A Delay Line Discriminator for IFM Using a Left-Handed Delay Line

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Abstract— **Recent developments in left-handed metamaterials and left-handed transmission lines have led to new approaches to the design of radio frequency components such as branch line couplers. In this paper, the design of a delay line discriminator for instantaneous frequency measurement (IFM) is investigated, where the delay line section is replaced by a composite right/left-hand (CRLH) transmission line. To demonstrate the CRLH design approach, experimental measurements and simulation results are compared for a 100 MHz delay line discriminator. The inherent phase advance of the CRLH transmission line structure is shown to reverse the slope of the frequency discriminator when compared to a right-handed transmission line structure.**

I. INTRODUCTION

An instantaneous frequency measurement (IFM) receiver is an important component in many radar detection systems. It has long been established that an IFM receiver based on a delay line discriminator (DLD) offers a number of advantages, including high instantaneous bandwidth, wide instantaneous dynamic range, high speed, and good sensitivity [2]. Though numerous improvements have been made to the design of these systems over the years, the basic principle of operation remains relatively unchanged, in that the frequency of an incoming signal is converted into a voltage proportional to the frequency.

Many designs for improving the resolution and performance of IFM systems have been presented before [3]-[6]. More recently, an FPGA-based digital solution has been proposed [5]. This digital solution, though novel and flexible, lacks the wide instantaneous bandwidth of its analog counterparts. Analog designs, on the other hand, require a delay line that can hinder implementation at low frequencies due to the size of the delay line.

Recently, composite right/left hand (CRLH) transmission lines have been proposed for a variety of important microwave applications [1]. The underlying notion of left-handed systems and metamaterials was proposed by Veselago in 1967. Veselago theorized that some materials are capable of exhibiting negative permittivity and negative permeability simultaneously giving rise to left-handed behavior. These concepts of left-handed (LH) materials have been extended to transmission line theory [1], and the underlying principles of composite right/left-hand transmission line theory have been developed. It has been proposed that a CRLH structure can be developed by periodically loading a regular transmission line with series capacitors and shunt inductors to result in a material that has negative refractive index [9]. It has been further observed that implementations of these kinds of CRLH structures at microwave frequencies tend to utilize periodic structures [9].

Although metamaterials and composite right/left-handed transmission lines provide new insights into the design of microwave systems, there is some controversy [9]. Proponents suggest that the concepts and theory of metamaterials and left-handed transmission lines provide new insights that have resulted in novel microwave applications. Detractors point out the physical problem of realizing a true left-handed transmission line and suggest that practical approximations with lumped-element inductors and capacitors would be better handled with using filter synthesis theory. Despite the continuing controversy, this paper explores the use of CRLH transmission line concepts in the design of delay line discriminator.

In practice, CRLH transmission lines exhibit left-handed characteristics over a range of frequencies set by the designer. Useful characteristics of CRLH lines include dispersion and an opposite sign phase response relative to normal right-hand lines. This left-handed behavior of CRLH transmission lines has been exploited by researchers to provide useful phase characteristics that can be adjusted to suit a variety of applications. By modifying the parameters of a CRLH transmission line, leading and lagging phase responses can be tailored to system requirements.

In addition to the ability to adjust phase response in CRLH structures, the discrete components used in the left-hand portion of the structures often result in reduction of the physical size of circuits. Although size reduction can also be achieved through a lumped-element implementation of conventional right-handed transmission lines, the present investigation focuses on investigating the phase response of a CRLH structure relative to a conventional right-handed transmission line. Nevertheless, the prototype of the proposed circuit is much smaller than a corresponding right-handed quarter-wave line would be.

A simple design for a DLD has been chosen to demonstrate the performance of a delay line discriminator using a CRLH transmission line. In the following section, the design of the DLD is first presented. Then in the subsequent section, simulation results and measured results are given.

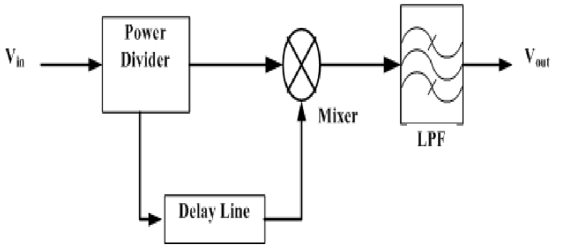


Figure 1. Block diagram depiction of the proposed delay line discriminator (DLD).

