

Wideband Phase Shifter Using 3 Types of LC Resonant Circuits for Phase Slope Alignment

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Abstract— This paper proposes a new wideband phase shifter, aligning phase slope between the reference line and main line to reduce the slope deviation using 3 types of LC resonance circuits (series, parallel and composite type). Compared to the conventional ones, the proposed phase shifters have several advantages such as a simple structure with single layer, accurate LC values from the derived formulas that are not optimization values. In addition, any phase shift value is applicable to the proposed theory, since the phase shift range of the proposed phase shifter can be implemented from 0 to 360 degree. The design theory of the proposed phase shifter is derived by taking a differential of difference between reference line and LC resonant circuit with respect to angular frequency, then calculate the value of each element of L and C at the center frequency. Although the proposed phase shifter is designed with only one or three resonant circuits in this paper, the number of resonant circuits constituting the main line can be three or more. By the design theory, the total sum of the phase values allocated to each resonant circuit may be a phase shift value to indicate a desired phase difference between the reference line and the main line. To validate the design theory, 180° wideband phase shifters with singles (series and parallel) and composite resonant circuits are designed, fabricated, and measured. The fractional bandwidth of the proposed circuits for a parallel and a composite resonant circuit are both greater than 64%. Therefore, the measurement results agree well with the design theory within 0.5 dB insertion loss and $\pm 10^\circ$ phase deviation, except fabrication error.

1. INTRODUCTION

With the surge of mobile devices, the requisite for high-speed mobile data transmission has been accumulating day by day. In the urban areas where data demand is concentrated, available radio frequency bandwidth is becoming saturated, with much more emphasis on the efficiency and optimal latency of data with simultaneously exponentially expanding traffic. Especially in near-term fifth generation (5G), technologies such as multiple inputs, multiple outputs (MIMO) [1] are at the pivotal point. MIMO enables multiple user terminals, which are spatially separated, to simultaneously communicate on the same frequency resource and propagate through multiple channels for efficient multiplexing. MIMO technology is developed on a massive beamforming antenna, and researches [1, 2] have been growing on this particular technology.

One of the major components of such a beamforming antenna is a phase shifter that outputs a uniform phase difference within a wide bandwidth. Thus, in order to maintain the uniform phase differences in wide bandwidth, different techniques for phase shifter structure have been proposed to acquire broadband and maximum phase shifts, such as Schiffman [3], multimode resonator [4], short stub and coupled line [5]. These structures [3–5] require a tight coupling (less than 0.2 mm) to obtain a wide bandwidth, resulting in narrow gaps and microstrip fabrication limitations. To improve the fabrication limitation due to the tight coupling, the coupling gap (0.3 mm) is upgraded by using the patterned ground plane under the coupled line [6], but it is still problematic to compensate the effect of fabrication error. Other approaches [7, 8] are to add open and short stubs for the narrow gap improvement method, but the impedance of the added stubs is required for an optimization step for the narrow gap improvement of the coupled line or for the transmission line impedance. In addition, there are only several phase shift ranges (90° or 180°) [7–9]. Abbosh and Wang [10, 11] also recommended a wide range and ultra-wideband (UWB) phase shifter. Although [10, 11] is UWB (over 126%) phase shifter, but the limitation of it is that not only its microstrip fabrication is difficult but also the process variation between layers would be affected due to interlayer structures.

In this paper, we propose the three types of new phase shifters using LC resonant circuits, instead of a coupled line, to align the phase slope to the reference line. It is implemented as a single layer structure and allows for various phase shift ranges from 0 to 360°. The LC values of the single resonant circuits and composite resonant circuit proposed from the phase shifter equations

can be obtained. The proposed phase shifters using LC resonant circuits for the demonstration were designed as a single and composite resonant type as 180° phase shift.

2. PHASE SLOPE ALIGNMENT CIRCUIT AND ANALYSIS

Figure 1 shows a circuit configuration of a typical phase shifter. The phase shifter is divided into a reference line and the mainline. The reference line consists of a transmission line with a port impedance Z_0 and a phase shift value θ (plus an additional length in some cases) for desired phase shift, where θ_0 is the angular frequency at central frequency. Meanwhile, the main line is implemented as a circuit to maintain the phase difference from the reference line, having the phase θ_T of the proposed circuit. In this paper, the proposed 3 types of LC resonant circuits for aligning the phase slope with reference line are applied to the main line as shown in Figure 2. Figure 2 shows the proposed phase slope aligning circuits which are series, parallel, and composite resonant circuits.

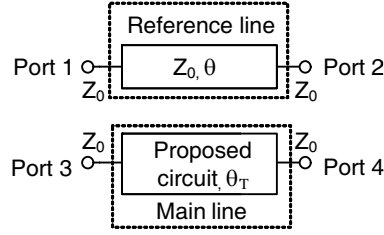


Figure 1: Circuit configuration of a phase shifter.

