JOURNAL OF ELECTROMAGNETIC ENGINEERING AND SCIENCE, VOL. 12, NO. 2, 166～170, JUN. 2012

http://dx.doi.org/10.5515/JKIEES.2012.12.2.166
ISSN 2234-8395 (Online) · ISSN 2234-8409 (Print)

Tunable Composite Right/Left-Handed Delay Line with Large Group Delay for an FMCW Radar Transmitter

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Abstract

This paper presents a tunable composite right/left-handed (CRLH) delay line for a delay line discriminator that linearizes modulated frequency sweep in a frequency modulated continuous wave (FMCW) radar transmitter. The tunable delay line consists of 8 cascaded unit cells with series varactor diodes and shunt inductors. The reverse bias voltage of the varactor diode controlled the group delay through its junction capacitance. The measured results demonstrate a group delay of 8.12 ns and an insertion loss of 4.5 dB at 250 MHz, while a control voltage can be used to adjust the group delay by approximately 15 ns. A group delay per unit cell of approximately 1 ns was obtained, which is very large when compared with previously published results. This group delay can be used effectively in FMCW radar transmitters.

Key words: Tunable Delay Line, Varactor Diode, Large Group Delay.

Ⅰ. Introduction

Many studies over the past 10 years have focused on various delay lines such as surface acoustic wave (SAW), magnetostatic wave (MSW), and composite right/left-handed (CRLH) delay lines [1]. These delay lines have been used in many applications; for example, in time or phase synchronization when designing linear power amplifiers [2], and in phased array antennas where the antenna feeding lines are adjusted to control the antenna beam direction and directivity [3]. Another major application is as a delay line discriminator, which finds the instantaneous frequency of a received signal by mixing the received signal and its time-delayed signal through a known delay line, followed by low-pass filtering of the mixed output [4].

This paper presents a tunable group delay line for a delay line discriminator that is a control circuit used to linearize the modulated frequency sweep of an FMCW radar transmitter [5]. A fabricated delay line has a CRLH transmission line configuration and uses varactor diodes in series in order to obtain sufficient tunable group delay to linearize a VCO output signal with an inherently nonlinear frequency sweep characteristic. A design frequency of 250 MHz and a group delay variation of ≤ 5 % within the frequency sweep bandwidth were chosen according to the specifications of a 24 GHz FMCW radar transmitter and frequency dividing ratios of the phase-locked loop (PLL) of the transmitter.

Previous studies have investigated nonlinear CRLH transmission lines with varactor diodes; however, the group delay results in these studies are so small that it is difficult to utilize them in the delay line discriminator of an FMCW radar transmitter. One of the recently reported group delays is approximately 2 ns [6], which is still a relatively small value when compared with the group delay of more than 8 ns in the present work. The design and simulation results of the tunable CRLH delay line are presented next, followed by the fabrication and measured results.

Ⅱ. Design and Simulation

In general, a tunable CRLH transmission line is composed of right-handed (RH) and left-handed (LH) transmission lines. The RH transmission line, which consists of a series L and shunt C, corresponds to a conventional transmission line; whereas the LH transmission line, with a series C and shunt L, shows a duality with the RH transmission line. Purely LH transmission lines ca-

Manuscript received March 7, 2012 ; Revised April 17, 2012 ; Accepted May 4, 2012. (ID No. 20120307-007J)
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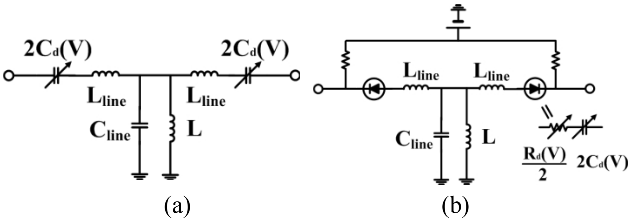


Fig. 1. Unit cell structures of a tunable CRLH transmission line described by (a) lumped elements only and (b) two varactor diodes and lumped elements. The series inductor (L_{line}) and shunt capacitor (C_{line}) arise from the connection lines between the varactor diodes.

nnot be practically implemented because they inevitably require RH transmission line sections to connect the series Cs and shunt Ls.

