Design of a Phase Shifter with Improved Bandwidth using Embedded Series-Shunt Switches

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Abstract — **A phase shifter with improved bandwidth using embedded series-shunt switches is presented. The FET switches become part of phase shifting filter elements as well as series-shunt switches. This improves the bandwidth of phase shifter because of having intrinsic characteristics of a high-pass and low-pass phase shifter. A phase shifter using resonated FET circuit is analyzed and compared. The conditions of circuit elements are derived in analytic form, which are used to obtain broadband phase characteristic. Two types of a Ku band 90^o phase shifter are designed. The proposed phase shifter exhibits more broadband phase characteristic than the resonated FET topology. The proposed approach enables to realize a compact phase shifter with broadband performance.**

I. INTRODUCTION

Phase Shifters are used to control phases in phased array systems, which are key components to have a beam forming of array antenna. MMIC based phase shifters are attractive because of the low cost, small size, and low power consumption. Digital phase shifters are frequently used in active phased array radar (APAR) system. There are many types of digital phase shifters, which include switched line, reflection, loaded-line, and high-pass/low-pass type phase shifters. Compared to the other phase shifters, high-pass/low-pass phase shifter is the smallest in volume. In MMIC implementation, passive FETs are typically used as switching elements. However, it is possible to incorporate the off-capacitances of switching FETs as filter elements. This has led a number of researchers to explore techniques for realizing the maximum theoretical bandwidth of an ideal high-pass/low-pass phase shifter. Ayasli reported a different implement of a switched-network phase shifter using six MESFETs [1]. A bridged- T type phase shifter can be used to design lower value phase shifting bits [2,3]. Campbell demonstrated a compact circuit topology using spiral inductors [4]. This topology obtains a differential phase shift between a reference state and a three-section high pass filter. However, the paper neglected to address analysis of constant phase response.

This paper presents a new embedded –FET type phase shifter using embedded series-shunt switches. A phase shifter using resonated FET circuit is analyzed and all circuit parameters are derived. Two types of a 90^o phase shifter using 0.25 μm pHEMT technology are designed and compared.

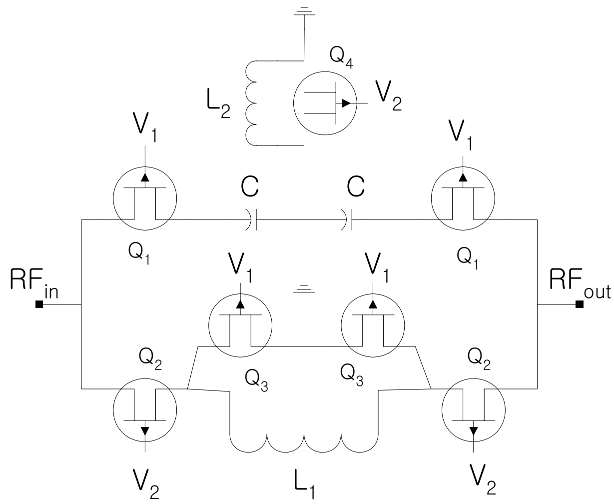


Fig. 1. The circuit schematic of the proposed phase shifter

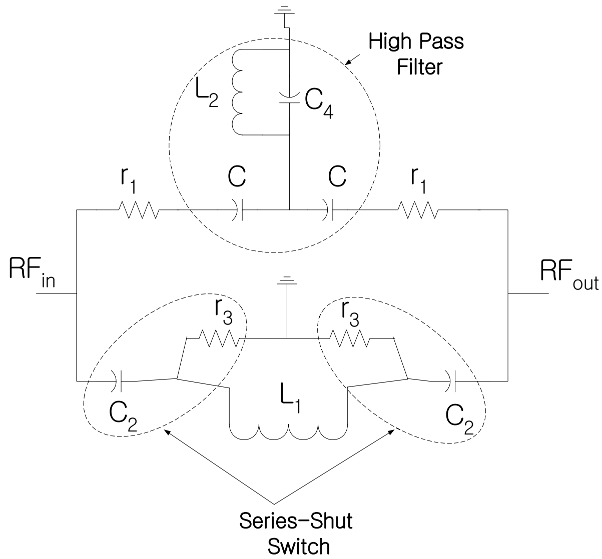


Fig.2. The circuit shown in Fig.1 where V_1=0V, V_2= -4V

II. THE PROPOSED PHASE SHIFTER

Fig.1 shows the proposed embedded-FET type phase shifter. When the control voltage V_1 is 0V and V_2 is – 4 V, the circuit of Fig.1 can be reduced to the form shown in Fig.2. The upper part of Fig.2 becomes a T-type high pass filter if the off capacitance of Q_4 is small enough

