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Coupled Line Phase Shifters and Its Equivalent Phase Delay Line for Compact Broadband Phased Array Antenna Applications

Sang-Min Han · Young-Sik Kim

Abstract

Novel coupled line phase shifters and its equivalent phase delay line for compact broadband phased array antennas are proposed. These phase control circuits are designed to be less complex, small size and to use a less number of active devices. The phase shifter is able to control a 120° phase shift continuously, and the phase delay line for a reference phase has a fixed 60° shifted phase. Both have the low phase error of less than ±3.5° and the low gain variations of less than 1 dB within the 300 MHz bandwidth. These proposed circuits are adequate to form the efficient beam-forming networks with compactness, broadband, less complexity, and low cost.

Key words : Phase Shifters, Phased Array Antennas, Beam-Forming Networks, Coupled Lines.

Ⅰ. Introduction

A phased array antenna system with electrically steering beam has many useful applications to smart antennas, mobile base station antennas for beam tilting, and so on[1]. Its beam-forming network is the most important subsystem for the control of a main beam. The beam-forming network has been issued for its complexities, cost, planar design, and efficient beam steering using the antenna arrangements[1]~[4]. It consists of power divider, phase shifters, and antenna feed lines. These components require broad bandwidth, low phase error, low gain variation, and less complexity. Antenna steering angle, as well as these considerable factors, depends on the performance of phase shifters.

Recently, the phase shifters using either a 3 dB branch line hybrid coupler[5]~[7] or a switched line[3] are the most popular, because these have moderate phase bits compared with other types and can be simply designed. However these don't only have the disadvantage of narrow bandwidth, large phase error and large size due to design dependency on wavelength, but also cause complicated systems[5]~[8].

In this paper, a compact, broadband, continuously controlled coupled line phase shifters are developed from our previous work[9] and its equivalent phase shift circuit is proposed. As a quarter-wave coupled line is adequate for the design of a broadband system[10],[11], the proposed ones have utilized the coupled line with low gain variations and phase errors, and a wide bandwidth. It is also shown that these phase shifters are more compact in size and less complex compared with previous approaches[6]~[8]. Moreover, the equivalent phase shift line is also designed for the feed line to an antenna element with a reference phase, which makes possible the low cost fabrication using less number of active devices.

Ⅱ. Coupled Line Phase Shifter Design

2-1 Single-Stage Coupled Line Phase Shifter

Fig. 1 shows the proposed configuration of the single-stage phase shifter using coupled line. The coupled line should be designed with tight coupling for broadband, low insertion loss, and low phase error. The length of the coupled line should be optimized in consideration of the effect of a diode capacitance.

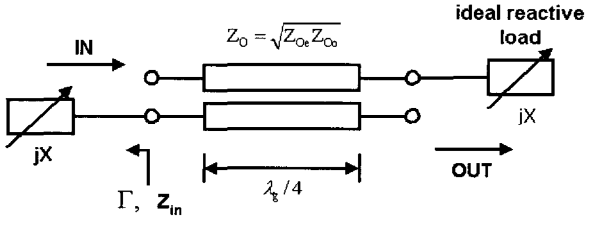

Fig. 1. Configuration of the coupled line phase shifter using reactive terminations.

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Department of Radio Sciences and Engineering, Korea University, 1, 5-ga, Anam-dong, Sungbuk-gu, Seoul, 136-701, Korea..

The phase variation is mainly affected by the termination impedance because the phase shift of a reflection type phase shifter is obtained from the phase variation ($\Delta\phi$) of reflection coefficient (Γ) at the termination load. At the center frequency, f_o, the phase shift at the output of the coupler is also $\Delta\phi$ in an ideal coupler. The impedance of the termination load which is the shunt stub with variable capacitance, is simply expressed as:

$$Z_{in} = R_s + jX, \tag{1}$$

where $X = (\omega L - 1/\omega C_d)$. R_s is the series resistance and C_d, L are the diode capacitance and the inductance of the microstrip pad and the via hole to GND, respectively. The Γ of the termination load is presented as follows:

$$\Gamma = |\Gamma|\, e^{j\phi} = \frac{(R_s - Z_o) + jX}{(R_s + Z_o) + jX}, \tag{2}$$

where $\phi = \pi - 2\tan^{-1}(X/Z_o)$. To evaluate the variations of the termination impedance as a reverse bias changes, the termination load is modeled including a varactor, a microstrip stub, and a bias circuit as shown in Fig. 2.

The termination resistances and reactances at each bias state are searched from 1.7 GHz to 2.5 GHz by simulation. For the purpose of broadband system, it must have the low resistance variations and linear reactance variation in the considered bandwidth. Additionally, the difference of the reactances at each bias have to be large in order to get a large phase shift.