Fig. 1 shows the two unit cell structures of a tunable CRLH transmission line that are described by lumped elements only or by two series varactor diodes, a shunt inductor, and lumped element models (L_{line} and C_{line}) of the parasitic RH transmission sections for a series connection of the varactor diodes. As shown in Fig. 1(b), the reverse-biased varactor diodes can be used instead of the lumped series capacitors in an equivalent circuit of the unit cell.

The group delay and Bragg cutoff frequency of the tunable delay line with cascaded CRLH unit cells can be expressed as equations (1) and (2), respectively.

$$\tau_d = N\frac{d\beta}{d\omega} = \frac{2N}{\omega\sqrt{4\omega^2 LC_d(V) - 1}}. \tag{1}$$

$$\omega_B = \frac{1}{2\sqrt{LC_d(V)}}. \tag{2}$$

In equations (1) and (2), N is the number of unit cells, L is the inductance of a shunt inductor, $C_d(V)$ is half of the junction capacitance of a reverse-biased varactor diode, and ω_B is the Bragg cutoff frequency [6]. The desired group delay can be obtained using the relevant L and C values. As shown in equation (1), with a finite number of unit cells, when the operating frequency is set close to the Bragg cutoff frequency, a very large group delay can be obtained. In general, signals cannot propagate below the Bragg cutoff frequency and impedance matching performance is severely degraded due to the abrupt change of the effective transmission line impedance near the Bragg cutoff frequency. Therefore, the group delay should be traded off against the insertion loss. In this paper, a large group delay region near the Bragg cutoff frequency is used for the delay line discriminator of a linear FMCW radar transmitter, while maintaining the insertion loss below a predetermined level.

Table 1. Design specifications of the delay line discriminator.

	Group delay [ns]	Insertion loss [dB]	Return loss [dB]	Group delay variation	Frequency
Target	≥ 7	≤ 7	≥ 10	≤ 5 %	250 MHz

The delay line discriminator, which is used in a PLL module to improve the frequency linearity of the FM-CW radar transmitter, usually requires a large group delay. Therefore, SAW delay lines are typically used [5]. The role of the delay line discriminator in the FMCW radar transmitter is to generate intermediate frequency (IF) error signals by mixing the VCO's linearly modulated signals and their delayed signals. In this paper, the design specifications of the delay line are determined on the basis of the system parameters of the 24 GHz FMCW radar transmitter in which the delay line is used; these specifications are listed in Table 1. The center frequency is 250 MHz, and the group delay variation during the frequency sweep should be below 5 % in order to obtain precise IF error signals, because a severe group delay variation could degrade the linearity. When considering the input power level of a phase-frequency detector, the insertion loss should be smaller than 7 dB, and the group delay should be more than 7 ns in order to obtain detectable and stable IF error signals. The design specifications shown in Table 1 were used to design a delay line with 8 cascaded CRLH unit cells, as shown in Fig. 2.

Table 2 lists the circuit design parameters of the tunable CRLH delay line. A group delay of 7.5 ns was calculated at 250 MHz using equation (1). For more accurate group delay estimation, the circuit parameters given in Table 2 and the SPICE model parameters of the varactor diode (Skyworks SMV1237) given by its

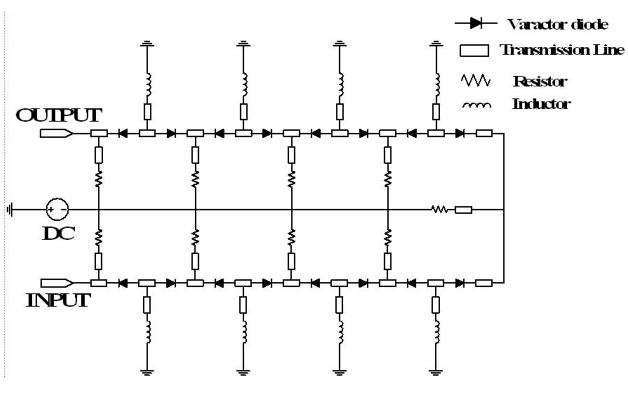


Fig. 2. Brief circuit description of the tunable delay line with a group delay of more than 7 ns.