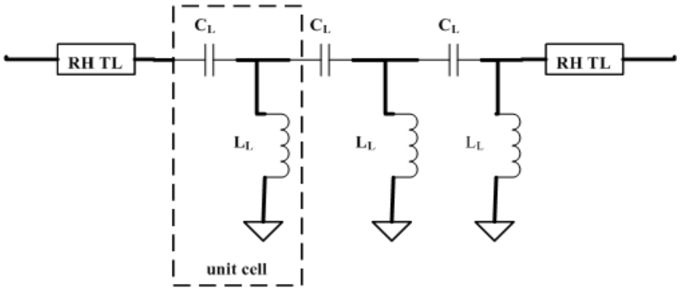


Figure 2. The composite right/left hand (CRLH) transmission line used for replacing the conventional transmission line delay line in the proposed delay line discriminator.

II. DESIGN APPROACH

The basic design of the proposed delay line discriminator is shown in Fig. 1. A radio frequency (RF) input signal V_{in} is first applied to the input of a power divider, with one output driving a quarter-wave delay line. The second output of the power divider and the delay line output then drive a double-balanced mixer. Finally, a low-pass filter (LPF) removes high frequency components from the final dc output signal V_{out}. For the prototype, a resistive 50 ohm power divider was used along with a Mini-Circuits SBL-1LH level-7 double-balanced mixer. The circuit was designed for an RF input level of 13 dBm at V_{in}.

In operation, the dc voltage at the output of a delay line discriminator is a function of the frequency of the input signal and is given as [2]:

$$V_{out} = \left(\frac{V^2}{2}\right)\sin(\omega\tau) \; , \qquad (1)$$

where V_{out} is the dc output voltage, V is the amplitude of the RF input signal, ω is the frequency of the input signal in rad/s, and τ is the time delay of the delay line in seconds. Thus, the dc output voltage V_{out} in Fig. 1 is dependent on the frequency of the input RF signal according to (1).

The quarter-wave delay line in Fig. 1 is used to generate 90 degree phase delay in one of the mixer inputs, thus driving the mixer with the two ports in quadrature phase. Typically the delay line is designed to give quadrature phase at the system center frequency. For the present design, a center frequency of 100 MHz would require a relatively long (0.75 m in free space) transmission line section for a quarter wave. As mentioned in the previous section, the proposed CRLH transmission line approach with discrete left-hand components will result in a much smaller circuit.

In the proposed circuit, the delay line of Fig. 1 is implemented as the CRLH transmission line of Fig. 2. The circuit consists of two right-hand transmission line sections (RH TL) and three left-handed unit cells. The three unit cells comprise the left-handed transmission line section of the CRLH line.

A right-handed unit cell and a left-handed unit cell are shown in Fig. 3, for purposes of illustrating unit cell circuit models for right-handed transmission lines and left-handed transmission lines. The LH transmission line model in Fig. 3(b) can be interpreted as the electrical dual of the RH transmission line model in Fig 3(a), with the capacitor and inductor interchanged. The RH transmission line behavior is similar to a low-pass filter and exhibits phase lag, whereas LH transmission line behavior is similar to a high-pass filter with a phase advance.

The phase of the CRLH transmission line section of Fig. 2 can be engineered using the phase advance property of the LH transmission line in conjunction with the phase delay property of the RH transmission line. The design equations for realizing a CRLH transmission line structure have been given as [7]:

$$\varphi_R = -\arctan\left[\frac{\omega\left(L_R/Z_{0R} + C_R Z_{0R}\right)}{2-\omega^2 L_R C_R}\right] < 0 \; , \qquad (2)$$

$$\varphi_L = -\arctan\left[\frac{\omega\left(L_L/Z_{0L} + C_L Z_{0L}\right)}{1-2\omega^2 L_L C_L}\right] > 0 \; , \qquad (3)$$

where

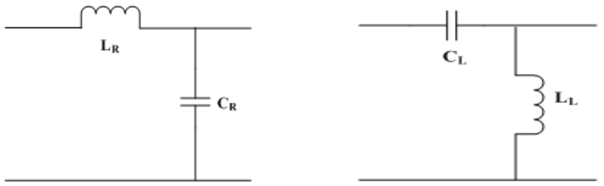
$$Z_{0R} = \sqrt{L_R/C_R}, \; Z_{0L} = \sqrt{L_L/C_L}, \qquad (4)$$

and where φ_R and φ_L are the phase responses of the unit cells of the RH and LH TL sections respectively. Z_{OR}, Z_{OL} are the characteristic impedances of the RH and LH transmission line respectively. C_R is the capacitance per unit length of the RH TR in F/m. L_R is the inductance per unit length of the RH TL in H/m. C_L is the capacitance per unit length of LH TL in F·m and L_L is the inductance per unit length of the LH TL in H·m. The propagation constant of a CRLH TL section (β) is the sum of the individual propagation constants of the RH (β_R) and LH (β_L) TL sections and is given by Eq. (5).

$$\beta = \beta_R + \beta_L = \omega\sqrt{L_R C_R} - 1/\left(\omega\sqrt{L_L C_L}\right), \qquad (5)$$

It can be seen form Eq. (5) that the LH section of a CRLH TL is dispersive and has a negative propagation constant. This unique feature combined with the fact that a CRLH TL exhibits phase advance can be used in a variety of microwave circuits [7].

