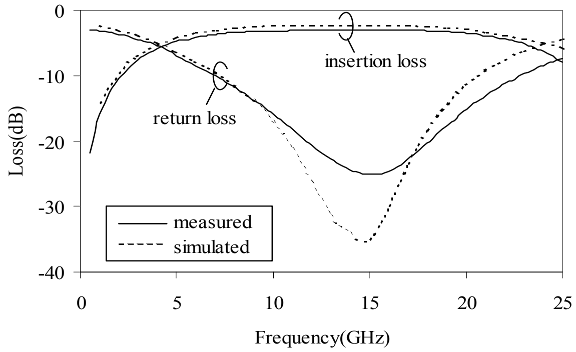
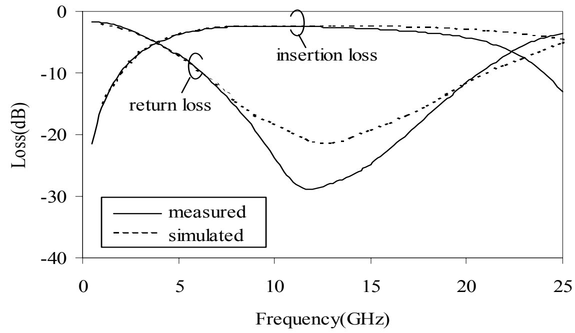


Fig. 9. Phase shift performance of the 180^{o} phase shifter.



(a) ON state



(b) OFF state

Fig. 10. Insertion and return loss performance of the 180^{o} phase shifter.

V. Conclusion

An ultra broad band reflection type 180^{o} phase shifter consisting of a 3-dB Lange coupler and a pair of novel reflective terminating circuits has been proposed. The reflective terminating circuit can achieve an 180^{o} phase difference independently of frequency. We have derived the determining condition of circuit elements of the reflective terminating circuit to achieve 180^{o} phase difference for all frequencies. The fabricated 180^{o} phase shifter MMIC utilizing the reflective terminating circuits has successfully demonstrated phase shift of 187 +/- 7^{o} over 0.5 to 20 GHz band.

References

[1] R. V. Garver, "Broad-Band Diode Phase Shifters," IEEE Trans. On Microwave Theory and Techniqes, Vol. MTT-20, No. 5, pp. 314-323, May 1972.

[2] M. Schindler, Y. Ayasli, A. Morris, L. Hanes, "Monolithic 6-18 GHz 3-bit Phase Shifter," IEEE GaAs IC Symposium, pp. 129-132, 1985.

[3] Atwater H.A, "Reflection Coefficient Transformations for Phase-Shift Circuits," IEEE Trans. Microwave Theory Tech., MTT-28, 6, pp. 563-567, June 1980.