Table 2. Circuit parameters of the tunable CRLH delay line.

	L	C_d(V)	Bias	Resistor	Cells
Value	22 nH	25 pF	3.3 V	10 kΩ	8

manufacturer were used in the Agilent ADS simulation. The transmission lines connecting the components were simulated using 2.5D electromagnetic (EM) simulation software (Momentum). As shown in Fig. 3, the S-parameter simulation demonstrates a group delay of 8.16 ns and an insertion loss of ~1.8 dB at 250 MHz.

Ⅲ. Fabrication and Measurement

A photograph of the fabricated tunable CRLH delay line is shown in Fig. 4; its area is 33×20 mm^2. A RO4003C substrate was used for the delay line because all components of the 24 GHz FMCW radar transmitter were mounted on the same substrate.

The simulated and measured results of the tunable CRLH delay line are compared in Fig. 5. The measured group delay agrees well with the simulated results. At the design frequency of 250 MHz, the measured group delay was 8.12 ns, which is a difference of only 0.04 ns when compared with the simulated group delay of 8.16 ns. The measured insertion loss was 4.5 dB at 250 MHz, which differs from the simulated insertion loss of 1.8 dB. This is partly because the linear equivalent circuit model of the unit cell does not include the frequency-dependent circuit elements near the Bragg cutoff frequency; thus it does not accurately describe the abrupt impedance mismatch effect.

The group delay and Bragg cutoff frequency values obtained using equation (1), the Agilent ADS software, and the measurements are compared and summarized in Table 3. The group delay obtained using equation (1)

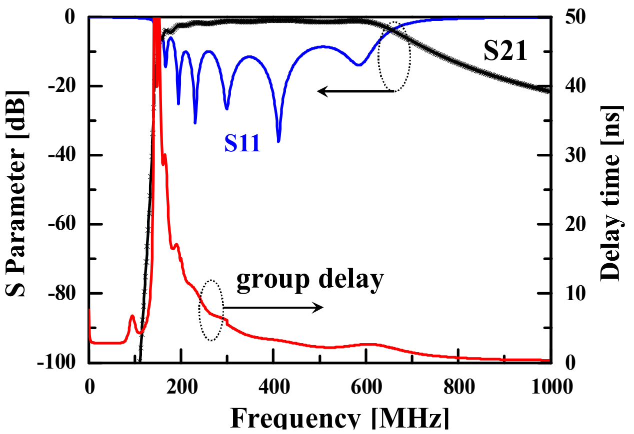


Fig. 3. Simulated results of the tunable CRLH delay line.

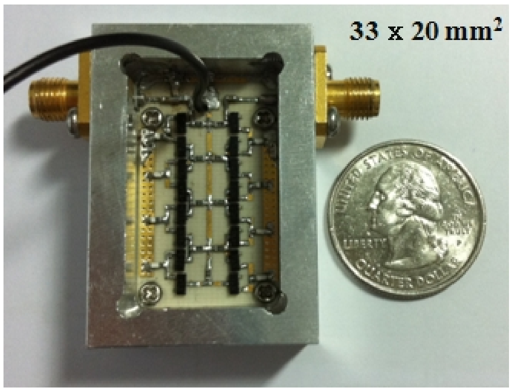


Fig. 4. Photograph of the fabricated tunable CRLH delay line.

Table 3. Performance of the fabricated tunable CRLH delay line at 250 MHz (Freq.=Frequency; unit: MHz).