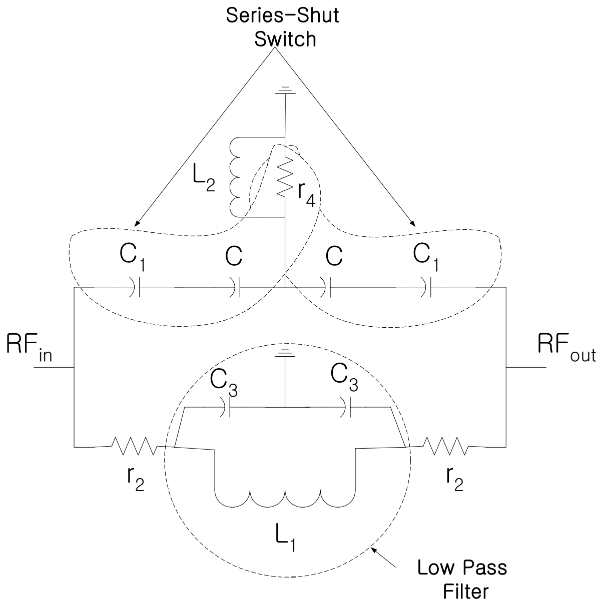


Fig.3. The circuit shown in Fig.1 where V1=-4V, V2= 0V

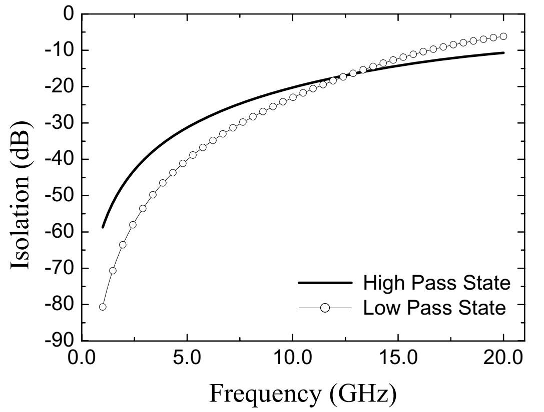


Fig.4.The simulated isolation characteristics of each series-shunt switch.

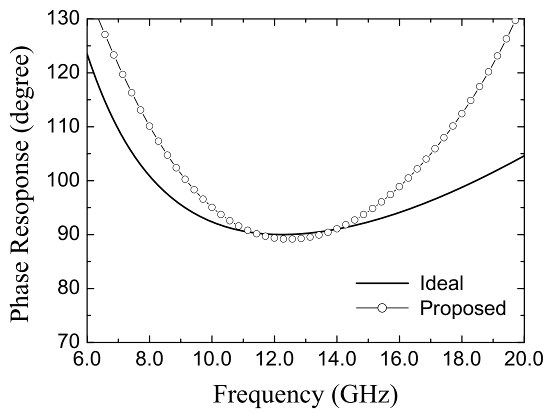


Fig.5. Comparison of simulated phase response using the proposed topology and ideal high-pass/low-pass phase response.

that it does not shunt L_2. The lower part of Fig.2 is comprised of two series-shunt switches if on-state resistances of Q_3 are negligible small compared with the reactive impedance in parallel with them.

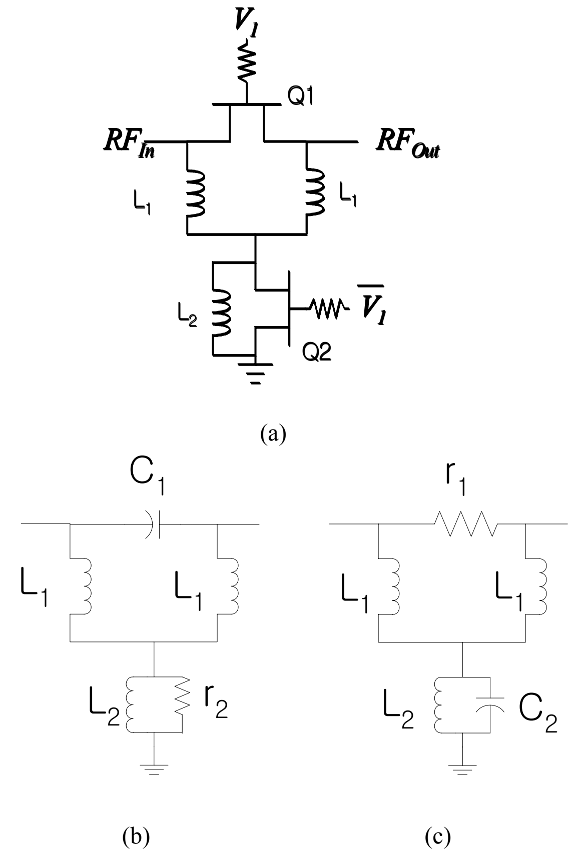


Fig.6. (a) The schematic of the phase shifter using resonated FET circuit (b) The equivalent circuit of high-pass filter state (c) The equivalent circuit of the reference state

These switches improve the isolation between the high pass filter and the lower part of Fig.2.