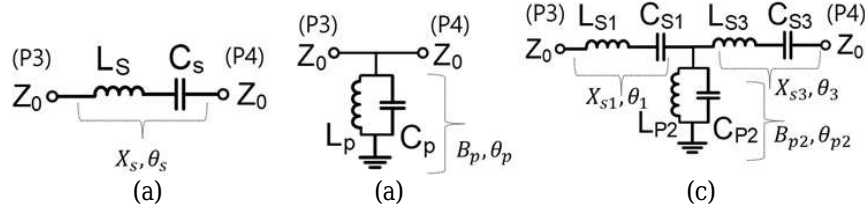


Figure 2: Circuit Structures of proposed phase slope alignment circuits for main line of Figure 1. (a) Series resonant circuit, (X_s : L_S & C_S reactance, θ_s : X_s phase). (b) Parallel resonant circuit (B_p : L_P & C_P susceptance, θ_P : B_P phase). (c) Composite resonant circuit (X_{s1} , B_{p2} , X_{s3} : each component's reactance and susceptance, θ_1 , θ_2 , θ_3 : each element's phase).

In general, the phase shifter is realized by the phase difference between the reference line and the main line. However, if the frequency deviates from the central frequency, the phase difference varies depending on the difference in phase slope between the reference line and the main line. Figure 3 shows the comparison result among a reference line with a 180° electrical length, a general single LC resonant circuit, and proposed LC resonant circuits according to the 180° phase shifter at 2 GHz. Simulation results show that the phase shifter using the composite resonance circuit has the widest 180° phase difference bandwidth, while the general LC resonance circuit maintains the phase difference of 180° only at the 2 GHz centre frequency due to the different phase slope with reference line. It is noted from the Figure 3 that for general resonant circuit, as the frequency varies in either direction from the center frequency, the phase deviates from the constant phase difference with respect to reference line. To improve the phase difference deviation according to the frequency change, the differential value of phase difference with respect to frequency should be zero as shown in (1).

$$\frac{d}{d\omega} \Delta\Phi = \frac{d}{d\omega} [\angle S_{21} - \angle S_{43}] = \frac{d}{d\omega} [\theta - \theta_T] = 0 \quad (1)$$

$$\angle S_{43} = -\theta_S = -\tan^{-1} \frac{X_S}{2Z_0} \quad (2)$$

Since phase $\theta_T = -\theta_S$ of main line for LC resonance circuit at f_0 resonant frequency is zero, phase slope of series LC resonant circuit in Figure 2(a) through (1) and (2) is expressed as (3) in order

to obtain constant differential phase shift value at central angular frequency ω_0 .

$$\omega_0 \left. \frac{d\theta_s}{d\omega} \right|_{\omega=\omega_0} = \omega_0 \frac{1}{2Z_0} \left. \frac{dX_s}{d\omega} \right|_{\omega=\omega_0} = \frac{1}{2Z_0} \left(\omega_0 L_s + \frac{1}{\omega_0 C_s} \right) = \theta_0 \quad (3)$$

Thus, since $\omega_0^2 = 1/(L_s C_s)$, each value of L_s and C_s is expressed as (4)

$$L_s = \frac{Z_0}{\omega_0} \theta_0, \quad C_s = \frac{1}{\omega_0^2 L_s} \quad (4)$$

As the same manner of (1)–(4), each value of L_p and C_p for the parallel resonant circuit in Figure 2(b) is also expressed as (5) [14].

$$L_p = \frac{1}{\omega_0^2 C_p}, \quad C_p = \frac{\theta_0}{Z_0 \omega_0} \quad (5)$$

In the same way as (1)–(4), all value of L_{S1} , C_{S1} , L_{S3} , C_{S3} , L_{P2} and C_{P2} for the composite resonant circuit in Figure 2(c) is expressed as (6)–(7).

$$\omega_0 \left. \frac{d\theta_T}{d\omega} \right|_{\omega=\omega_0} = \frac{1}{2Z_0} \left(\omega_0 L_{S1} + \frac{1}{\omega_0 C_{S1}} + \omega_0 L_{S3} + \frac{1}{\omega_0 C_{S3}} \right) + \frac{Z_0}{2} \left(\omega_0 L_{P2} + \frac{1}{\omega_0 C_{P2}} \right) \quad (6)$$

$$L_{S1} = \frac{Z_0}{\omega_0} \theta_1, \quad C_{S1} = \frac{1}{\omega_0^2 L_{S1}}, \quad L_{S2} = \frac{Z_0}{\omega_0} \theta_2, \quad C_{S2} = \frac{1}{\omega_0^2 L_{S2}}, \quad L_{P1} = \frac{1}{\omega_0^2 C_{P1}}, \quad C_{P1} = \frac{\theta_3}{Z_0 \omega_0} \quad (7)$$

Thus, total $\theta_T = \theta_1 + \theta_2 + \theta_3 = \sum \theta_i$ is expressed through (6)–(7), where i is the number of resonance circuit constituted by main line, and the number of resonant circuit is not limited to only three, but may be several. Figure 3 shows the results of the circuit simulation by applying the derived LC values. Unlike the conventional LC resonant circuit, the single phase shifters and composite phase shifter maintain a constant phase slope within a fractional bandwidth of 66%, more than 95%, respectively.