Bias (V)	Theory (using equation (1))		Simulation		Measurement	
	Group delay	Bragg freq.	Group delay	Bragg freq.	Group delay	Bragg freq.
3.3	7.5 ns	137.2	8.16 ns	144	8.12 ns	144.8

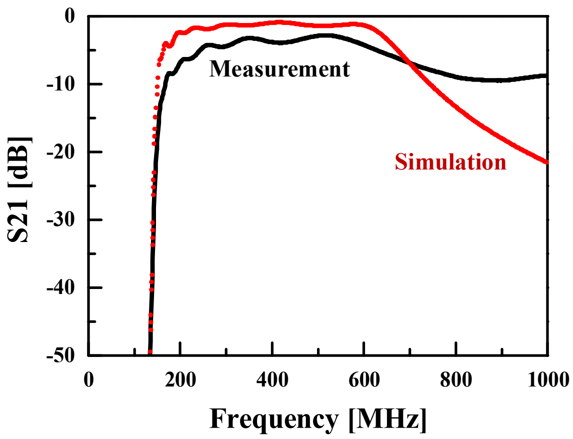
was predicted to be 7.5 ns at 250 MHz. However, if the transmission lines inserted between the varactor diodes in implementation are considered, the group delay increases to 7.8 ns, which results in a delay error of 4.1 %.

Table 4 compares the performance of the fabricated tunable delay line with the previous results. References [1], [6], and [7] used varactor-based CRLH delay lines, whereas reference [8] used a resonator-based delay line.

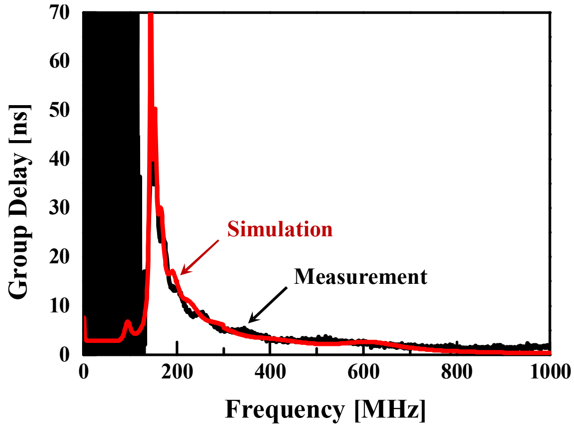
Table 4. Performance of the fabricated tunable delay line compared with previous results.

	Group delay [ns]	Insertion loss [dB]	Return loss [dB]	Center frequency [GHz]	Cells/ area [mm^2]
This work	8.12	4.5	15	0.25	8 cells/ 33×20
Ref. [1]	1	2	24	9.5	3 cells/ N.A.
Ref. [6]	2.2	5	10	1.42	5 cells/ 25×17
Ref. [7]	8.54	3.4	10	2	30 cells
Ref. [8]	4.02	2.7	24.4	0.911	790×390

1. In reference [6], the area of the tunable delay line was approximated using the photograph of the fabricated CRLH delay line.
2. In reference [7], the area of the unit cell is approximately 14.5×10 mm^2 and the whole area can be estimated from the number of unit cells and the unit cell area.

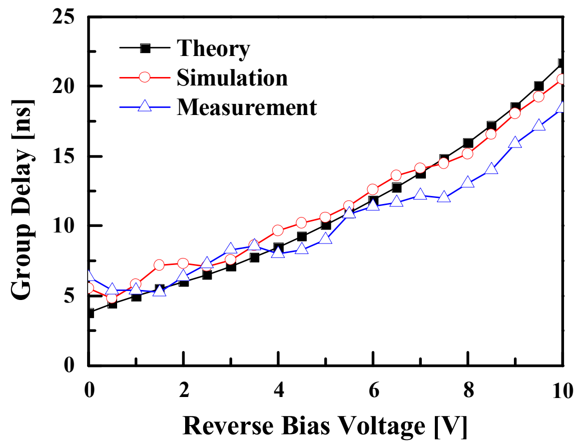


(a) Insertion loss

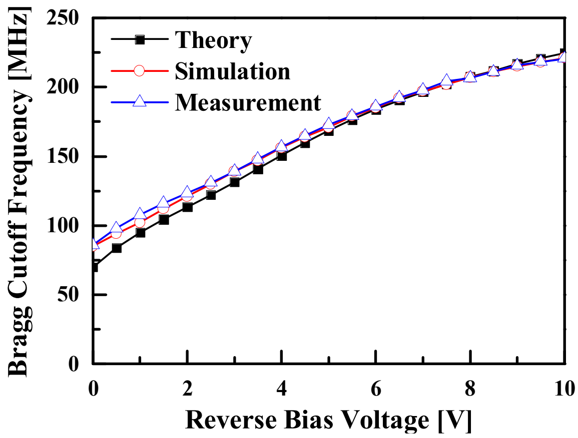


(b) Group delay

Fig. 5. Comparison of the simulated and measured results.