Fig. 3 presents the impedance plots of the termination load. The resistance as the loss factor of the phase shifter has small values and low variation of about 0.25 Ω for 40 % bandwidth. And each reactance plot is nearly linear and maintains the same difference between bias states which accounts for the phase shift at each frequency. Therefore, it can be shown that these variations of termination load impedance excite the broadband properties of the phase shifter in band.

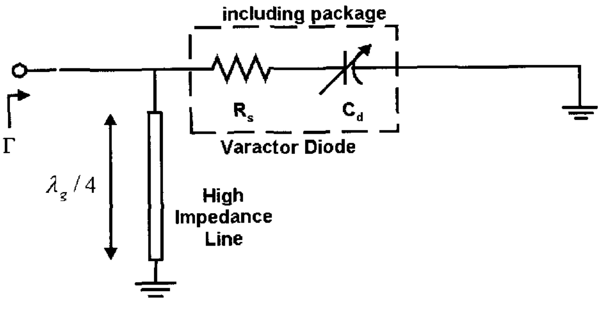
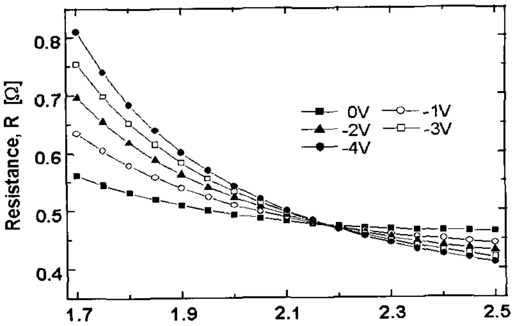
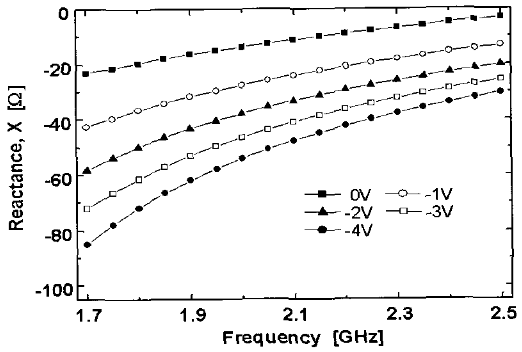


Fig. 2. Model for the termination load evaluation.



(a) Resistances



(b) Reactances

Fig. 3. Termination load impedance of the coupled line phase shifter.

The termination load characteristics are evaluated for C_d and Γ as the reverse bias voltages at a center frequency, f_o of 2.1 GHz. These results are given in Table 1. The $\Delta\phi$ is up to 65° and the magnitude of $|\Gamma|$ is almost unity. From this result, it is found that C_d is operated as the main variable of function ϕ in this circuit and this phase shifter has the capacity of phase shift of up to about 65°.

The phase shifter is designed using an ADS simulator. The coupled line with tight coupling is required for low phase error and its resonance frequency must be avoided in bandwidth for a wide bandwidth. And

Table 1. Termination load characteristics as reverse bias voltages.

Bias [V]	C_d [pF]	[mag./deg.]
0	16.267	0.982 / − 169.352
− 1	4.452	0.983 / − 142.396
− 2	2.923	0.985 / − 125.176
− 3	2.282	0.987 / − 112.809
− 4	1.918	0.989 / − 103.374

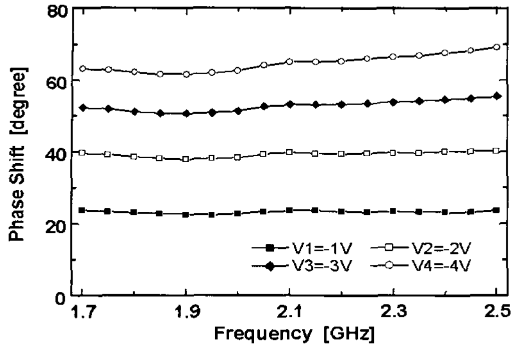


Fig. 4. Experimental results of the single-stage phase shifter.

varactor diodes require high dynamic range and low parasitic effects.

The proposed phase shifters have been implemented on a microstrip line on substrate with a high dielectric constant, $\varepsilon_r = 10.2$ for tight coupling. The selected diodes were Infineon BBY52-02W surface-mounted varactor diodes, which have low series resistance, $R_s = 0.9\ \Omega$, and series inductance, $L_s = 0.6$ nH. It has compact circuit sizes of 13.5×5.8 mm^2, which are about one fourth that of a conventional one.