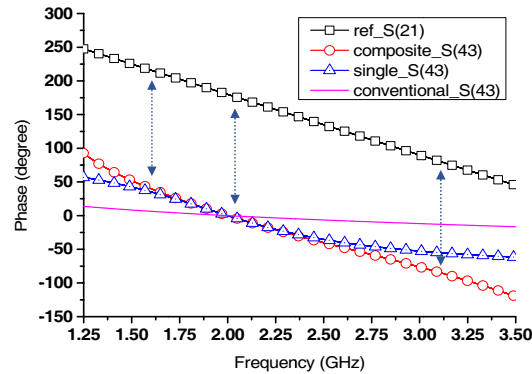


Figure 3: Circuit simulation results for phase comparison with a conventional and proposed phase shifter.

3. RESULTS AND DISCUSSION

Circuit and EM Simulation are conducted using ANSYS Designer and HFSS software [16]. Figures 4(a) and (b) show the phase shifter's circuit simulation results applied with series, parallel, and composite resonant circuit, respectively.

If the proposed circuit is organized only single resonant circuit, the fractional bandwidth (FBW) is about over 66%, whereas the FBW results are more than 95% within $\pm 10^\circ$ phase error for the composite resonant circuit. The proposed circuits show that the phase shift range is implemented from 0° to maximum 360° , unlike the conventional circuits [5–13]. Figure 4 shows an increase in phase difference deviation within the fractional bandwidth as the phase shift value in single resonant circuits increases. For single resonant circuits, phase slope alignment is possible only near the resonant frequency shown in Figure 3, because of 1 resonant frequency. Thus, it is difficult to compensate the slope alignment as it goes far from the resonant frequency. To solve this problem, wideband phase slope alignment is possible using the composite resonator circuit.

Figure 5 shows magnitude measurement results of the proposed phase shifter using LC resonant circuit at 180° phase shift. The measurement magnitude results show broadband characteristics from 1.1 to 3 GHz for the composite resonant circuit, while the parallel resonant circuit has a bandwidth from 1.8 to 2.2 GHz at a return loss of less than -10 dB near resonant frequency. Parallel lumped elements for single and composite resonant circuits are converted to short stubs [15] for easy fabrication, as shown in fabricated photograph of Figures 6(a) and (b).

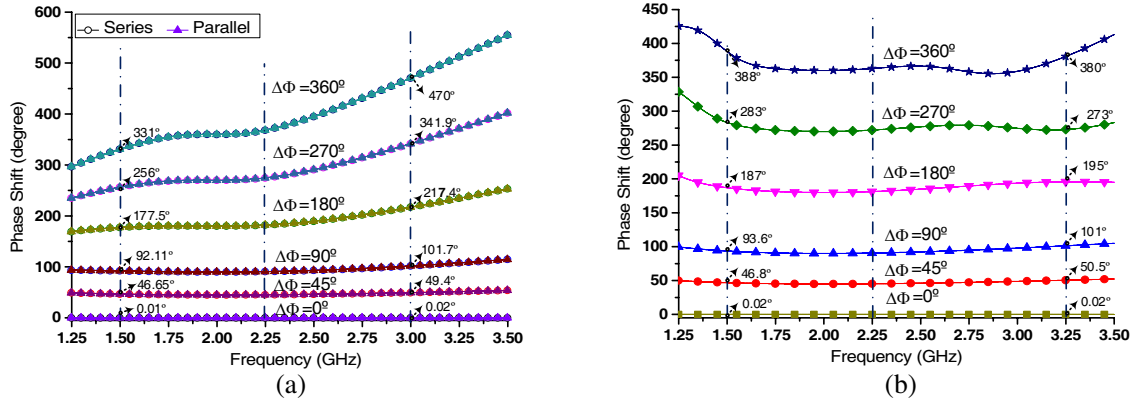


Figure 4: Simulation results of proposed phase shifter as phase shift from 0° to 360° . (a) Series and parallel single resonant circuits. (b) Composite resonant circuit.