When V_2 is 0V and V_1 is – 4V, the circuit of Fig.1 reduces to the form shown in Fig.3. The lower part of Fig.3 becomes a Π-type low pass filter by an inductor L_1 and the off capacitances of Q_3. A series-shunt switch is formed by the off capacitance of Q_1 with capacitor C and the on-resistance of Q_4.

In order to show the characteristics of the proposed topology, a 90^o phase shifter is designed. Fig.4 shows the simulated isolation characteristics of each series-shunt switch. The isolation of low-pass state is better than that of high-pass state because two series connected capacitors improve it. The isolations drop below 20 dB up to 1O GHz. The choice of FET size determines the phase shifter performance such as insertion loss, bandwidth, and amplitude balance. The larger the FETs used, the lower insertion loss but the poorer the bandwidth. Fig.5 shows the comparison simulated phase response using the proposed topology with ideal high-pass/low-pass phase response. The phase response of the proposed phase shifter is similar to the ideal one even if the bandwidth is not same. The difference between the phase response of the proposed phase shifter and ideal phase response increases with increasing frequency due to degradation of the isolation. However, this topology enables to realize a compact phase shifter with broadband performance.

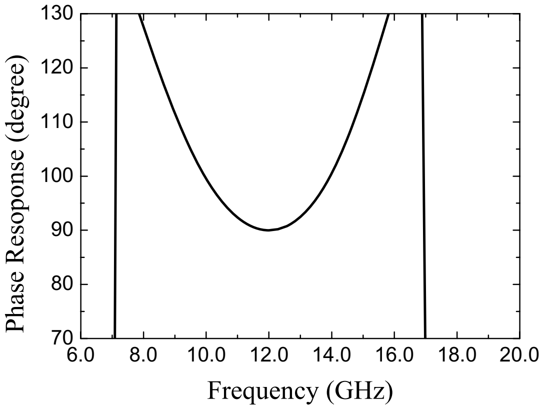
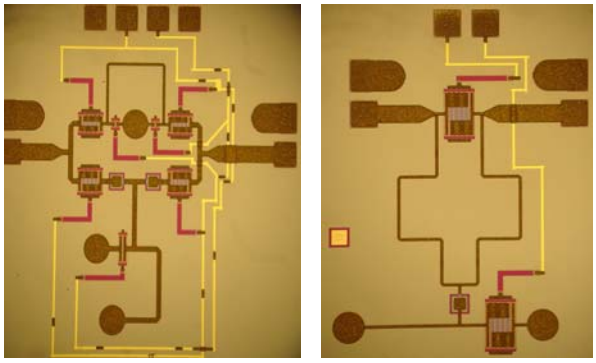


Fig.7.The ideal phase difference characteristic using resonated FET topology.



(a) (b)

Fig.8. (a) the photograph of the proposed 90^o phase shifter (b) the photograph of the resonated FET type 90^o phase shifter

III. A PHASE SHIFTER USING RESONATED FET CIRCUIT

We discuss another phase shifter using resonated FET circuit as shown in Fig.6 (a). An additional capacitor, which is parallel combination of the off-capacitance of Q_1, is removed [4]. This topology obtains a differential phase shift by switching between a reference state and a Π-type high pass filter state. When Q_1 is off and Q_2 is on, the circuit is form of high pass filter if the resistive component r_2 is small compared with the reactive impedance of L_2. Satisfying the impedance matching condition, the inductance and capacitance required to realize insertion phase ϕ_o at frequency ω_o are equal to the following

$$L_1 = \frac{Z_o}{\omega_o \tan(\phi_o / 2)} \tag{1}$$

$$C_1 = \frac{1}{\omega_o Z_o \sin(\phi_o)} \tag{2}$$

With (1) and (2) satisfied, the derivative of the insertion phase can be represented by

$$\left.\frac{d}{d\omega}(\phi_h)\right|_{\omega=\omega_o} = \frac{2}{Z_o}(-2Z_o{}^2C_1 + L_1) \tag{3}$$

where ϕ_h is the insertion phase of the high pass state

When Q_1 is on and Q_2 is off, the signal passes through Q_1 while the Q_3 is parallel resonated with the inductor L_2. By neglecting r_1, the circuit is simplified to a resonated circuit. The impedance matching condition and the derivative of the insertion phase can be derived in the same way, and expressed in (4) and (5), respectively.