In the CRLH transmission line of Fig. 2, each left-handed unit cell is designed to provide a phase advance of 35 degrees, and each RH TL section is designed to have a phase lag of 7.5 degrees at the center frequency of 100 MHz. The effective total phase of the overall CRLH transmission line is a 90



(a) (b)

Figure 3. Unit cell equivalent models of the transmission line sections. (a) Right-handed (RH) transmission line unit cell. (b) Left-handed (LH) transmission line unit cell.

degree phase advance, in contrast with a 90 degree phase delay for a conventional RH line. In either case, the phase is in quadrature at the mixer.

As noted above, the center frequency of operation is 100 MHz for this design. The values of the capacitor and inductor that make up a unit cell of the LH section of the CRLH transmission were calculated using design equations from [7]. The calculated values for a unit cell of the LH section are C_L = 56 pF and L_L = 136 nH. Three of these unit cells are used in the design to yield a collective phase advance of 105 degrees. The RH sections of the design are designed using the normal equations for transmission lines. The dimensions of a single RH section are of length 7.5 mm and width 2.5 mm an FR4 substrate with a thickness of 1.6 mm. Two of these RH sections are used in the design to yield a total phase lag of 15 degrees, so that the phase of the whole circuit meets the requirement of 90 degree phase advance.

III. SIMULATIONS AND MEASUREMENTS

The circuit of Fig. 1 was simulated for the delay line of Fig. 2 and the foregoing component values. A resistive power divider comprised of two 100 ohm resistors was used for simplicity. In the simulation, the mixer was modeled with a conversion gain of -7 dB and a phase shift of 180 degrees, to approximate the device used in the prototype. For the purpose of comparison, a DLD circuit using the conventional transmission line section for the phase delay component was also simulated along with the proposed CRLH transmission line DLD.

The simulation results for the DLD of Fig. 1 is presented in Figs. 4. Here, the dc output voltage is plotted as function of RF input frequency, for an RF input level of 13 dBm. The response of the conventional DLD using an RH TL is plotted as the dashed blue line in Fig. 4. The proposed DLD design using a CRLH TL is plotted as the solid red line in Fig. 4. The results for the two designs are comparable near the 100 MHz center frequency, except that RH TL design has positive slope and the CRLH design has positive slope. Below the center frequency, the CRLH design reaches a peak near 50 MHz, much sooner than the corresponding RH TL minima at 0 Hz. Thus, the CRLH DLD has steeper magnitude slope between 50 and 100 MHz.

In the band of frequencies of interest (~50-150 MHZ), the proposed CRLH DLD has an initial steep negative slope that decreases at higher frequency, while the RH TL DLD has a constant positive slope. In addition, the response of the proposed CRLH DLD flattens out after 150 MHz, whereas the response of the RH DLD begins to enter the second half cycle of the periodic DLD response given in equation (1). The pronounced change in slope in the CRLH response of Fig. 4 indicates the expected dispersion in the CRLH design. Nevertheless, the responses of the two DLD designs are quite similar near the design center frequency of 100 MHz, except for the opposite slopes.

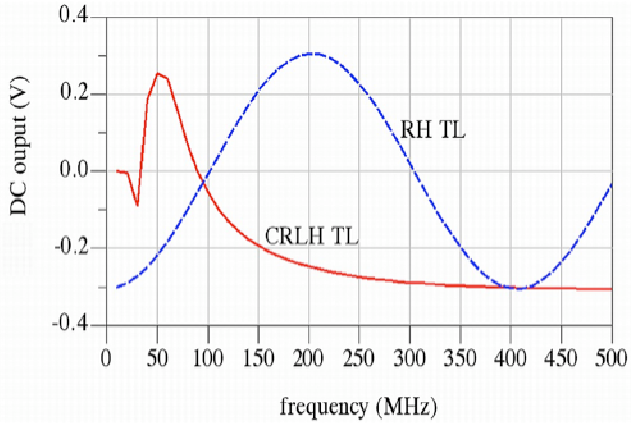


Figure 4. Simulation results of the CRLH DLD in solid red line and that of the RH DLD in a dashed blue line. The dc output voltage is plotted as a function of frequency for both DLDs for comparison.

In Fig. 5, the simulated phase responses of the RH and CRLH delay lines are presented. Here, the phase response of the RH TL is plotted as the blue dashed line and the phase of the CRLH delay line is plotted as a solid red line. The phase of the CRLH line is 90 degrees at 100 MHz while that of the conventional right-handed delay line is -90 degrees, as previously discussed. In addition, the phase response of the CRLH delay line is clearly nonlinear, indicating the dispersion expected in CRLH designs. The phase responses of Fig. 5 also follow along the lines of the DLD responses of Fig. 4, in that the phase response of the proposed DLD has a steeper slope than that of the conventional DLD below 50 MHz.