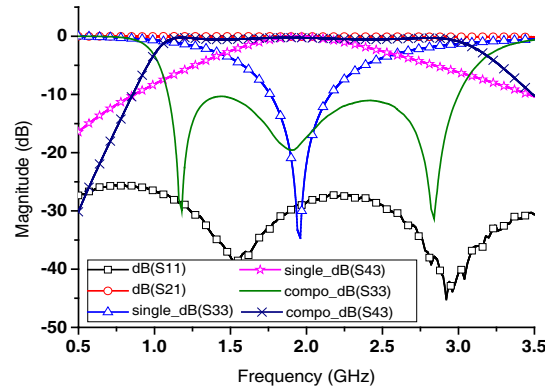


Figure 5: Magnitude measurement results of proposed phase shifter using the phase slope alignment circuit according to the parallel and composite resonant circuit.

Figure 6(c) shows the phase differences of phase shifters with the proposed single and composite resonant circuits. The single resonant circuit has a bandwidth from 1.25 to 2.55 GHz for $\pm 10^\circ$ phase deviations, while the composite resonant circuit has a bandwidth of 1.5 to 2.9 GHz. For two series parts of the composite resonant circuit, the phase shifter is implemented using chip inductor and chip capacitor symmetrically (3.9 nH, 1.3 pF). Thus, the measurement results are slightly narrower bandwidth than that of the circuit simulation results (1.25–3.5 GHz) due to the frequency-dependent variations in inductor and capacitor values of chip capacitor. Except for fabrication tolerances, the measured magnitude and phase characteristics are similar to those of the simulation results, and the measurement results of the composite resonant circuit are better than those of the single resonant circuit. Thus, the validity of the designed phase shifter could be confirmed well.

A performance comparisons between the proposed phase shifter and the reported 180° phase shifters are presented in Table 1. The proposed phase shifter is implemented using a single layer structure with reasonable phase deviation and insertion loss over 64% bandwidth. Since the proposed phase shifter has a phase shift range of 0° to 360° , it is possible to develop a phase shifter using various phase shift values. In addition, a method of aligning an arbitrary phase slope to a reference line may contribute to improving the phase bandwidth of various microwave circuits.

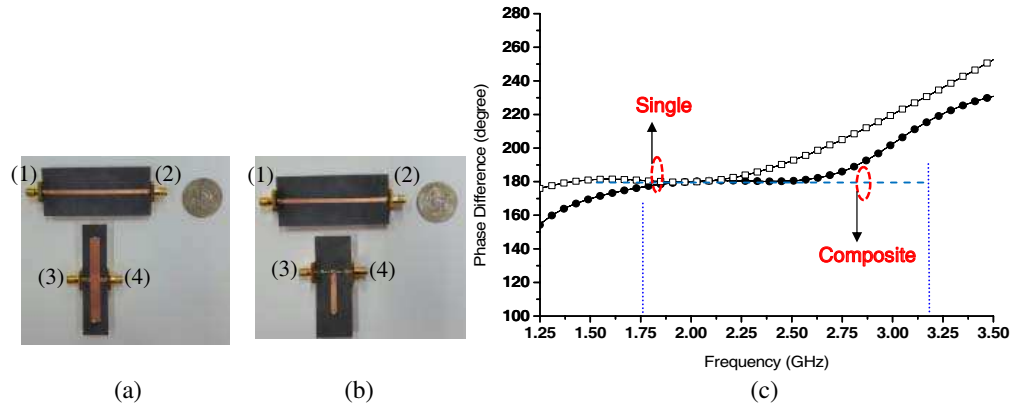


Figure 6: Fabricated photograph of the phase shifter using single (a) and composite (b) resonant circuit, and measurement results of the phase differences (c).

Table 1: Performance comparisons with reported 180 phase shifters.

Ref#	Max. PR($^{\circ}$)	PD	IL	FBW (%)
[2]	45 ~ 270	± 3.4	≤ 1.2	44
[6]	180	± 4	≤ 0.7	66.8
[10]	45 ~ 180	± 8	≤ 0.6	100
[11]	90 ~ 180	± 4	≤ 1	67
This work	0 ~ 360	± 10	≤ 0.5	64

Max.PR: Maximum Phase Range, PD: Phase Deviation,
IL: Insertion Loss, FBW: Fractional Bandwidth

4. CONCLUSION

This letter proposes a wideband phase shifter using three types of LC resonant circuit to align the phase slope with reference line. In order to increase bandwidth, a formula that equalizes the phase slope is applied, and is used to derive the LC component values. The proposed phase shifter has a phase range from 0° up to 360° . To verify the proposed design theory, 180 $^{\circ}$ phase shifters with single and composite resonant circuit are implemented on microstrip line. Thus, magnitude and phase of 3 types of resonant circuits are 100%, 64% in fraction, respectively. Therefore, the proposed phase slope alignment circuit is applicable for beamforming antenna array, or adjusting the output phase slope for microwave circuit for wider bandwidth.

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