From the measured results in Fig 4, the proposed phase shifter has phase shifts of 23°, 39°, 53°, and 65° and a phase error in the 800 MHz bandwidth of ±0.5° ~ ±3.5° at the reverse bias from −1 V to −4 V, respectively. Their insertion losses are about 3±05 dB and return losses are about 8±0.5 dB.

2-2 Two-Stage Coupled Line Phase Shifter

A 120° coupled line phase shifter with four bits is designed for IMT-2000(1.92~2.17 GHz). For optimum properties in the bandwidth, the coupled lines of the phase shifter are tuned at the center frequency of 2.045 GHz. As the coupled line phase shifter can control phase bits continuously, all varactor diodes are biased by the common reverse voltage, simultaneously. Phase bits are assigned to 30°, 60°, 90°, and 120°. On the condition of the phase shift with more than 120°, phase error and gain variations increase rapidly.

As this phase shifter utilizes the wave reflections at each terminations, the reflected signals on the stage 1 affects on the stage 2 and vice versa. This interfering signal makes the other stage phase shifter operate with large group delay, which becomes the cause of phase error. Therefore, the shunt connected isolation resistor is required between each stage, while it degrades the insertion loss. The layout of the cascaded circuit is presented in Fig. 5.

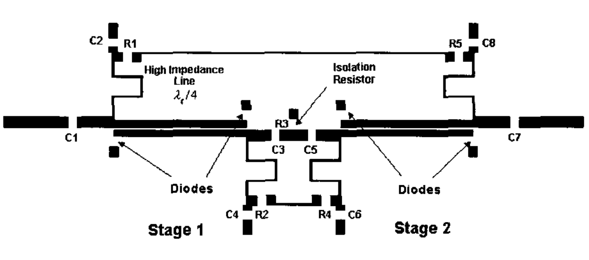
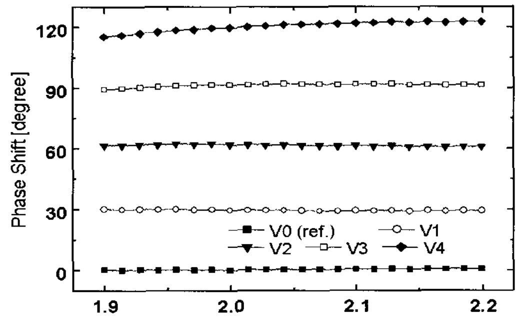
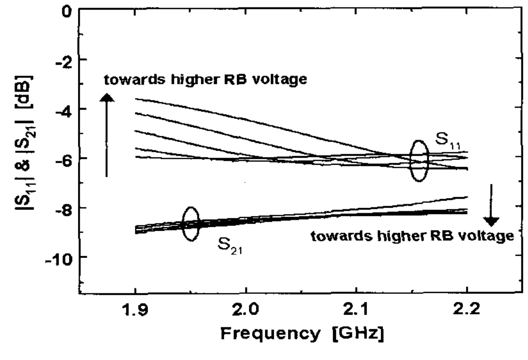


Fig. 5. Layout of the two-stage coupled line phase shifter.

The two-stage phase shifter has been implemented on the same substrate and diodes as the single stage. The bias circuit made of $\lambda/4$ high impedance line is played the role of low pass filter with a cutoff frequency of 3 GHz. The experimental results are presented in Fig. 6. It has the phase errors of ±0.4°, ±0.4°, ±0.4°, ±1.4°, and ±3.6° from V0 to V4, respectively and the gain flatness at each state of 0.9 to 1.1 dB. The S_{21} are about −8.5 dB, which is caused by 3 dB attenuation of the isolation resistor, in addition to cascaded two 3 dB couplers. From these results, it is presented that this



(a) Phase shifts



(b) S_{11} and S_{21}

Fig. 6. Experimental results of the two-stage 120° phase shifter.

phase shifter is adequate for a broadband beam-forming network, because the signals with the same magnitude and phase can be transmitted to antenna elements in the bandwidth. However, as its port is not well impedance matched due to the coupled line designed to avoid resonance, they need other impedance matching. However these can help the isolation among ports.

Ⅲ. Phase Delay Line Design

For the purpose of beam control to both directions at the center of an steering angle, a beam-forming network with the odd number of antenna element needs a reference phase feed line without changing its phase, as shown in Fig. 7. This phase is the reference of the phase shift and the other phase shifter has to be capable of plus/minus phase shift from the reference phase. In general, the same phase shifter is used at the reference port, which increases the complexity and fabrication cost.

In this paper, in order to implement the network of low complexity and a less number of active devices, the equivalent phase delay line is proposed. It operates as a reference phase shift line and is located at the center port of the beam-forming network. The phase delay line requires the same group delay as well as the exact value of shifted phase for the performance of a beam-forming network within a full band.