(a) Group delay



(b) Bragg cutoff frequency

Fig. 6. Group delay and Bragg cutoff frequency with the reverse bias voltage applied to varactor diodes.

The current work achieves a group delay performance comparable to reference [7]; however, the current study only used 8 unit cells when compared with the 30 unit cells used in reference [7]. The smallest insertion loss was measured in reference [1], partly as a result of the small number of unit cells.

The principal advantage of the varactor-based delay line is that the group delay could be tuned by adjusting the reverse bias voltage of the varactor diodes. Fig. 6 shows the variation in the group delay and Bragg cutoff frequency with the reverse bias voltage. The group delay increased from 5 ns to 20 ns at 250 MHz and the Bragg cutoff frequency increased from 75 MHz to 220 MHz, with a reverse bias voltage of 0 V to 10 V. The junction capacitance of the varactor diode is inversely proportional to the reverse bias voltage. This implies that a smaller capacitance increases the Bragg cutoff frequency, which becomes significantly closer to the operating frequency of 250 MHz. Therefore, the group delay is greatly enlarged through the increase of the reverse bias voltage. In contrast, the insertion loss degrades due to the impedance mismatch effect when the Bragg cutoff frequency approaches the operating frequency of 250 MHz. The measured results indicate that the insertion loss increases from 4.5 dB to 8 dB. The measurements also demonstrate that the insertion loss could be improved by approximately 1 dB if straight microstrip lines are used rather than meandered microstrip lines.

Ⅳ. Conclusion

A tunable CRLH delay line was developed for a delay line discriminator that is used in a linearized FMCW radar transmitter. The fabricated tunable CRLH delay line exhibited a very large group delay of 8.12 ns and a reasonable insertion loss of 4.5 dB at 250 MHz. In addition, the delay line exhibited a group delay variation of 5～20 ns with a reverse bias voltage of 0～10 V. Compared with the previous results, a very large group delay per unit cell of approximately 1 ns was successfully obtained. The tunable delay line developed in this work could be used in many applications that require a large group delay, as well as in linearized FM-CW radar transmitters.

References

[1] C. Lijun, Z. Qi, and X. Shanjia, "Delay lines based on left-handed transmission line structure," *Proc. Antennas and Propagation Society International Symposium 2006*, pp. 1189-1192, 2006.

[2] S. Rummery, G. Branner, "Power amplifier design using feedforward linearization," *Proc. the 40th Midwest Symposium on Circuits and Systems*, pp. 545-548, 1997.

[3] H. Visser, *Array and Phased Array Antenna Basics*, John Wiley & Sons, England, Chapter 7, pp. 212-219, 2005.

[4] R. Mulagada, T. Weldon, "A delay line discriminator for IFM using a left-handed delay line," *Proc. IEEE SoutheastCon 2010*, pp. 185-188, 2010.

[5] R. Habel, M. Pelletier, F. Chenier, M. Lecours, and C. Delisle, "Design of a high resolution millimeter wave FM-CW radar," *Proc. Canadian Conference on Electrical and Computer-Engineering*, pp. 51-54, 1993.

[6] W. Tang, H. Kim, "Compact, tunable large group delay line," *Microwave and Optical Technology Letters*, vol. 51, no. 12, pp. 2893-2895, Dec. 2009.

[7] S. Abielmona, S. Caloz, "Experimental demonstration and characterization of a tunable CRLH delay line system for impulse/continuous wave," *IEEE Microwave and Wireless Components Letters*, vol. 17, no. 12, pp. 864-866, Dec. 2007.

[8] S. Park, H. Choi, and Y. Jeong, "Microwave group delay time adjuster using parallel resonator," *IEEE Microwave and Wireless Components Letters*, vol. 17, no. 2, pp. 109-111, Feb. 2007.

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