The proposed CRLH DLD prototype was built on an FR4 substrate with a thickness of 1.6 mm. Surface mount chip components were used for the discrete elements constituting the LH section of the CRLH TL. A Microcircuits level-7 mixer (SBL-1LH) was used, with a conversion gain of -7 dBm. A photograph of the fabricated prototype of the proposed

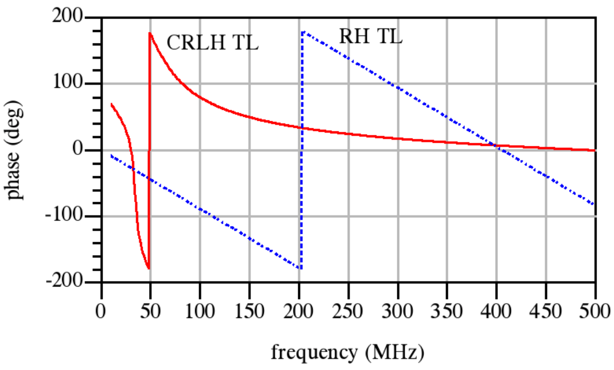


Figure 5. Phase response of the CRLH DLD is the solid red line and that of the RH DLD is the dashed blue line. The responses of both delay lines are presented alongside each other for ease of comparison

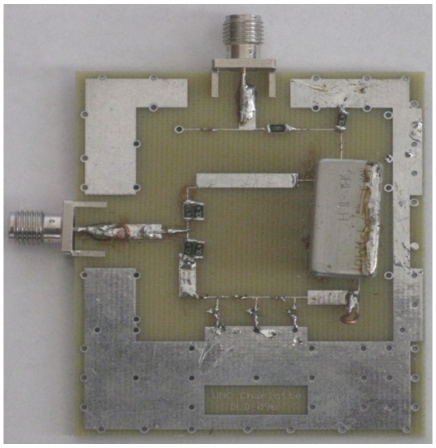


Figure 6. Photograph of the fabricated circuit.

CRLH DLD of Fig. 1 is shown in Fig. 6.

The measured values for the dc output voltage V_{out} of the CRLH DLD prototype of Fig. 6 are presented in Fig. 7. The measured response of the prototype circuit closely resembles the simulation results, as can be seen by comparing the solid red CRLH DLD plot in Fig. 5 with the measured CRLH DLD plot in Fig. 7. The prototype was measured in Fig. 7 with an RF input level of 13 dBm, while the input frequency was swept from 1 to 500 MHz. The relatively high power of 13 dBm was required to overcome the losses in the resistive power divider.

As expected, the measured response of the prototype is dispersive, and even more so at lower frequencies. Despite the dispersion, the steep slope of the proposed DLD can provide increased frequency sensitivity that may be desirable in some applications.

IV. CONCLUSION

A novel approach to design a DLD with CRLH transmission line section is proposed. The measured results of the proposed circuit were in excellent agreement with simulated results. Using a delay line composed of a composite right-left handed transmission line produced a delay line transmission line discriminator with opposite slope response as the conventional transmission line delay line system. In addition, since the left-handed portion of the CRLH line was comprised of discrete components, the physical size of the circuit was much smaller than would be possible using a conventional right-handed transmission line for the delay line. There are few future options that can be explored. A more complex circuit consisting of power divider and couplers using CRLH transmission line structures to increase can be investigated. Similarly, dual band properties of the CRLH transmission lines can be explored.

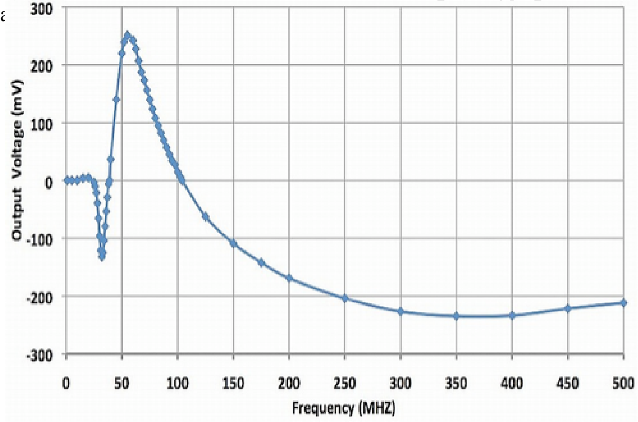


Figure 7. Measured results of the fabricated proposed DLD. The output dc voltage is plotted as a function of the frequency of the input signal.

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