The proposed phase delay line configuration is shown in Fig. 8. The phase delay line is designed similarly to the coupled line phase shifter to achieve the same group delay. The diode is replaced by equivalent capacitors, C_{eq}, because a varactor is equivalent to variable capacitor. And the coupled line length can be tuned for the accurate value of the capacitance. However, as varactor diodes have series resistance and series inductance as well as the variable capacitance, the parasitic values can be achieved by tuning the length of stub lines, θ_s. The stub tuning compensates for the difference of group delay between the phase delay line and the phase shifter.

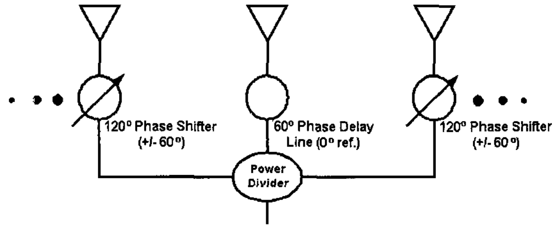


Fig. 7. Configuration of the beam-forming network using a phase delay line.

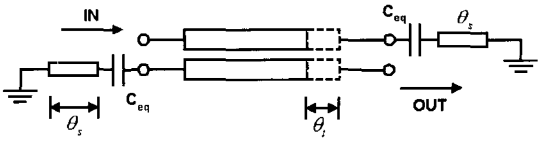


Fig. 8. Schematic of the phase delay line for a reference phase.

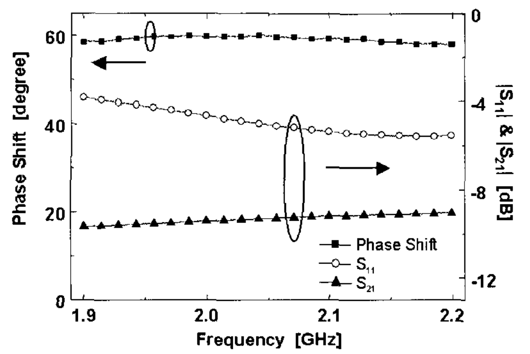


Fig. 9. Experimental results of the 60° phase delay line.

The proposed phase delay line with a 60° phase shift is implemented and its experimental results are compared with the coupled line phase shifter with a 60° phase shift state. These measured results are shown in Fig. 9. The phase shift values relative to the reference state of the phase shifter are well fit to 60° phase shift, and have low phase error of less than ±1.1°. The insertion loss is about 9.2 dB and its gain variation is 0.6 dB. These values are much similar to those of the phase shifter. Therefore, the proposed phase delay line is well matched to the previously designed 60° phase shifter.

Ⅳ. Conclusion

New compact broadband phase shifters using coupled lines and its equivalent phase delay line are proposed for the design of phased array antenna system. They have been designed and implemented with regard to compact size, broadband, and low phase error, as compared with conventional reflection type phase shifters using 3-dB branch line. The proposed phase shifter can control the phase from 0° to 120° continuously and the phase delay line for the reference phase port of a beam-forming network has almost the same characteristics as those of the 60° coupled line phase shifter.

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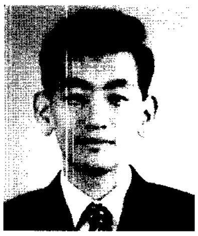
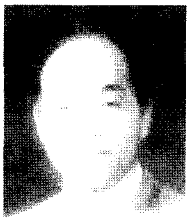
Sang-Min Han



He was received the B. S. and M. S degrees in Radio Sciences and Engineering from Korea University, Seoul, Korea, in 1996, and 1998, respectively, and is currently Ph.D candidate in Radio Communication Technology Lab. From 1999 to 2001, he was a Lecturer at the School of Electrical Engineering, Korea University. His current research interests include phased array antennas, advanced RF front-end systems, and RFIC/MMIC's.

Young-Sik Kim



He was received the B. S. degree in electronics engineering from Korea University, Seoul, Korea, in 1973, and the M.S. and Ph.D. degrees in electrical engineering from the University of Massachusetts at Amherst in 1986 and 1988, respectively. From 1988 to 1989, he was a Post-Doctoral Research Fellow at the University of Massachusetts at Amherst. From 1989 to 1993, he was with the Mobile Communications Division, Korea Electronics and Telecommunications Research Institute, Daejeon, Korea. Since 1993, he has been with the Department of Radio Sciences and Engineering, Korea University, where he is currently a Professor. His main field of interest is millimeter-wave antennas and front-end systems and mobile telecommunication systems.