$$L_2 = \frac{1}{\omega_o^2 C_2} \tag{4}$$

$$\left.\frac{d}{d\omega}(\phi_{ref})\right|_{\omega=\omega_o} = -C_2 Z_o \tag{5}$$

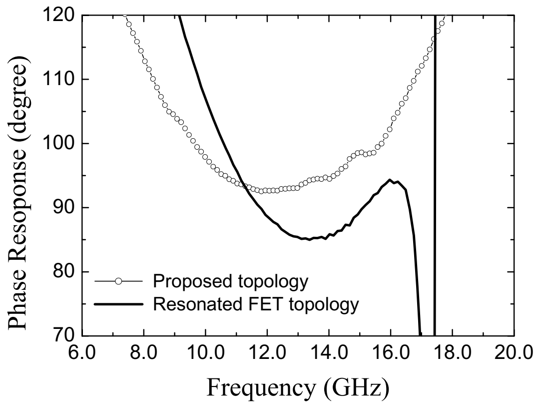


Fig.9 Measured data comparision of the proposed topology and the resoanted FET topology.

where ϕ_{ref} is the insertion phase of the reference state

Using the equality of (3) and (5), it is necessary to satisfy following condition for a constant phase characteristic.

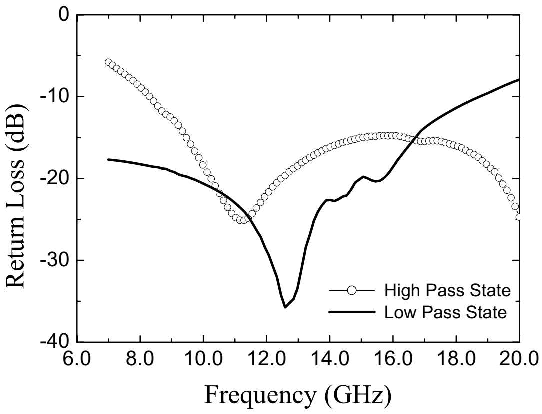
$$C_2 = 4C_1 - \frac{2L_1}{Z_o{}^2} \tag{6}$$

Therefore, the circuit elements are expressed as functions of ω_o and ϕ_o . Under the assumption of Z_o=50 Ω, ϕ_o =90^o and ω_o =2π × 12 GHz, the ideal phase differecne characteristic of the phase shifter is plotted in Fig.7. This exhibits narrower phase response than the proposed phase reponse shown in Fig.5.

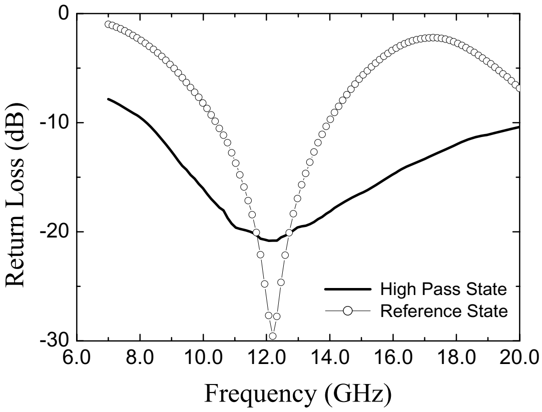
IV. EXPERIMENTAL RESULTS

The proposed phase shifter and resonated FET type phase shifter are designed and implemented using 0.25um pHEMT technology. Photographs of the fabricated phase shifters are shown in Fig.8. Microstrip lines as inductors are implemented. A spiral inductor can be used with use of extensive EM simulation.

The phase shifters are measured using on-wafer probing system. Fig.9 compares the phase response of the



(a)



(b)

Fig.10. (a) measured return loss of the proposed topology (b) measured return loss of the resonated topology.

proposed and resonated approaches. The proposed phase response exhibits a smaller phase variation at the operation frequency band. The phase response of the resonated FET topology is limited up to 17 GHz. Fig.10 (a) and (b) show the return losses of each topology. The measured return loss of the proposed topology is observed to be less than 10 dB from 8.5 GHz to 18.5 GHz. However, the resonated topology is strongly determined by the reference state regardless of a characteristic of the other state. Therefore, the return loss of the reference state restricts the bandwidth of the phase shifter.

V. CONCLUSION

A novel phase shifter using embedded series-shunt switches has been demonstrated using 0.25 μm pHEMT switches. This topology approaches the intrinsic bandwidth of an ideal high-pass/low-pass phase shifter. To compare with this topology, the phase shifter using resonated FET circuit is analyzed and designed. All circuit parameters are derived to obtain a minimum phase variation around the operating frequency. The proposed phase shifter exhibits more broadband characteristics than the resonated FET configuration.

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